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Indicators of Climate Change in California

Fourth Edition

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INDICATORS OF CLIMATE CHANGE IN CALIFORNIA

Fourth Edition
November 2022

California Environmental Protection Agency

Office of Environmental Health Hazard Assessment

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The Office of Environmental Health Hazard Assessment (OEHHA) acknowledges that the work that led to this report took place on the homelands of California Tribes, who have lived in harmony with the land and its natural resources since time immemorial. OEHHA thanks and acknowledges the wisdom and knowledge shared with us so generously by the Tribes in preparation of this report.

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Lake Oroville (California Department of Water Resources); Thomas Fire in Santa Barbara, December, 2017; worker on a roof in extreme heat; Chinook salmon (US Fish and Wildlife Service); flooded road, 2019 (Pala Band of Mission Indians); San Francisco sky glowing orange from wildfire smoke, September, 2020

In memory of Harry Williams (1956-2021) and Monty Bengochia (1951-2022)

Harry was a Nüümü (Bishop Paiute) Elder and internationally recognized expert in the ancestral water systems of the Payahuunadü — Owens Valley. Harry guided OEHHA along our path working with Tribes. Harry was a Warrior, a Water Protector and friend to many, especially to Mother Earth.

Monty Bengochia was a Nüümü (Bishop Paiute) Elder, water protector and advocate for sacred sites, youth, traditional foods and medicine, as well as a gifted singer. Monty was an important advisor and served on OEHHA Tribal Indicators Working Group. His guidance and insight helped us understand the impacts of climate change on the Payahuunadü.

Harry and Monty will forever be missed, but never forgotten.

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Message from the Secretary

California is a global leader on climate action. This report shows why we are meeting the climate challenge head-on: We can't wait. The effects of climate change are already cascading through our weather, water supplies, plants, and animals – they are affecting our people, and are felt acutely by California's Tribes. Already, we are navigating through record-setting heat, drought and wildfires and noticing ways that nature has changed just since our own childhoods.

This fourth edition of the *Indicators of Climate Change in California* report distills the effects of climate change into 41 indicators, scientific observations that track climate-related trends and patterns across the state over time. Together, these patterns tell the state's climate change story, from its underlying causes and resulting changes in climate to the compounding impacts on public health and the state's natural environment.

The results are stark. California has warmed by an average of 2.5 degrees Fahrenheit since 1895 and drought conditions were comparable to the most severe drought periods on record at the end of 2021. Glaciers have essentially disappeared from the Trinity Alps in Northern California, and, in 2020, wildfire smoke plumes were present in each county for at least 46 days. When the first edition of this report was published in 2009, a key objective was to see if actual impacts of climate change could be documented over time. Today, the report's findings are a clear call to action.

California Tribes face unique threats from climate change and I am pleased that this report includes, for the first time, an evaluation of the impacts climate change has had on California's Native American Tribes and on Tribal resources. The perspectives of the state's first and longest standing stewards are key to informing the actions we need to build a better future for generations to come, and it is critical that we center Tribal perspectives in those efforts to confront climate change.

This report also shows why we must continue to act quickly. This summer, California adopted nation-leading regulations banning the sale of new gas-powered cars by 2035. The forthcoming 2022 Scoping Plan builds on such policies to provide a path to achieving both California's 2030 climate goals and state carbon neutrality no later than 2045, a goal codified by AB 1279 (Muratsuchi, Chapter 337, Statutes of 2022). Since 2004, California has steadily reduced its greenhouse gas emissions, and the indicators in this report present 41 reasons why we're not taking our foot off the accelerator.

Indicators of Climate Change in California is a resource for those seeking to understand how climate change has already affected the state. It is also a key part of the state's strategy to build climate resilience based on the best available science. By charting where we've been, this report prepares us to step boldly into the future.

Yana Garcia, Secretary
California Environmental Protection Agency

Summary

California is experiencing a climate crisis that is increasingly taking a toll on the health and well-being of its people and on its unique and diverse ecosystems. Every Californian has suffered from the effects of record high temperatures, dry winters, prolonged drought, and proliferating wildfires in recent years. California's biodiversity is threatened as alterations to habitat conditions brought about by a changing climate are occurring at a pace that could overwhelm the ability of plant and animal species to adapt.

This fourth edition of the *Indicators of Climate Change in California* report continues to track changes in the state's climate and its impacts in the state. Indicators are scientific measurements that track trends and conditions relating to climate change. Collectively, the indicators portray a statewide picture of how climate change has been impacting the environment and people of California. Through these indicators, the report tells the state's climate change story, starting with the human influences on climate, or "drivers," followed by the changes in climate Californians have been experiencing, and then their consequences on the physical environment, on plant and animal species, and on human health.

This report contains a new section highlighting how California Tribes* have witnessed climate change. Eight Tribes provide accounts of their unique experiences in this section. OEHHA also conducted a series of Tribal listening sessions with over 40 Tribes. These reflect a diversity of perspectives, cultures, beliefs, landscapes, and climate change experiences, and are represented in various sections throughout the report. The information shared in these sessions illustrates the value of Tribal knowledge, acquired from long histories of interaction with the Earth that predate instrumental records. These long-term perspectives advance the understanding of climate change, and can inform policy and action.

REPORTS ON THE IMPACTS ON CALIFORNIA TRIBES

Amah Mutsun Tribal Band
Big Pine Paiute Tribe of the Owens Valley
Big Valley Band of Pomo Indians of California
Bishop Paiute Tribe
Karuk Tribe
North Fork Rancheria of Mono Indians of California
Pala Band of Mission Indians
Santa Ynez Band of Chumash Indians

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* In this report, the term "California Tribes" refers to all Tribal Nations in the state, including those that are non-federally recognized and currently landless.

This summary presents highlights following the organization of the report: (1) climate change drivers; (2) changes in climate; (3) impacts on physical systems; (4) impacts on vegetation and wildlife; (5) impacts on human health; and (6) impacts on Tribes. While many indicators clearly show a trend in the direction expected with climate change, they also reflect the variability that is inherent in the Earth's atmosphere, oceans and other complex systems across seasons, between years, or even between decades.

INDICATORS OF CLIMATE CHANGE IN CALIFORNIA

CLIMATE CHANGE DRIVERS

Greenhouse gas emissions
Atmospheric greenhouse gas concentrations
Atmospheric black carbon concentrations
Acidification of coastal waters

CHANGES IN CLIMATE

Air temperature
Extreme heat events
Winter chill
Cooling and heating degree-days
Precipitation
Drought

IMPACTS ON PHYSICAL SYSTEMS

Snow-water content
Snowmelt runoff
Glacier change
Lake water temperature
Salmon River water temperature
Coastal ocean temperature
Sea level rise
Dissolved oxygen in coastal waters

IMPACTS ON VEGETATION AND WILDLIFE

On vegetation

Marine harmful algal blooms
Forest tree mortality
Wildfires
Ponderosa pine forest retreat
Vegetation distribution shifts
Changes in forests and woodlands
Subalpine forest density
Fruit and nut maturation time
Navel orange worm

On wildlife

Spring flight of Central Valley butterflies
Migratory bird arrivals
Bird wintering ranges
Small mammal and avian range shifts
Copepod populations
Nudibranch range shifts
Chinook salmon abundance
Cassin’s auklet breeding success
California sea lion pup demography

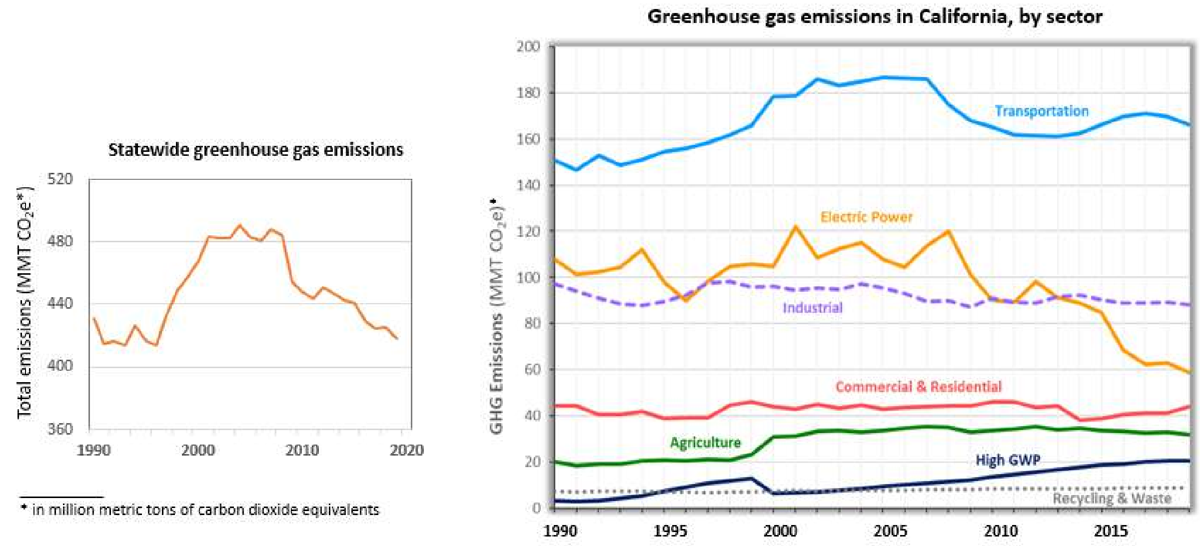
IMPACTS ON HUMAN HEALTH

Heat-related deaths and illnesses
Occupational heat-related illness
Valley fever
Vector-borne diseases
Wildfire smoke

Climate Change Drivers

Since the Industrial Revolution, the burning of coal, gasoline and other fossil fuels, along with changes in land use, have increased global greenhouse gas concentrations in the atmosphere by more than 50 percent. Much of the warming is due to carbon dioxide, the most abundant greenhouse gas, which persists for centuries in the atmosphere. Methane, fluorinated gases, and black carbon (a particulate produced by burning) are more powerful heat trapping gases that have also significantly increased, along with atmospheric concentrations, although these chemicals are less persistent in the atmosphere. The evidence is unequivocal that the buildup of greenhouse gases in the atmosphere from human activities is driving changes in climate, leading to cascading impacts.

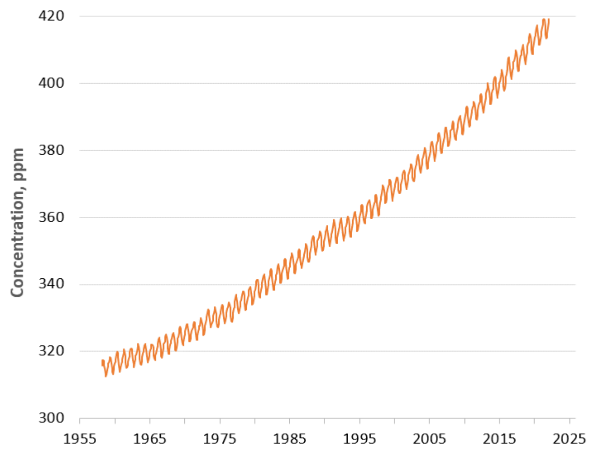
In California, **greenhouse gas emissions** peaked in 2004 and have since been trending downward – evidence of the success of the state's pioneering efforts in reducing emissions. Notably, the 2020 emissions reduction goal (of 1990 levels) was reached in 2016, four years ahead of schedule. Carbon dioxide comprised about 80 percent of the total greenhouse gas emissions in 2019. The transportation sector is the largest source, accounting for 40 percent of all such emissions.



Left: After peaking in 2004, statewide greenhouse gas emissions have declined, falling below 1990 levels (431 million metric tons of carbon dioxide equivalents) in 2016. Right: The transportation and electric power sectors drive most of the year-to-year changes in emissions. Use of renewable energy has led to large decreases in emissions in the electric power sector.

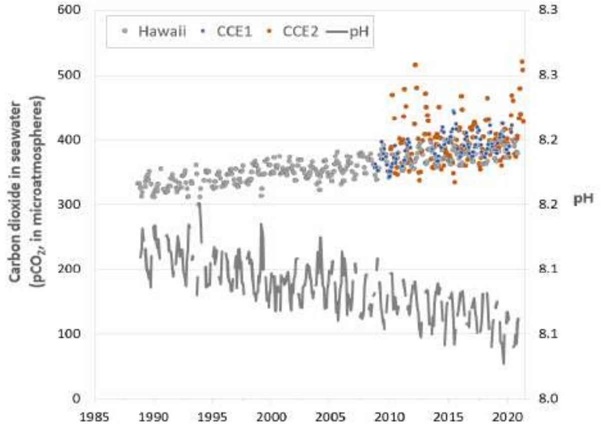
Reductions in emissions will not be immediately reflected as corresponding declines in their **atmospheric concentrations**. Global carbon dioxide concentrations have increased by about 30 percent over the past six decades. Similarly, atmospheric levels of other greenhouse gases (methane, nitrous oxide and certain fluorinated gases) continue to increase.

Monthly average atmospheric carbon dioxide concentrations, parts per million (ppm)



Carbon dioxide concentrations have increased from 315 ppm in 1958 to about 416 ppm in 2021 at Mauna Loa, Hawaii, where the longest continuous global measurements have been taken. Measurements at California coastal sites also show increasing trends (not shown).

Seawater carbon dioxide and pH off Point Conception, CA and Hawaii



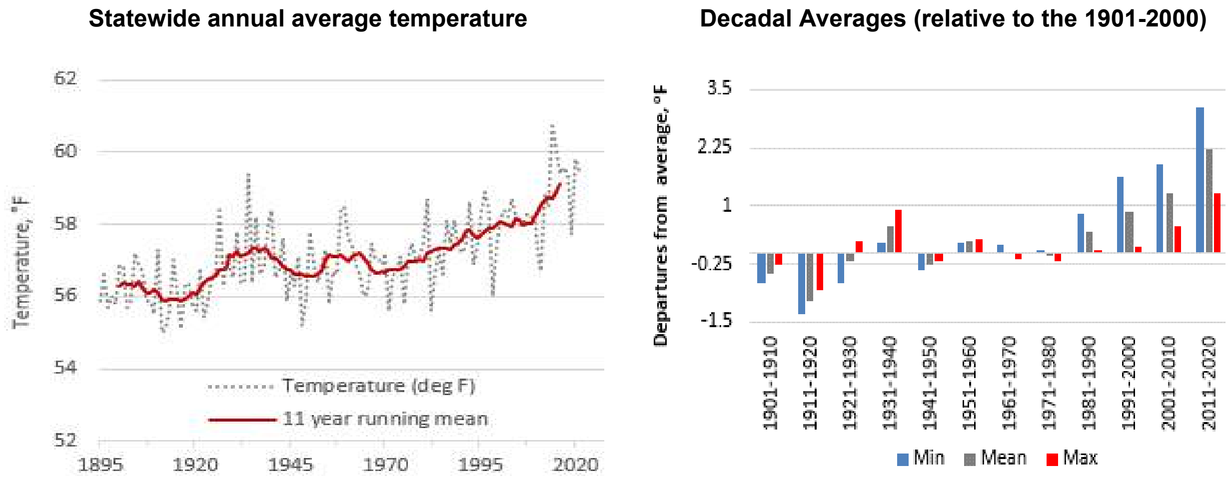
Levels of carbon dioxide in seawater off Hawaii have increased (by about 1.8 microatmospheres per year) over the past three decades, accompanied by increasing acidity (decreasing pH). While not long enough to show a trend, levels off Central California over the same period are similar (CCE1), but are more variable closer to the coast (CCE2).

The ocean absorbs 20 to 30 percent of carbon dioxide emissions, reducing this greenhouse gas buildup in the atmosphere. However, this drawdown of atmospheric carbon dioxide comes at a cost. It changes the chemistry of seawater, leading to **ocean acidification**. Measurements off Hawaii since 1988 show carbon dioxide levels in seawater steadily increasing along with acidity. Signs of ocean acidification are becoming evident in California, where levels similar to Hawaii's have been measured off the Central coast since 2010. Ocean acidification makes it harder for the shells of ecologically and economically important species including krill, oysters, mussels, and crabs to form, and can even cause them to dissolve. Coupled with warming ocean waters and reduced dissolved oxygen levels ocean acidification poses a serious threat to global marine ecosystems.

Changes in Climate

Climate is generally defined as “average weather,” or the long-term weather pattern in an area. Human influence has warmed the atmosphere, ocean, and land, leading to measurable, widespread, and rapid changes in our climate. These changes impact California in multiple ways, and are magnified when multiple climate-related phenomena occur at the same time. For example, warm rain events and melting snowpack increase flood risk; unusually high temperatures accompanied by a lack of rainfall exacerbate drought; and hot, dry, windy conditions increase wildfire risk.

Since 1895, annual average **air temperatures** in California have increased by about 2.5 degrees Fahrenheit (°F). Warming occurred at a faster rate beginning in the 1980s. Recent years have been especially warm: Eight of the ten warmest years on record occurred between 2012 and 2022; 2014 was the warmest year on record. Temperatures at night, which are reflected as minimum temperatures, have increased by almost three times more than daytime temperatures. Nighttime warming has been more pronounced in the summer and the fall, increasing by about 3.5°F over the last century, and Southern California has warmed faster than Northern California.

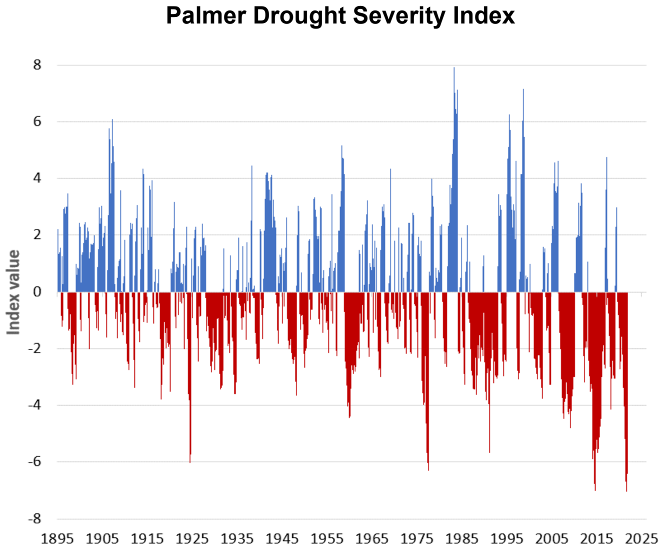

Statewide annual average temperature

Decadal Averages (relative to the 1901-2000)

Annual average statewide temperatures have increased, warming at a faster rate beginning in the 1980s. Decadal averages show marked warming during the last four decades—with each decade successively warmer than the preceding. Compared to yearly averages between 1901 and 2000, average minimum and maximum temperatures were higher by 3.1°F and 1.3°F, respectively, in 2011 to 2020.

As air temperatures have warmed, more **precipitation** has been falling as rain instead of snow at high elevations. The amount of annual precipitation has also become more variable in the past four decades. Winter storms transporting large volumes of water vapor —called “atmospheric rivers” — play a role in this variability. The duration, intensity, and frequency of these storms are affected by warmer air and changing ocean conditions.

Although a naturally occurring feature of California's climate, **drought** conditions have become more frequent and more intense. A combination of hotter temperatures and low precipitation years – especially when snowpack and snowmelt runoff are low--mean drier conditions. California has been getting drier since 1895. By the end of the 2021 water year (which begins in October and ends in September the next year), drought conditions were comparable to those during 2012 to 2016, the most severe drought period on record. In California and across the southwestern United States, 2000 to 2021 has been the driest 22-year period over the past 1,000 years, part of what scientists call an emerging "megadrought" era.



The Palmer Drought Severity Index measures the relative dryness of a region by incorporating readily available temperature, precipitation, and soil moisture data. Between 2010 and 2021, there were 48 months when Index values were at or below -3 (representing severe drought), including eight months with values below -6 (representing very extreme drought).

Indicators of **changes in climate** also show that:

- **Extreme heat events** in California have become more frequent since 1950, especially in the last decade. These are events when temperatures are at or above the highest 5 percent of historical values. Over the past 70 years, extreme heat events increased by 1 to 3 per decade at 10 of 14 locations studied. Heat waves, defined as two or more consecutive heat events, have also become more frequent in the past decade. Averaging 1 to 3 per year in earlier decades, daytime heat waves more than doubled to 5 to 6 per year in five locations studied; nighttime heat waves similarly increased to 5 to 7 per year at 10 locations, and up to as high as 10 per year at one (Blue Canyon).

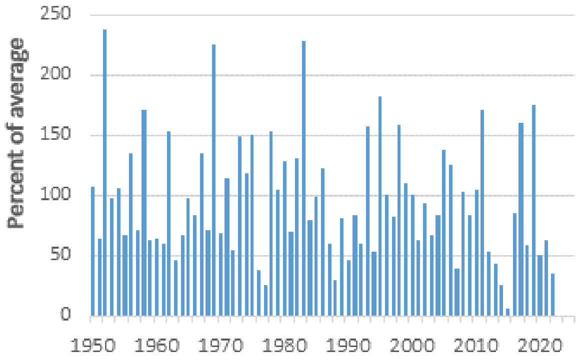
- Across California's Central Valley, **winter chill**, a period of cold temperatures required for dormancy by fruit and nut trees to flower and fruit, has been declining.

- The energy needed to cool buildings during warm weather — measured by "**cooling degree days**" — has increased in California, while the energy needed to heat buildings during cold weather — measured by "**heating degree days**" — has decreased.

Impacts on Physical Systems

Warming temperatures and changing precipitation patterns have altered California's "physical systems" — the ocean, lakes, rivers, glaciers, and snowpack – upon which the state depends. Winter snowpack and spring snowmelt runoff from the Sierra Nevada and southern Cascade Mountains historically provided approximately one-third of the state's annual water supply. The amount of water stored in the snowpack, referred to as **snow-water content**, varies widely from year to year, and is lower in years with warm winters. Measured on April 1st, when the snowpack has historically been deepest, snow-water content has ranged from a high of about 240 percent of average in 1952 to a record low of 5 percent of average in 2015. In 2022, it was 35 percent of average.

Snow-water content, as a percentage of average

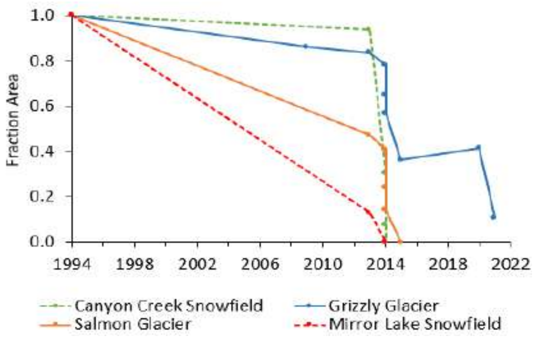


Credit: DWR

Snow-water content measured on April 1st (when the snowpack has historically been deepest) has ranged from a high of about 240 percent of average in 1952 to a record low of 5 percent of average in 2015. In 2022, snow-water content was 35 percent of average. Average snow-water content is about 28 inches.

Reduced snowpack and earlier spring warming have led to an eight percent drop in the fraction of spring **snowmelt runoff** into the Sacramento River and the San Joaquin River over the past century. Reduced spring runoff means less water for domestic and agricultural uses, for hydroelectric generation, and for cold-water habitats and forest ecosystems.

Change in area: Trinity Alps glaciers and snow fields

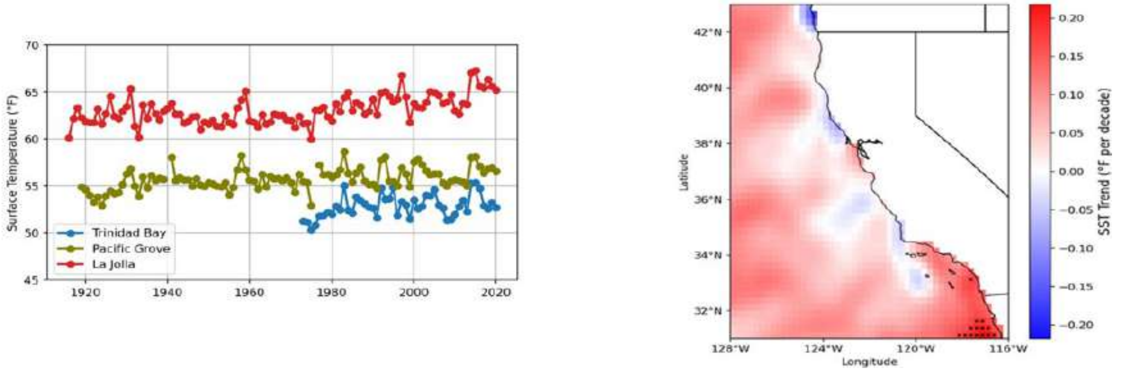


By 1994, Grizzly and Salmon Glaciers had lost about 80 percent of their 1885 area (not shown). By 2015, Salmon Glacier and the two snowfields had disappeared. By 2021, what remains of Grizzly Glacier is about 10 percent of its 1994 area.

Snow and cold temperatures also sustain glaciers and year-round snowfields. Today, glaciers are among the most visible casualties of climate change. Winter temperatures determine glacier mass gain and summer temperatures determine glacier loss. Mountain **glaciers** have melted dramatically over the past century. Since 1903, seven of the largest glaciers in the Sierra Nevada have lost 65 to 90 percent of their area.

In the Trinity Alps, two snowfields and one of two glaciers had disappeared entirely by 2015. What remains of the second glacier in 2021 is arguably too small to be considered a glacier any longer. While glaciers may feel remote and inaccessible, glacial runoff provides critical cold freshwater habitat for many aquatic species, including California salmon populations.

The ocean absorbs about 90 percent of the excess heat from rising global temperatures. California **coastal ocean temperatures** have warmed, particularly off Southern California. A century of measurements at La Jolla show sea surface temperatures warming by 0.3°F per decade—a trend corroborated by four decades of satellite-based data. The dire ecological consequences of warming waters were evident during a period of unusually high ocean temperatures (a “marine heat wave“) off the California coast from 2014 to 2016: mass strandings of marine mammals and sea birds, initiation of a toxic algal bloom that led to the closure of crab fisheries, and loss of kelp forests. Changes in the abundance and distribution of prey forced humpback whales to move closer to shore, leading to a record number of whale entanglements in fishing gear.



Annual average sea surface temperatures at selected shore stations (1916-2020)

Satellite-based sea surface temperature trends along the California Coast (1982-2021)

Left: Nearshore coastal waters have warmed 0.2°F per decade at Pacific Grove, and 0.3°F per decade at La Jolla and Trinidad Bay. Right: Satellite-based records show that waters off the California coast are largely warming. A distinct warming trend is evident off Southern California, especially near shore.

Indicators of the impacts of climate change on **physical systems** also show that:

- **Sea level rise** is occurring along the California coast, at 1 to 2 millimeters (0.04 to 0.08 inch) per year. (The exception is Crescent City, where movement of the Earth’s plates have caused an uplift of the land surface.) Sea level rise can lead to flooding, beach erosion, bluff retreat, and other impacts on low-lying areas of the coast.
- Increased air temperatures and reduced snowmelt have led to warming temperatures in freshwater bodies. **Lake water temperatures** at Lake Tahoe, when averaged across all depths, have increased by about 1°F over the past half century. Surface water temperatures have warmed by almost twice as much in the same period; six of the last ten years ranked among the warmest. Warming waters affect the lake’s key physical and biological processes. In the Northern California Klamath Mountain region, **Salmon River water temperatures** have increased by as much as 2°F per decade since the mid-1990s, threatening spring-run Chinook salmon in the watershed.
- **Oxygen concentrations** in ocean waters off Southern California have declined since the mid-1990s. Declining dissolved oxygen concentrations, in concert with ocean acidification and warming ocean temperatures, threaten species diversity and abundance, and marine food webs.

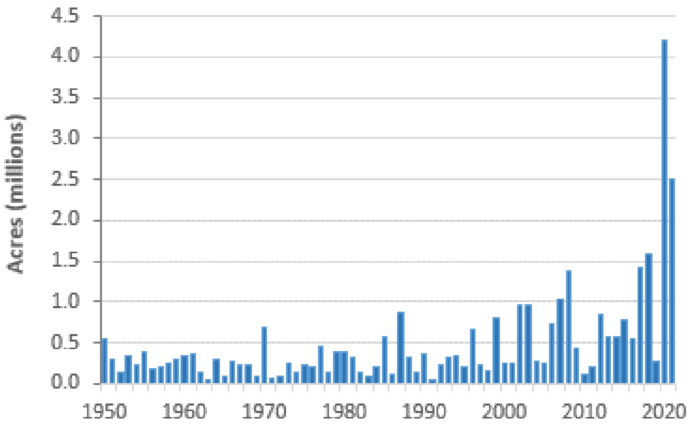
Impacts on vegetation and wildlife

Climate change has altered habitats and impacted ecosystems across the planet, threatening biodiversity. In California, plant and animal species have responded to a changing climate. Some species have moved northward or to higher elevations. Others have experienced shifted timing of key life cycle events, altered community composition, or population decline. These responses have been shown to track climate patterns, including natural variability, as well as the influence of land use, land management, environmental pollution, and other human activities.

Vegetation

When plant water demand exceeds the amount available in the soil, vegetation becomes stressed, and more easily succumbs to attacks by pests and pathogens. Hot and dry conditions increase the water deficit and make dead vegetation easier to burn, heightening wildfire risk. The unprecedented scale of **tree deaths** in California forests has increased fuel loads, increasing the risk of large, severe wildfires. An estimated 170 million trees died between 2010 and 2021, peaking in 2016, the fourth year of the extreme drought.

Statewide annual acres burned



The area burned by wildfires has increased in the last two decades. The average area burned each year in the 2000s and 2010s was twice the 1990s average, and in 2020-2021 was ten times higher.

Over the last 20 years, the area burned by **wildfires** across California has increased dramatically. In 2020 alone, 4.2 million acres burned, more than double the area burned in any other year on record. Ten of the 20 largest wildfires since 1950 burned in 2020 and 2021. The 2020 August Complex burned more than one million acres in seven counties, making it the state's first "gigafire." The recent wildfires have caused deaths and injuries, widespread exposures to harmful levels of wildfire smoke, displacement and disruption of communities, damage to structures and property, and tragic losses among some of the state's most iconic species: coast redwoods, giant sequoias, and Joshua trees.

Crops are also affected by climate change. In parts of the Central Valley, certain **fruits and nuts** are maturing more quickly with warming temperatures, leading to earlier harvests. The report presents data on prunes and one walnut variety. Shorter maturation times generally lead to smaller fruits and nuts, potentially causing a significant loss of revenue for growers and suppliers. Processing tomatoes have also been maturing faster over the past four decades in Yolo County and four other top tomato-producing counties.

Indicators of the **impacts of climate change on vegetation** also show that:

- The state's **forests and woodlands** have changed: today there are 80 percent more small trees and 70 percent fewer large trees in parts of Southern California forests compared to the 1930s; similar patterns are seen statewide. Pines occupy up to 55 percent less area, and in certain parts of the state, oaks cover up to 40 percent more area. Reduced moisture and warmer conditions favor oaks over pines; wildfires remove conifers and facilitate the establishment of broadleaf forests. These changes are influenced by climate factors as well as forest management. These changes are influenced by climate factors as well as forest management and fire suppression practices.

- Changes in the distribution or density of vegetation have also been observed. On the western side of the northern Sierra Nevada Mountains the lower edge of the **Ponderosa pine forest** has moved upslope. Across the north slope of Deep Canyon in the Santa Rosa Mountains in Southern California the dominant plant species have moved upslope. In the **subalpine forests** of the Sierra Nevada (elevations 7,500 to 11,000 feet), small tree densities have increased, while large tree densities have decreased.

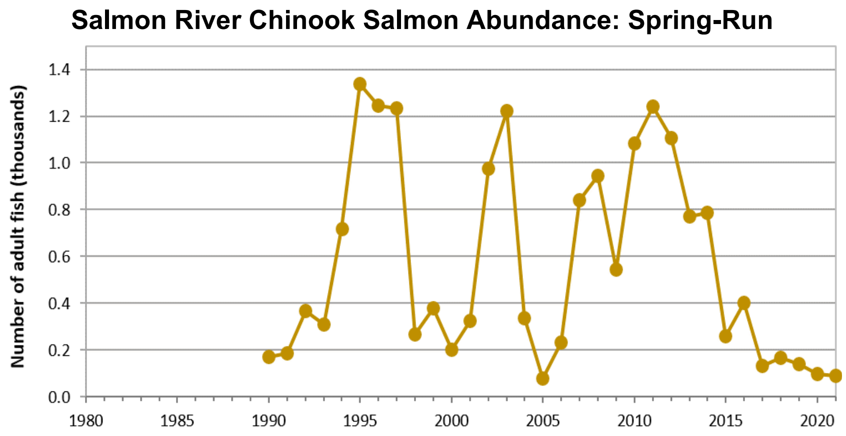
- The risk of crop damage has increased as certain insects multiply faster with warmer temperatures. The **navel orangeworm,** for example, is an insect pest that causes severe damage to Central Valley walnuts, almonds, and pistachios. Over the past four decades, the time required for this pest to complete its life cycle has decreased and the number of generations per season has increased. Each new generation during a season poses an increased threat to California's nut crops.

- Patterns of **marine harmful algae blooms** in California coastal waters have been changing, influenced in part by warming ocean temperatures. The presence of the algae and the toxins they produce is highly variable, and monitoring data are not long enough to discern trends. However, since 2018 blooms of red tide-forming algae have become more frequent and more abundant at Santa Cruz Wharf. Toxins produced by these algae can move up the food chain, and when consumed, can cause illness in people, or death in fish, marine mammals, and seabirds.

Wildlife

A landmark study conducted over a century ago (known as the Grinnell Survey) serves as a historical baseline of the habitat conditions and the distribution and abundance of birds and mammals at study sites in selected regions of California. These sites were resurveyed to document habitat and species changes over the past century. Today, certain birds and mammals are found at different elevations in the Sierra Nevada (Lassen, Yosemite and Sequoia and King's Canyon) compared to a century earlier. **Range shifts** were observed in almost 75 percent of the small mammal species and over 80 percent of the bird species surveyed. In the Mojave Desert, which has become warmer and drier over the past century, widespread collapse of bird communities has occurred. Populations of prairie falcons, turkey vultures, chipping sparrows, mourning doves and other birds have declined. By contrast, small mammal populations have remained stable. As desert conditions became hotter and drier, dehydration was a major factor in the decline of bird populations.

Climate-influenced changes in freshwater and ocean conditions are threatening the survival of Chinook salmon in Northern California rivers. Chinook salmon are legendary for migrating from the streams where they were hatched to the ocean, travelling as far as a thousand miles, only to return to the same streams to spawn. **Chinook salmon abundance** across the state has historically declined due to dams and other human influences that restrict fish passage.



In the Salmon River, spring-run numbers have generally plummeted over the last decade. The counts in each of the last five years have ranged from about 90 (in 2021) to 170 (in 2018), far below the long-term average (570 fish).

The timing of the adult migration from the ocean to the stream where they were born defines salmon "runs." Most of California's Chinook salmon runs are in the Central Valley in the Sacramento and San Joaquin River basins, and in the Klamath Basin in the Klamath and Trinity Rivers and tributaries, including the Salmon River. Salmon River spring-run populations have suffered huge declines, with extremely low counts in the last five years. They have hence been designated as a threatened species. These counts reflect a clear signal of the impacts of climate change on salmon, given the minimal human influences on the Salmon River watershed.

The Sacramento River is home to four salmon runs: the winter, spring, fall, and late-fall runs. When environmental conditions threaten salmon survival, hatcheries and cold water dam releases help sustain and rebuild fish populations. These practices became especially important during the 2012-2016 drought, which caused reduced flows in the watershed, elevated water temperatures, and decreased prey availability. The winter-run, the least abundant of the runs, has seen periods of alarmingly low numbers, and is listed as a threatened species. This run spawns in the summer months when water temperatures are their warmest and has persisted largely due to cold water releases and addition of hatchery fish.

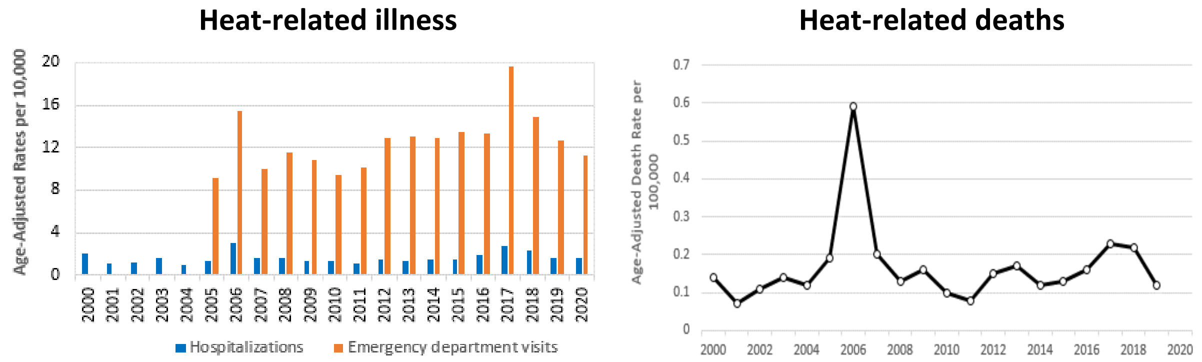
Indicators of the **impacts of climate change on wildlife** also show that:

- **Copepod populations** in the California Current fluctuate, mirroring the variability in ocean conditions that reflect changes in temperature and ocean currents. Cold waters from the north transport copepod species with higher nutritional value than those carried by warm waters from the tropics. During the period of unusually warm ocean conditions in 2015 to 2016, the copepod community was dominated by warm-water species. Copepods are at the base of the food chain, and when cold-water copepods are abundant, so are other species, notably salmon and the small fish that they prey on.
- Species responses to changing ocean conditions have included:
  - Fewer **California sea lion pup** births, higher pup mortality, and poor pup conditions at San Miguel Island off Santa Barbara during years when sea surface temperatures are unusually warm in their breeding area. In these years, the fish they feed on are less abundant and the nursing mothers must either travel farther to obtain food, or eat less nutritious prey.
  - A northward expansion of the range of a **nudibranch** sea slug, *Phidiana hiltoni*, from the Monterey Peninsula to Bodega Bay since the mid-1970s, a distance of almost two hundred miles.
  - Variability in the breeding success of **Cassin's auklets**, a seabird species on Southeast Farallon Island near San Francisco, associated with fluctuating availability of krill and other prey in nearby ocean waters.
- Over the past 50 years, several **Central Valley butterfly species** have been appearing earlier in the spring, a shift correlated with hotter and drier conditions in the region. Changes in seasonal timing among interacting species—for example, butterflies and their plant food sources—could disrupt population dynamics across animal and plant species.
- Observed responses among migrating birds include changing patterns of spring and fall **migratory bird arrivals** at Point Reyes National Seashore in northern California, and range shifts northward and closer to the coast among **wintering bird species** statewide.

Impacts on human health

Climate change directly impacts human health through exposures to heat, floods, and other weather events. In addition, it indirectly affects health by exacerbating health threats through higher levels of air pollutants, degraded water quality, and increased populations of disease vectors.

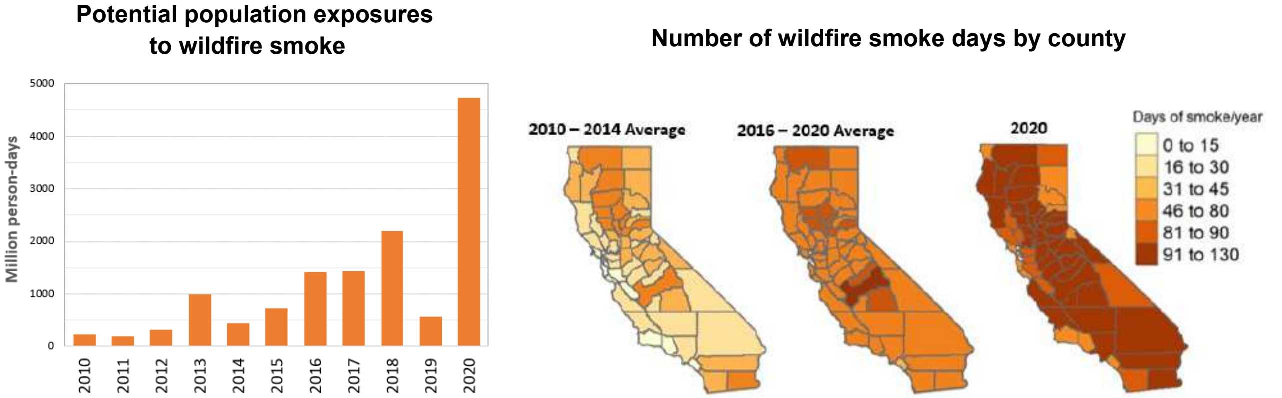
Heat causes more reported deaths per year on average in the United States than any other weather hazard, yet heat-related illnesses and deaths are generally preventable. Heat rash, heat cramps, heat exhaustion, and heat stroke fit the classical case definition of heat-related illness. However, heat exposure can produce other health effects, and aggravate a broad range of health conditions. As temperatures warm, emergency department visits due to heat-related illnesses are on the rise in California. Hospitalizations and deaths spike in years with especially high summertime temperatures. This is notable given that **heat-related illnesses and deaths** are often unrecognized and underreported, and therefore the actual number of victims is likely considerably higher.



Left: California heat-related hospitalizations and emergency room visits for which heat stress was explicitly listed as the diagnosis are shown. Emergency room visits and hospitalizations were highest in 2017, when summertime temperatures were unusually high, and in 2006, the year of a prolonged heat wave. (Data for emergency department visits were not available until 2005.)

Right: Deaths for which the main or contributing cause is coded as heat-related were highest in 2006. Period covered is from May to September of each year.

As climate change increases the frequency, size, and duration of wildfires in the state, the health of Californians is increasingly threatened by exposures to **wildfire smoke**. Wildfire smoke consists of fine particulate matter (PM2.5) and other hazardous compounds that can irritate the eyes, nose and lungs, and worsen chronic heart and respiratory diseases. Wildfire smoke can also impact mental health. Based on satellite imagery, an estimate of potential exposure of people in areas where wildfire smoke plumes were present ("person-days") has been increasing since 2010. There were fewer days each year, on average, when smoke plumes were present in 2010 to 2014 compared to 2016 to 2020. The last five-year period includes 2020, the worst year on record for wildfires. That year, the fire season was marked by several large wildfires burning at the same time; smoke plumes were present in every county for at least 46 days. For weeks, daily maximum PM2.5 levels remained hazardous, according to the Air Quality Index, in several areas of the state.



Left: Potential exposures to wildfire smoke – based on the number of days when plumes were present and the number of people living in those areas (measured as "person-days") – have significantly increased over the past decade. Right: In 2010-2014, smoke plumes were present in 11 counties at least 46 days per year on average, compared to 56 counties in 2015-2020. In 2020, when a record-high 4.2 million acres burned across the state, smoke plumes were present in every county for 46 days or more; 36 counties had 91 or more smoke plume days.

Indicators of the **impacts of climate change on human health** also show that:

- **Occupational heat-related illnesses** reported by California workers increased between 2000 and 2017 from a rate of about 3.5 to 10 per 100,000. Employees in protective services (firefighters and police) and farmworkers had the highest rates of illness.

- With warming temperatures and changes in precipitation, the number of mosquitos (known as "vectors") carrying West Nile Virus increase. This is just one example of **vector-borne disease** patterns in California affected by climate change. West Nile Virus currently poses the greatest mosquito-borne disease threat in the state. Higher temperatures shorten the time it takes both for the mosquito to complete its life cycle (from egg to adult) and for the virus to multiply in the mosquito. As a result, there are a greater number of infected mosquitoes to potentially infect humans.

- The incidence of **Valley fever** has increased over the past 20 years in California. Valley fever is caused by inhaling spores of the *Coccidioides* fungus that is endemic in the soil in the Central Valley and Central Coast regions of the state. Although the reasons for increased cases are likely multifactorial, drought, dry soil conditions, and other climate-related changes play a major role in fungal proliferation and spore dissemination, and eventual human and animal infection with Valley fever.

Impacts on California Tribes

Climate change poses a threat to California's Tribes through impacts on the ecosystems in which they live and are connected, as the health of a Tribe is tied to the health of the environment. California Tribes are the original biologists, historians, climatologists, and scientists of this land. Tribal knowledge, acquired from long histories of their interaction with the earth, is a key component in advancing the full understanding of climate change and addressing its impacts.

Credit: L'eaux Stewart

The Eastern Sierras route to the Palisades, part of the traditional territory of the Big Pine Paiute Tribe of the Owens Valley

When Tribes speak of nature, they include themselves. The earth provides food, medicines, fibers and ceremonial materials that are embedded within cultural, social, spiritual, economic, political systems, and daily Tribal life. Knowledge of the unique interactions between species and their habitat provides the foundation for Tribal actions to manage the landscape.

Climate change is impacting Tribes throughout California. Warming temperatures, changing precipitation patterns, and intensifying droughts have increased reliance on groundwater, degraded aquatic habitat, stressed vegetation, and diminished previously abundant wildlife. As the environment is impacted by climate change, Tribal health suffers. From the Tribal lands in the Owens Valley, where emissions from the now dry Owens Lake make it the largest single source of particulate matter (PM10) in the United States, to the soaring temperatures in Southern California, Tribes are experiencing a wide range of impacts. They have seen a reduction of native foods and culturally important plants and

Credit: Joe Ferreira (UCD), Richard Macedo (CDFG); CDFW, 2021

Culturally important species include (clockwise from left): Owens Valley pupfish, Clear Lake hitch, and big horn sheep.

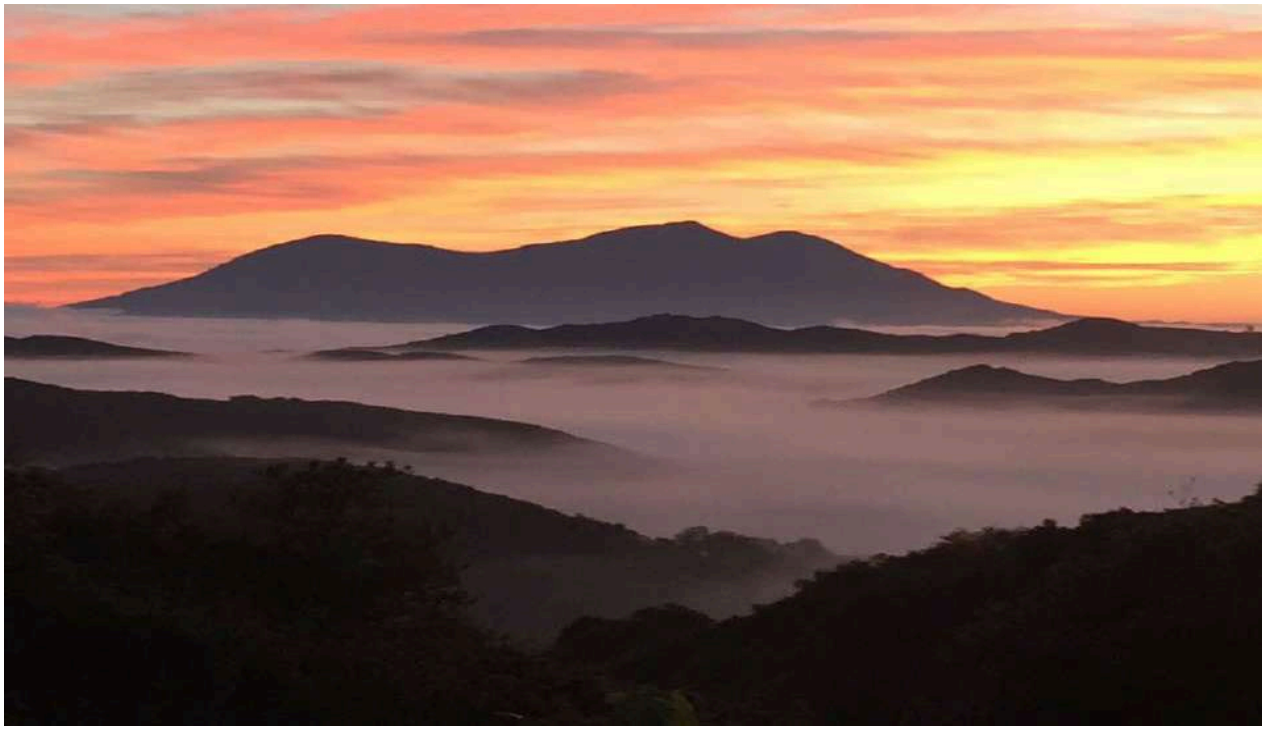
animals. In addition to PM10 exposures, elevated ozone concentrations on warmer days, and more frequent days with wildfire smoke pose risks to the health of the Tribes. Toxins produced by harmful algal blooms threaten their food and water and impair their ability to use lakes and rivers. The physical, cultural, and spiritual health of Tribes are suffering as climate change intensifies.

Credit: Karuk Tribe

One of 22 Karuk Tribal cultural indicators, the Púfpuuf, or Pacific Giant Salamander, camouflaging with its environment

Coastal Tribes have witnessed rising sea levels, along with the loss of kelp forests, making parts of the coast more vulnerable to erosion and exposing cultural artifacts. Kelp forests, which used to provide a protective buffer to the coast, are collapsing along parts of the coast due in part to the cascading impacts of warming ocean waters. Coastal Tribes note that access to traditional sites along the shoreline is more difficult with these impacts and this hampers the Tribe's ability to pass knowledge down to younger generations.

California Tribes are acting to protect their communities from the adverse effects of climate change. Habitable climate is critical to protecting tribal sovereignty, culture, and community cohesion. The Tribes are actively working to manage and protect their lands and limit the impact climate change is having on their right to hunt, fish, gather, and continue their cultural practices – activities that are integral to their health, well-being, and livelihood.



Credit: Middleton Rancheria of Pomo Indians of California

Sunrise at Mount Konocti, Lake County

Emerging climate change issues

Changes and impacts in California's environment that are plausibly influenced by climate change, though not yet established, are referred to in the report as emerging issues. Scientifically defensible hypotheses, models, and/or limited data support the assertion that certain observed or anticipated changes are in part due to climate change.

Among the emerging issues described in this report are:

- Reductions in the duration and extent of Central Valley and coastal fog, which play a vital role in their respective ecosystems.
- Increased lightning activity with warming air temperatures.
- Apparent increased frequency and extent of harmful algal blooms in freshwater bodies, and how much is attributable to climate change versus nutrient discharges and other anthropogenic factors.
- Transmission of bluetongue, a viral disease of sheep, goats, and cattle transmitted by biting midges.
- Changing climate conditions that allow invasive agricultural pest species like the Oriental fruit fly to thrive in places where they previously could not survive.
- Influence of shifts in temperature and rainfall on reported declines in bumble bee populations globally and in California, in light of other factors including insecticides, pathogens infections and habitat loss.
- Increasing levels of aeroallergens plants and mold, which trigger asthma and hay fever.
- Increasing risks of food- and waterborne infections due to changes in climate.
- Increasing transmission of zoonotic diseases, that is, infectious diseases shared between humans and animals.

Introduction

The stark reality of climate change in California is clear: record-high temperatures, an unrelenting drought, and unprecedented wildfires. The evidence continues to mount of the impacts of climate change on the health, safety, and well-being of the state's residents, and on its unique ecosystems that are home to one of the most diverse arrays of plant and animal species in the world. This fourth edition of the *Indicators of Climate Change in California* report captures much of this evidence.

The Office of Environmental Health Hazard Assessment (OEHHA) prepares these reports on behalf of the California Environmental Protection Agency under state law (Public Resources Code Section 71080 et seq.), which designates the Office as the lead agency for the development and maintenance of environmental indicators for the Agency. The report presents a collection of indicators that track climate change, its drivers, and its impacts. Indicators are scientifically based measurements of observed phenomena that describe, and facilitate communication about, the various aspects of climate change.

The first edition of this report in 2009 presented 27 indicators showing evidence of the discernable impacts of climate change in California consistent with global observations. Today, the evidence for human-induced climate change is unequivocal. An ever-growing body of data – from paleoclimate studies, instrumental measurements, satellite imagery, and improved computer models – allow scientists to better understand climate processes, including extreme events. Since the first report, California has witnessed a continuation of most trends: increases in air, ocean and freshwater temperatures, rising sea levels, and declining spring snowmelt. This report and the previous edition show that recent years have been punctuated by alarming discontinuities: record high temperatures, record low snowpack, exceptional drought, record-breaking wildfires, unprecedented marine heat waves, and disappearing glaciers, among other things.

A new section in this fourth edition focuses on how climate change has impacted California's Tribal Nations. Tribal experiences and knowledges, acquired from long histories of interactions with the Earth, is a key component in advancing the full understanding of climate change and addressing its impacts. This section recognizes the value of Tribal knowledges, which embody long-term observations and perspectives that pre-date instrumental records, in informing decision-making across California.

By documenting historical trends, this report adds to the body of scientific information on the understanding of climate change and its impacts on the state. More than 100 scientists and researchers in state and federal government, academia and research institutions, as well as over 40 California Tribes, contributed to the development of this report. The report showcases reliance on data and scientific research as the foundation for the state's climate policy. By bringing together indicators that provide a retrospective picture of climate change in California, it complements the California Climate Change Assessments, which focus on original research and projections to advance the understanding of climate-related vulnerability; the State Adaptation Strategy, which outlines what the state is doing to address impacts and build resilience; and the Scoping Plan, which lays out approaches to reach California's emissions reduction goal and to move towards carbon neutrality. It also serves as a resource for scientists, educators, and the public.

Report structure and content

This report is organized into six sections, starting with the (1) human influences on climate, or "**drivers**," followed by (2) **changes in climate**, then their impacts (3) on **physical systems**, (4) on **plant and animal species**, and (5) on **human health**. The report contains a new section (6) on the impacts of climate change on **California Tribes** in eight chapters written by their respective Tribe, along with summaries of three listening sessions during which additional Tribes offered their perspectives.

Of the 41 indicators in this report, 6 are new, 24 have been updated to incorporate new data (including five indicators with additional metrics), 5 are updated with relevant information but without new data, and 6 are the same as the Third Edition (2018).

Each indicator chapter presents one or more graphs or maps illustrating the change over time, followed by a discussion of:

- What does the indicator show?
- Why is the indicator important?
- What factors influence the indicator?
- Technical considerations (describing characteristics, strengths, and limitations of the data)
- Contributor(s) to the chapter
- References cited

The section on Tribal impacts captures the knowledge, observations, and perspectives of each tribe regarding the direct and indirect impacts of climate change on their lives, livelihood, and ecosystems.

The last section of the report on ***emerging climate change issues*** identifies changes in California's environment that are plausibly — but not yet established to be — influenced by climate change. The link to climate change is supported by scientifically defensible hypotheses, models, and/or limited data. However, factors such as land use and environmental pollution, as well as the inherent variability of the climate system, make it difficult to attribute these changes as impacts due to climate change. Additional data or further analyses are needed to determine the extent to which climate change plays a role.

To support its efforts to update existing indicators and identify new indicators, OEHHA continually monitors the scientific literature, publications of research organizations, governmental entities and academia, and other sources for information relating to climate change and its impacts on California. Since 2013, OEHHA has compiled bibliographies of selected publications presenting observations and new or emerging scientific information on climate change, with an emphasis on California. The bibliography is available online as a searchable database.

This indicator report will continue to be updated periodically. OEHHA welcomes input from the research community, governmental agencies, Tribal governments, non-governmental organizations, and other interested parties. It is our goal that the indicators, both individually and collectively, address the key aspects of climate change and promote informed dialogue about the state's efforts to monitor, prepare for, and mitigate climate change and its impacts.

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Climate Change Drivers

The Earth’s climate is a complex, interactive system consisting of the atmosphere, land surfaces, water bodies, snow and ice, and living organisms. This system is influenced by its internal dynamics and by external factors, both natural and human-induced. Examples of natural factors include solar radiation and volcanic eruptions. Human-induced factors include fossil fuel combustion and deforestation (IPCC, 2021). The Earth has experienced natural cycles of climatic changes throughout its history. However, the current warming trend is unusual in that it is happening at an unprecedented rate due to human activity.

Heat-trapping greenhouse gases are the major human-influenced drivers of climate change, with carbon dioxide (CO_2) being the largest contributor. Primarily emitted from fossil fuels, annual average global concentrations of CO_2 exceeded 400 parts per million (ppm) in 2015 for the first time since records began. This benchmark provides a stark reminder that atmospheric greenhouse gases continue to increase. Moreover, given that CO_2 persists in the atmosphere, levels will likely stay above 400 ppm for generations to come (IPCC, 2021).

California showed its commitment to limiting greenhouse gas emissions when it enacted the California Global Warming Solutions Act of 2006 (also known as AB 32). The law established the nation’s first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective emissions reductions. California reached its target of reducing greenhouse gas emissions to 1990 levels by 2020, four years ahead of schedule, and emissions continue to decline, as an indicator in this section illustrates. Through further actions California aims to achieve carbon neutrality by 2045. This means that all greenhouse gas emissions are balanced by their removal from the atmosphere, either through carbon sinks or carbon capture and storage. The main natural carbon sinks are soil, forests and oceans.

Since the mid-1980s the ocean has absorbed approximately 20 to 30 percent of the CO_2 released into the atmosphere by human activities. While this has significantly slowed CO_2 buildup in the atmosphere, it has changed the chemistry of seawater (Bindoff et al., 2019; Canadell, et al., 2021; Friedlingstein et al., 2022). This change – called ocean acidification – is observed in California waters, and threatens the state’s marine ecosystems, impacting some of the most ecologically and economically important species.

Other greenhouse gases include methane, nitrous oxide, and fluorinated gases such as hydrofluorocarbons and perfluorocarbons. Methane, hydrofluorocarbons, and anthropogenic black carbon are more powerful warming agents than CO_2, and have significantly shorter lifetimes in the atmosphere. Reducing emissions of these "short-lived climate pollutants" can have more immediate effects in slowing the rate of warming. California has a comprehensive strategy to reduce short-lived climate pollutants, and trends for certain pollutants show significant reductions.

International climate agreements aim to prevent "dangerous anthropogenic interference with the climate system." The 2015 Paris Agreement commits to efforts to limit the global temperature increase to 1.5°C (2.7°F) (UNFCCC, 2016). There are options available now to do so and at least halve global emissions by 2030, including the use of renewable energy, which has become more cost-efficient and helped slow the growth rate of global emissions.

INDICATORS: CLIMATE CHANGE DRIVERS

Greenhouse gas emissions *(updated)*
Atmospheric greenhouse gas concentrations *(updated)*
Atmospheric black carbon concentrations *(no update)*
Acidification of coastal waters *(updated)*

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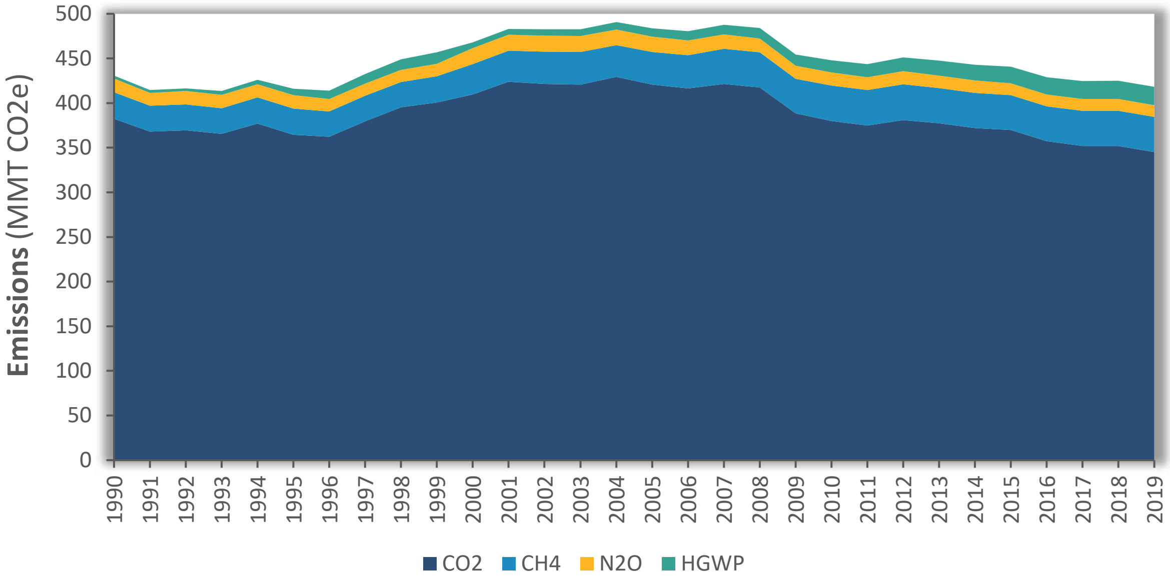
GREENHOUSE GAS EMISSIONS[1]

Statewide greenhouse gas (GHG) emissions peaked in 2004, but have since been on an overall downward trajectory. Emissions have remained below California's GHG emissions reduction goal (431 million metric tons of carbon dioxide equivalent) since 2016. Similarly, GHG emissions have steadily decreased on a per capita and gross state product basis.

Figure 1. Greenhouse gas emissions in California 1990 - 2019, disaggregated by pollutant*



Source: CARB, 2007; CARB, 2021a

**Based on IPCC Fourth Assessment Report 100-year global warming potentials*

MMTCO$_2$e = million metric tons of carbon dioxide equivalents

What does the indicator show?

California's combined emissions of the greenhouse gases (GHG) carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high global warming potential (high-GWP) gases reached peak levels in 2004, but have since decreased and remained below the 1990 emissions levels since 2016 (CARB, 2021a). GHG emissions are expressed in million metric tons (MMT) of

What are "CO$_2$ equivalents"?

Emissions of greenhouse gases other than carbon dioxide (CO_2) are converted to **carbon dioxide equivalents,** or **CO$_2$e,** based on their global warming potential (GWP). GWP represents the warming influence of different greenhouse gases relative to CO_2 over a given time period and allows the calculation of a single consistent emission unit, CO$_2$e.

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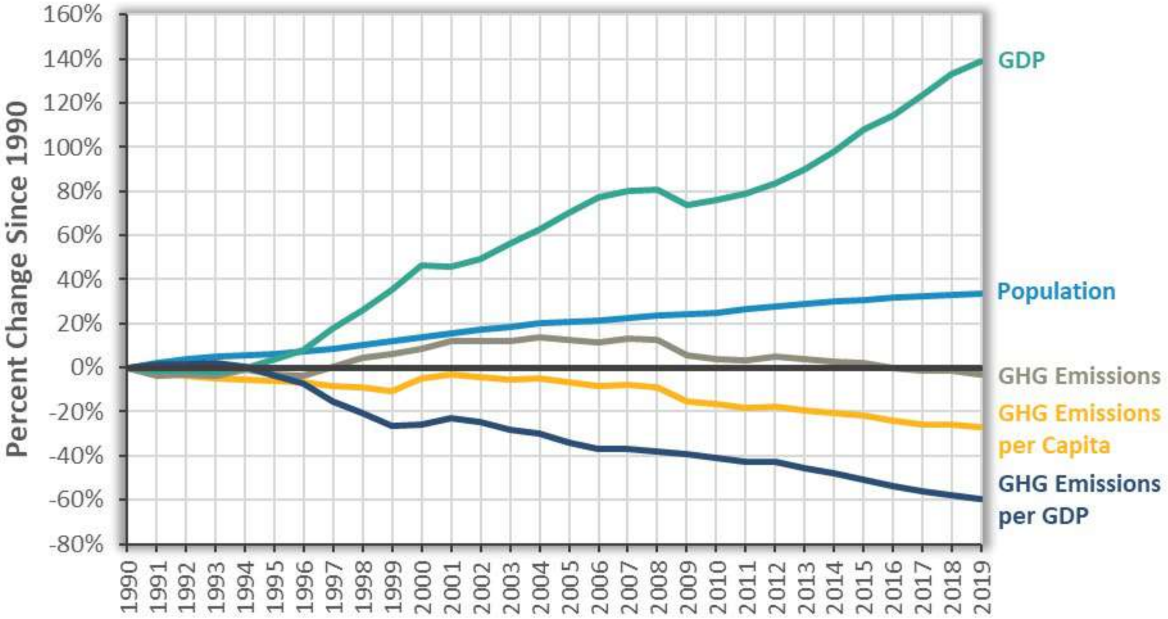
[1] A new edition of the California Greenhouse Gas Inventory has since been released and includes data through 2020. The inventory is available at the California Air Resources Board's website.

carbon dioxide equivalents (CO_2e) based on 100-year global warming potential values as specified in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2006).

CO_2 accounts for the largest proportion of GHG emissions, making up 83 percent of total emissions in 2019. In comparison, CH_4 and N_2O account for 9 percent and 3 percent of total GHG emissions, respectively. The remaining 5 percent of GHG emissions consist of high-GWP gases including hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). Among these GHGs, methane and a subset of HFCs[2] are also considered short-lived climate pollutants (SLCPs), which are powerful climate forcers that remain in the atmosphere for a much shorter period than longer-lived climate pollutants such as CO_2. SLCPs are discussed further below (see *Why is this indicator important?*).

Figure 2. Trends in California's population, economy and greenhouse gas (GHG) emissions since 1990



Source: CARB, 2007 and 2021a; Census, 2012; DOF, 2021

GHG emissions per person (per capita) and per dollar of gross domestic product (GDP, a measure of the state's economic output) show declining trends between 1990 and 2019 (Figure 2). During the same period, the state's population and GDP increased by 33 percent and 139 percent, respectively. California's 2019 GHG emissions are

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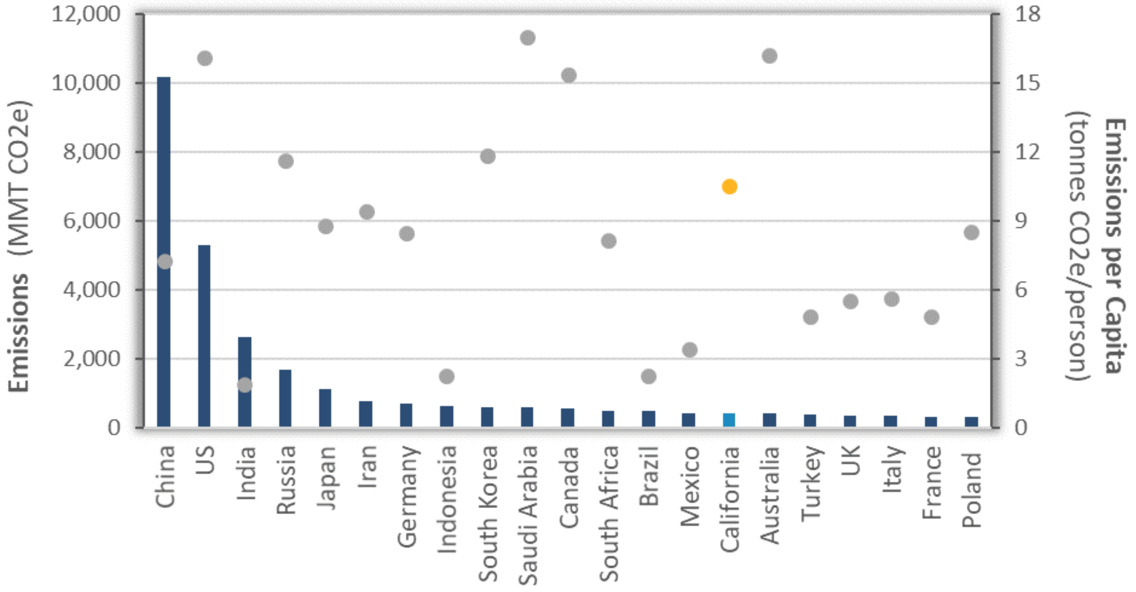
[2] These include HFC-152a, HFC-32, HFC-245fa, HFC-365mfc, HFC-134a, HFC-43-10mee, HFC-125, HFC-227ea, and HFC-143a.

3 percent lower than in 1990, but emissions per capita have declined by over 25 percent and emissions per dollar of GDP (carbon intensity) have declined by almost 60 percent. Total GHG emissions have also decreased from the peak in 2004 by 15 percent. A combination of factors contributed to this decrease in carbon intensity of the California economy. These factors include incrementally higher energy efficiency standards, growths in renewable energy sources, carbon pricing from the Cap-and-Trade Program, improved vehicle fuel efficiency, and other regulations.

Figure 3. 2019 Total (bars) and per capita (markers) California emissions as compared to the top 20 emitting nations

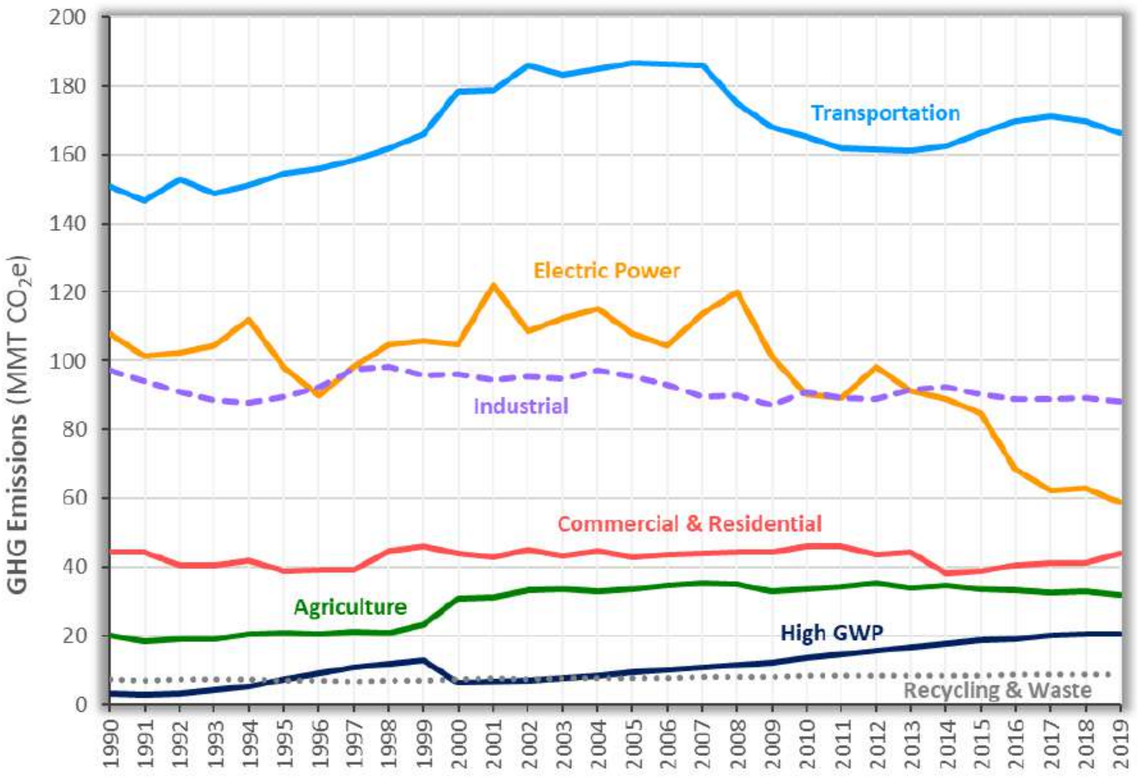


Sources: CARB, 2021a; DOF, 2020; Statista, 2021; World Bank, 2021

Figure 3 shows 2019 total emissions and emissions per capita for California compared to the top 20 emitting nations. If California were a country, it would be the fifth largest economy in the world. It would have the 15th highest total emissions, and the 7th highest per capita emissions. The state's 2019 per capita emissions are 35 percent lower than those of the United States (CARB, 2021a, Statista, 2021, World Bank 2021).

Figure 4 shows GHG emissions from 1990 to 2019, organized by categories as defined in the California Air Resources Board's (CARB) *Scoping Plan* (CARB, 2008). The transportation sector and the electric power sector are the primary drivers of year-to-year changes in statewide emissions. Transportation sector emissions increased between 1990 and 2007, followed by a period of steady decrease through 2013, and have followed a generally declining trend since. Most recently, total transportation emissions have steadily decreased from 2017 through 2019 due to a significant increase in biodiesel and renewable diesel use, which now accounts for 27 percent of total on-road diesel sold in California. Emissions from the electric power sector are variable over time but have decreased by more than 50 percent between 2008 and 2019 due to a continuing increase in renewable energy. High-GWP gases make up a small portion of total emissions but are steadily increasing as they replace ozone-depleting substances that are being phased out under international accord (UNEP, 2016). Emissions from the other sectors show some year-to-year variations, but their trends are relatively flat over time.

Figure 4. Greenhouse gas emissions in California from 1990 – 2019, disaggregated by sector*

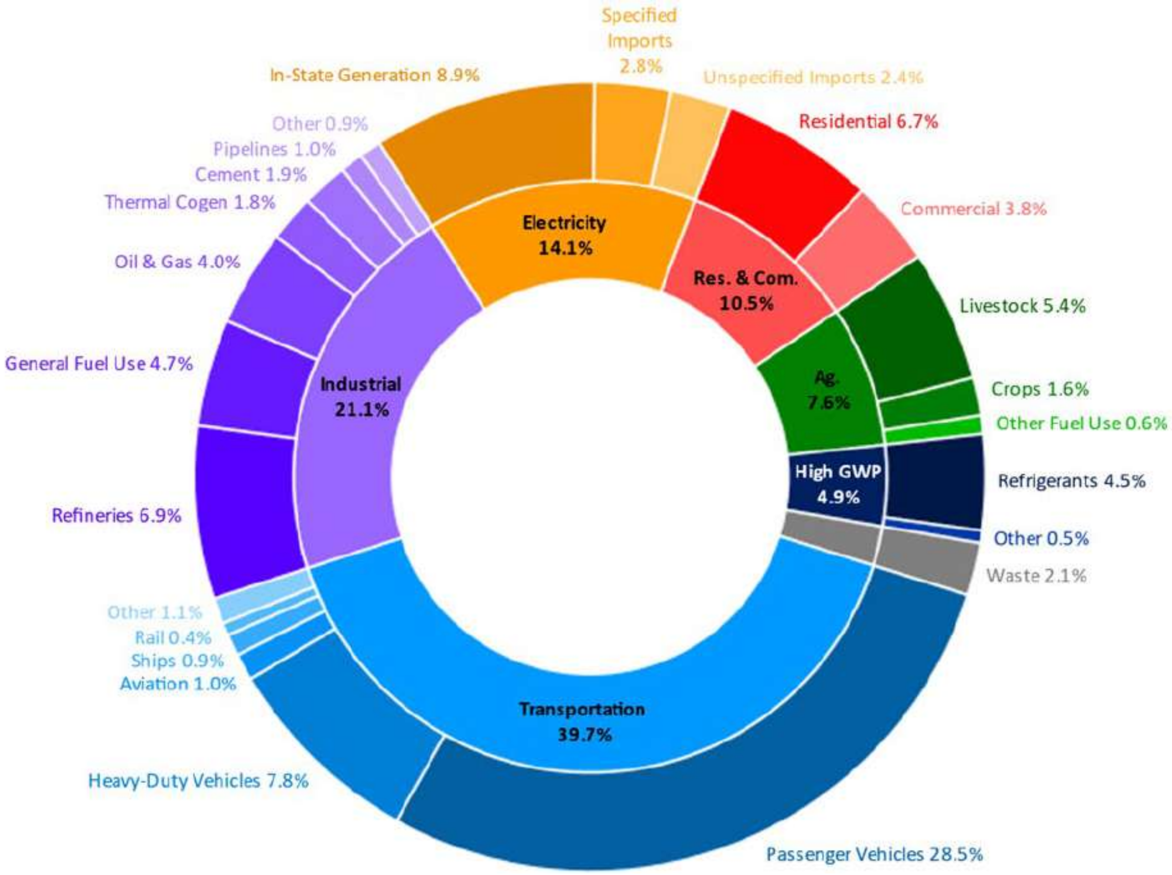


Source: CARB, 2021a

**Based on IPCC Fourth Assessment Report 100-year global warming potentials.*
Note: High-GWP gases do not represent an "economic sector," but are classified as such for purposes of organizing and tracking emissions, sources, and emissions reduction strategies.

Transportation is the largest source of GHGs, accounting for 39.7 percent of the total emissions in 2019 (Figure 5). Cars, light duty trucks, and sport utility vehicles constitute the highest contribution to transportation emissions. Industrial activities account for 21.1 percent of emissions and include fossil fuel combustion and fugitive emissions from a wide variety of activities such as manufacturing, oil and gas extraction, petroleum refining, and natural gas pipeline leaks. The electricity sector (in-state generation and electricity imports) accounts for 14.1 percent of emissions, followed by residential and commercial sources, which collectively account for 10.5 percent. The commercial sector, which includes schools, health care services, retail, and wholesale, accounts for 3.8 percent. The residential sector, where home natural gas use makes up the majority of emissions, accounts for 6.7 percent of statewide emissions. Emissions from the agricultural sector, which come from livestock, crop production, and fuel combustion, contributed 7.6 percent; these are mostly comprised of emissions from livestock. High-GWP gases are primarily used in refrigeration and air conditioning, as well as foams and consumer products and comprised 4.9 percent of 2019 emissions. Recycling and waste was the smallest contributor at 2.1 percent and includes emissions from landfills, wastewater treatment, and compost.

Figure 5. Greenhouse gas emissions by sector



Source: CARB, 2021a

Why is this indicator important?

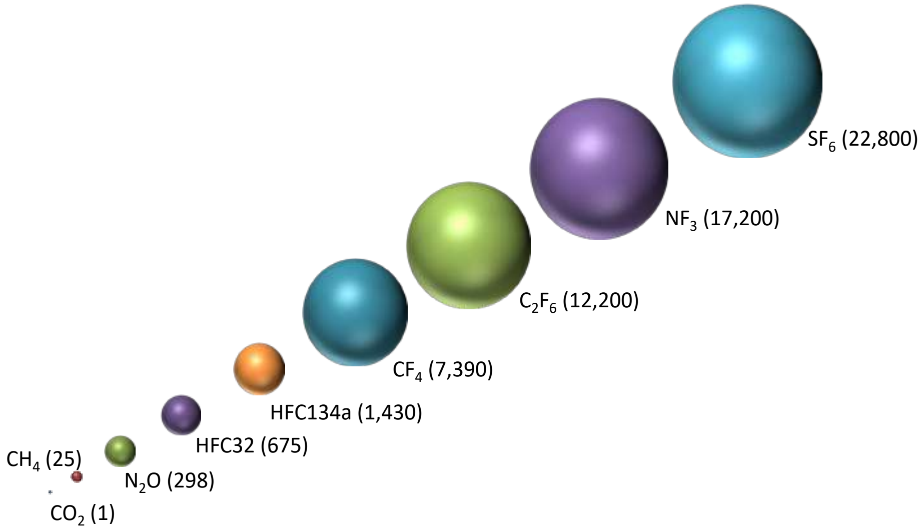
Atmospheric concentrations of GHGs have increased since the Industrial Revolution, enhancing the heat-trapping capacity of the earth's atmosphere. Accurately tracking GHG emissions trends in California provides critical information to policymakers as they assess climate change mitigation options and track the progress of GHG emissions reduction programs.

GHG emissions reduction targets are intended to prevent atmospheric concentrations from reaching levels at which catastrophic and irreversible impacts occur. The 2015 Paris Agreement aims to hold the increase in the global average temperature to well below 2 degrees Celsius (°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C above pre-industrial levels (UNFCCC, 2016). These efforts would significantly reduce the risks and impacts of climate change (Xu and Ramanathan, 2017). However, if global emissions continue to increase at the current rate, global warming is likely to reach 1.5°C between 2030 and 2052 (IPCC, 2018).

Since each GHG absorbs energy and warms the atmosphere to a different degree, understanding the pollutants' relative effects on climate change is also important for setting priorities and meeting emission reduction goals. Current international and national GHG inventory practice, as defined by the IPCC Guidelines, uses 100 years as the standard timeframe for GHG inventories. (Other timeframes may be used for different purposes. For example, discussions related to SLCPs typically use the 20-year timeframe.)

As illustrated in Figure 6, in a 100-year timeframe, CO_2 has the lowest GWP of all GHGs reported in the statewide inventory on a per unit of mass basis. Non-CO_2 emissions are converted to CO_2 equivalents (CO_2e) using GWP. GWP is a measure of the extent to which a particular GHG can alter the heat balance of the earth relative to carbon dioxide over a specified timeframe. For example, the GWP of SF_6 is 22,800, meaning that one gram of SF_6 has the same warming effect as 22,800 grams of CO_2.

Figure 6. 100-Year global warming potential of greenhouse gases based on the IPCC Fourth Assessment Report

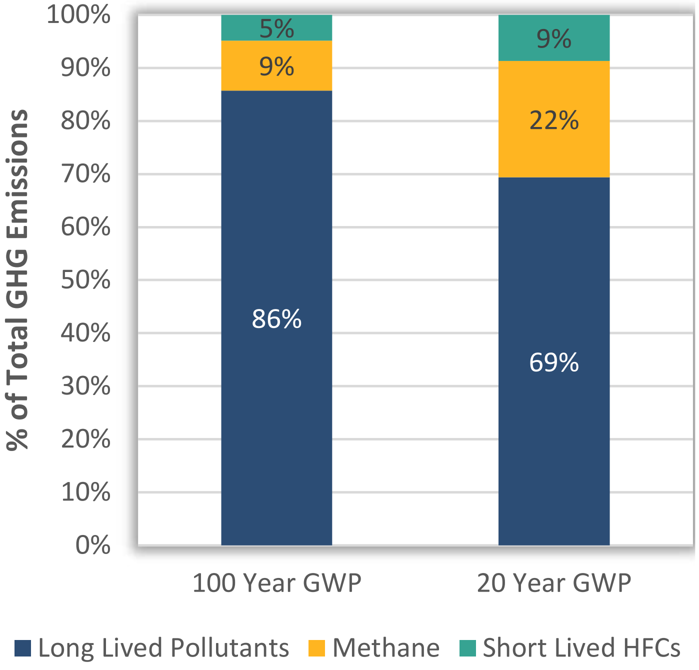


Source: IPCC, 2007

Emissions of CO_2, the main contributor to climate change, stay in the atmosphere for hundreds of years. Reducing CO_2 emissions is critically important but will not result in near-term cooling because of this long residence time. In contrast to CO_2, because SLCPs remain in the atmosphere from days to decades, a reduction in these emissions can have a more immediate impact, slowing the rate of warming.

Because SLCPs do not persist in the atmosphere for longer than decades, it is useful to consider a 20-year timeframe when discussing their impacts on climate change and planning for mitigation measures. Figure 7 shows the contribution of SLCP emissions to total GHG emissions in 2019. This contribution is based on their GWP and their atmospheric lifetime. Emissions of short-lived HFCs and methane in 2019 account for 14 percent of the total GHG emissions in a 100-year timeframe; however, when considering a 20-year timeframe, they account for 31 percent. In addition to methane and short-lived HFCs, black carbon, a class of particulate matter, is also considered an SLCP (see *Atmospheric black carbon concentrations* indicator).

Figure 7. SLCP contribution to total GHG emissions in 2019, over a 100-year and 20-year timeframe



Source: CARB, 2021a

What factors influence this indicator?

Statewide GHG emissions reflect activities across all major economic sectors, which are influenced by a variety of factors including population growth, vehicle miles traveled, economic conditions, energy prices, consumer behavior, technological changes, drought, and regulations, among other things.

Because GHG emissions from each sector are simultaneously influenced by multiple factors, one-to-one attribution between each factor and the magnitude of changes to sector emissions can be difficult to quantify. For example, improved economic conditions can result in an increased number of motor vehicles per household, and can boost vehicle miles traveled thus increasing GHG emissions, while using more fuel-efficient vehicles, public transportation, or driving less can reduce emissions.

GHGs are emitted from a variety of sources, but most notably from the combustion of fossil fuels used in the industrial, commercial, residential, and transportation sectors.

GHG emissions also occur from non-combustion activities at landfills, wastewater treatment facilities, and certain agricultural operations. A discussion of trends in certain economic sectors, sources of SLCPs, and the influence of regulatory requirements is presented in the following sections. Further information is provided in CARB (2021b).

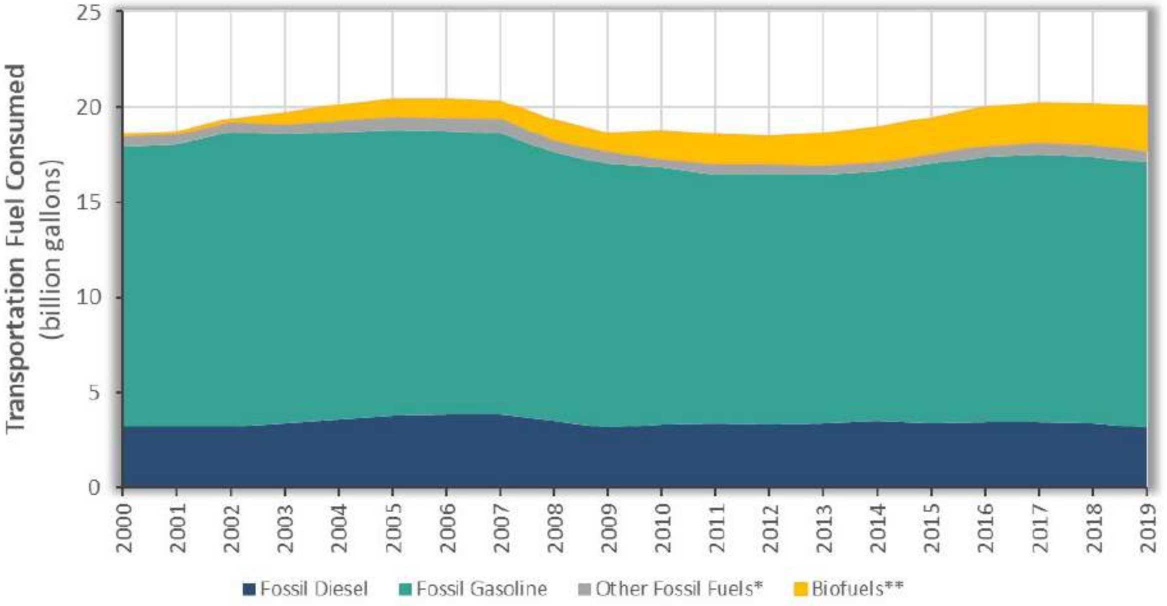
Transportation

Although California's population has grown by 33 percent since 1990 (Figure 2), GHG emissions from the transportation sector have increased by only 10 percent (Figure 4). Furthermore, transportation emissions in 2019 were 11 percent lower than the peak level in 2005. The decrease in transportation GHG intensity per capita is largely due to a significant increase in biodiesel and renewable diesel use, which is up 61 percent from 2018 and now accounts for 27 percent of total on-road diesel sold in California. California is also a world leader in the adoption of advanced alternative vehicles such as plug-in electric and hybrid vehicles. The state is the nation's largest market for zero-emission vehicles (ZEVs) due to California's regulation and vast portfolio of complementary policies. The state continues to lead in this area as recently shown by Governor Newsom's 100 percent ZEV sales for passenger vehicles target by 2035 (Newsom, 2020).

Transportation emissions are related to the amount of fuel burned. Combustion of fossil fuels such as gasoline and diesel produce GHGs that are counted towards California's inventory. On the other hand, emissions from the combustion of biofuels such as ethanol and biodiesel, which are derived from carbon that was recently absorbed from the atmosphere as a part of the global carbon cycle, are not counted pursuant to international GHG inventory practices (IPCC, 2006). Thus, displacing fossil fuels with biofuels can reduce the climate change impacts of the transportation sector.

The trends in the use of fossil fuels (blue, teal, and grey) and biofuels (yellow) are shown in Figure 8. Gasoline use is declining slightly, and biofuel use is increasing — trends contributing to the reduction in GHG emissions from transportation. Declining gasoline consumption is related to higher ethanol use, as well as to improved fuel economy and increased use of alternative fuel vehicles such as electric or hydrogen fueled vehicles. Biofuel diesel alternatives (i.e., biodiesel and renewable diesel) have been in use since 2010, and volumes are increasing rapidly. Between 2012 and 2019, biofuel diesel alternatives increased from 1 percent to 27 percent of the total transportation diesel use.

Figure 8. Trends in transportation fuel combustion from 2000 – 2019



Source: CARB, 2021a

**Other fossil fuels include: aviation gasoline, jet fuel, LPG, residual fuel oil, and natural gas.*
***Biofuels includes gallons of ethanol, biodiesel, and renewable diesel*

Residential and Commercial

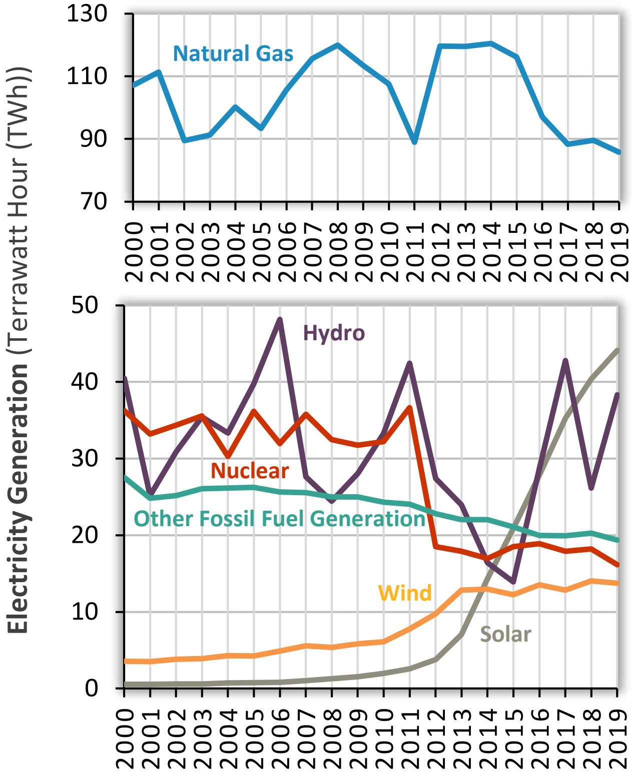
California's steady population growth from 1990 through 2019 has been accompanied by an increased demand for housing, among other things. More housing often means additional demand for residential energy and increased associated GHG emissions, yet emissions from the residential and commercial sector decreased over the same period. Residential and commercial building code standards are updated regularly to improve building efficiency (e.g., insulation thickness, window design, lighting systems, and heating/cooling equipment specification). These energy efficiency standards have saved Californians billions of dollars in reduced electricity bills (CEC, 2015), and have reduced the emissions of GHGs and criteria air pollutants. The per capita electricity consumption in California is near the lowest in the nation, primarily due to mild weather and energy efficiency programs (EIA, 2021). Still, emissions from residential and commercial buildings have continued to rise since 2014, due in part to increases in natural gas use.

Electric Power

The electric power sector includes two broad categories: in-state power generation (including the portion of industrial and commercial cogeneration emissions attributed to electricity generation) and imported electricity. Since the early 2000's, the deployment of renewable and less carbon-intensive resources have facilitated the continuing decline in fossil fuel electricity generation. The Renewables Portfolio Standard (RPS) Program and the Cap-and-Trade Program continue to incentivize the dispatch of renewables over fossil generation to serve California load. Higher energy efficiency standards also reduce growth in electricity consumption driven by a growing population and economy.

California's in-state electricity is derived from a variety of sources (see Figure 9). Natural gas, which is used to produce the majority of in-state electricity, accounted for 39 percent of the electricity generation in 2019. Solar energy accounted for 20 percent, hydro accounted for 18 percent, and nuclear accounted for 7 percent of in-state generation. Nuclear power declined after the 2012 shutdown of the San Onofre Nuclear Generating Station. Hydro power reached historic lows in 2015 due to drought. An increase in solar and wind power has compensated for the decline in hydro power and nuclear generation in recent years. Wind, solar, hydro, and nuclear power are zero-emission sources. In 2019, California was the nation's top producer of electricity from solar, geothermal, and biomass energy, and the state was second in the nation in conventional hydroelectric power generation (EIA, 2021).

Figure 9. In-state Electricity Generation by Source



Source: CARB, 2021b

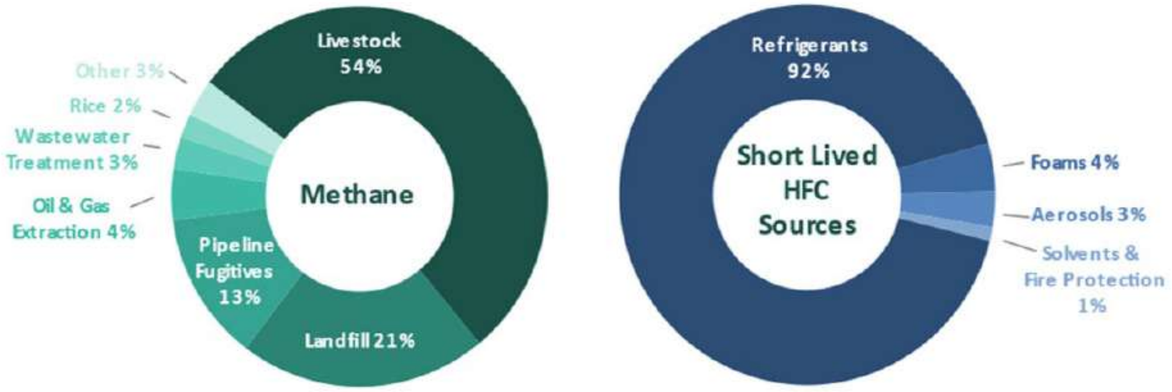
Emissions from imported electricity peaked in 2004 and have since dropped 67 percent by 2019. Compared to 2011 levels, imports of hydro, solar, wind, and nuclear energy nearly tripled, while imports of coal energy dropped by 67 percent. In 2019, imports of hydro, solar, wind, and nuclear energy grew nine percent in one year.

Weather can also have notable influences on GHG emissions from the electricity sector. A warmer summer increases electricity demand for air conditioning, and consequently increases the emissions from power plants that must ramp up to meet the additional demand.

Short-Lived Climate Pollutants

Sources of methane and short-lived HFCs in California are shown in Figure 10. Livestock represents the largest source of methane. Methane is produced from livestock manure management and from the guts of ruminant animals such as cows. Organic waste deposited in landfills or managed in wastewater treatment plants also produce methane emissions. As the primary component of natural gas, methane is also emitted by oil and gas extraction and during its storage, processing, and transport. Natural gas is used for many purposes including electricity production and heating.

Figure 10. 2019 Sources of short-lived climate pollutants*



Source: CARB, 2021b

**Based on the 2019 edition of the GHG inventory and 100-year GWP*

Short-lived HFCs are used as replacements for ozone-depleting substances that are being phased out under the Montreal Protocol (UNEP, 2016). The majority of HFC emissions comes from refrigeration and air-conditioning systems used in the residential, commercial, industrial, and transportation sectors. Foams, aerosols, solvents, and fire protection are other sources of HFCs.

Climate Change Policies and Regulations

California's pioneering efforts in the adoption and implementation of policies are reducing GHG emissions. The California Global Warming Solutions Act of 2006 (Nuñez, Chapter 488, Statutes of 2006), also known as Assembly Bill (AB) 32, established the nation's first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective GHG emissions reductions. AB 32 set a goal of reducing GHG emissions to the 1990 level by 2020 and requires the state to complete a Climate Change Scoping Plan that lays out the path to meet the emissions reduction target, and to update that plan at least every five years. The first Climate Change Scoping Plan was adopted by the Board in 2008 (CARB, 2008). Senate Bill 32 (Pavley, Chapter 249, Statutes of 2016) codified in statute the goal of further reducing GHG emissions to 40 percent below the 1990 level by 2030. In 2017, the Board adopted the 2017 Climate Change Scoping Plan, which lays out the path to meet this target (CARB, 2017). Executive Order B-55-18 calls for achieving carbon neutrality no later than 2045, and to achieve and maintain net negative emissions thereafter. As of mid-2022, CARB is working with state agencies on the next Scoping Plan update, which will identify a technologically feasible and cost-effective path to achieve carbon neutrality by no later than 2045 while also assessing the progress the state is making towards reducing its greenhouse gas emissions by at least 40 percent from 1990 levels by 2030. A complete list of climate change legislation and executive orders can be found in the appendix.

Technical considerations

Data characteristics

A GHG inventory is an estimate of GHG emissions over a specified area and period from known sources or categories of sources. Emission inventories generally use a combination of two basic approaches to estimate emissions. The top-down approach utilizes nationwide or statewide data from various federal and state government agencies to estimate emissions. The bottom-up approach utilizes activity data (e.g., fuel quantity, animal population, tons of waste deposited in the landfill) to compute unit level emissions that are then aggregated to the state level for a particular source category. In either approach, calculation assumptions are made to estimate statewide GHG emissions from different levels of activity data. These calculations typically reference the 2006 IPCC Guidelines for National Greenhouse Gas Inventories or the U.S. Environmental Protection Agency's national GHG emission inventory, but also incorporate California-specific methods and considerations to the extent possible.

Strengths and limitations of the data

The methods used to develop the California GHG emission inventory are consistent with international and national inventory guidelines to the greatest extent possible. Emission calculation methodologies are evaluated over time and refined by incorporating the latest scientific research and monitoring activities.

The California GHG inventory includes emissions from anthropogenic sources located within California's boundaries. Pursuant to AB 32, California's inventory also includes imported electricity. The inventory, however, excludes emissions that occur outside California during the manufacture and transport of products and services consumed within the state across all sectors. On the other hand, California is a net exporter of multiple products, especially agricultural commodities. California exported about a quarter of all agricultural products (CDFA, 2014). The state's GHG inventory includes the carbon sequestered in California-produced agricultural products that are exported and consumed outside the state. In addition, GHG mitigation effects may cross geographic borders as part of international and sub-national collaboration, or as a natural result of implementation of state programs. The state's GHG emission inventory does not account for emission reductions outside of its geographic border that may have resulted from California's adopted programs.

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APPENDIX.

California's Climate Change Legislation, Executive Orders, and Other References

AB 32 (Nuñez and Pavley, Chapter 488, Statutes of 2006), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200520060AB32

AB 74 (Ting, Chapter 23, Statutes of 2019), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB74

AB 398 (Garcia, E., Chapter 135, Statutes of 2017), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB398

AB 617 (Garcia, C., Chapter 136, Statutes of 2017), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB617

AB 1493 (Pavley, Chapter 200, Statutes 2002), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200120020AB1493

AB 1550 (Gomez, Chapter 369, Statutes of 2016), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1550

AB 3232 (Friedman, Chapter 373, Statutes of 2018), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB3232

EO B-55-18, https://www.ca.gov/archive/gov39/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf

EO N-82-20, https://www.gov.ca.gov/wp-content/uploads/2020/10/10.07.2020-EO-N-82-20-signed.pdf

EO N-79-20, https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf

CARB Board Resolution 17-46, https://ww3.arb.ca.gov/board/res/2017/res17-46.pdf

CARB Board Resolution 20-5, https://ww3.arb.ca.gov/board/res/2020/res20-5.pdf

Governor's Energy Emergency Proclamation, https://www.gov.ca.gov/2021/07/30/governor-newsom-signs-emergency-proclamation-to-expedite-clean-energy-projects-and-relieve-demand-on-the-electrical-grid-during-extreme-weather-events-this-summer-as-climate-crisis-threatens-western-s/

SB 32 (Pavley, Chapter 249, Statutes of 2016), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB32

SB 44 (Skinner, Chapter 297, Statutes of 2019), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200SB44

SB 84 (Committee on Budget and Fiscal Review, Chapter 50, Statutes of 2017), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB84

SB 100 (De León, Chapter 312, Statutes of 2018), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100

SB 150 (Allen, Chapter 646, Statutes of 2017), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB150

SB 350 (De León, Chapter 547, Statutes of 2015), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB350

SB 375 (Steinberg, Chapter 728, Statutes of 2008), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=200720080SB375

SB 535 (De León, Chapter 830, Statutes of 2012), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201120120SB535

SB 605 (Lara, Chapter 523, Statutes of 2014), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201320140SB605

SB 743 (Steinberg, Chapter 386, Statutes of 2013), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201320140SB743

SB 1013 (Lara, Chapter 375, Statutes of 2018), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1013

SB 1018 (Committee on Budget and Fiscal Review, Chapter 39, Statutes of 2012), http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_1001-1050/sb_1018_bill_20120627_chaptered.html

SB 1275 (De León, Chapter 530, Statutes of 2014), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201320140SB1275

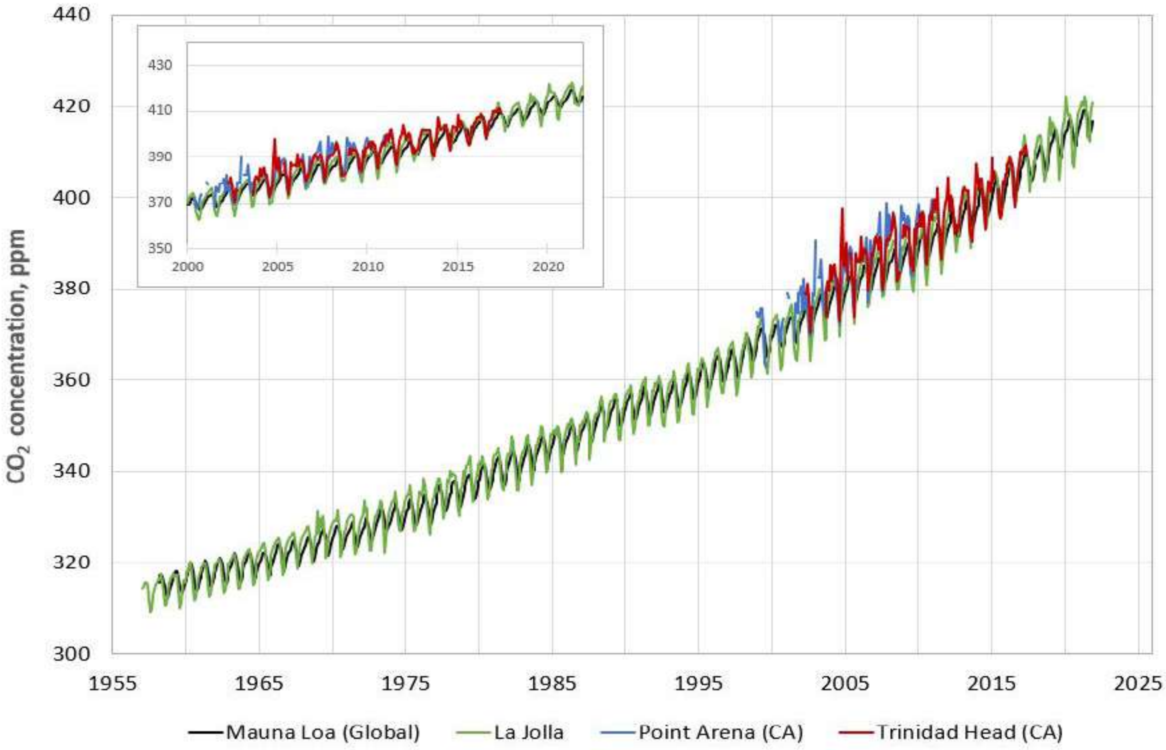
SB 1371 (Leno, Chapter 525, Statutes of 2014), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201320140SB1371

SB 1383 (Lara, Chapter 395, Statutes of 2016), https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1383

ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS

Atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and certain fluorinated gases continue to increase globally and in California. The annual average global concentration of carbon dioxide was 414 parts per million (ppm) in 2020, and 416 ppm in 2021[*], with a maximum monthly average of 419 parts per million in May of 2021.

Figure 1. Monthly average atmospheric carbon dioxide (CO_2) concentrations



Source: NOAA 2022a, 2021a, and Conway et al., 2011 (Mauna Loa, Point Arena, and Trinidad Head); SIO, 2022 (La Jolla)

Note: Measurements at Point Arena are available from 1999 to 2011; Trinidad Head from 2002 to 2017.

What does the indicator show?

Atmospheric concentrations of greenhouse gases (GHG) are increasing globally, as illustrated in Figures 1 to 4. These graphs show the ambient concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and a variety of fluorinated gases (F-gases) at the global background site of Mauna Loa on the island of Hawaii, as well as at regional background sites in California. The measurements are presented in parts per million (ppm) for CO_2 and CH_4, parts per billion (ppb) for N_2O, and parts per trillion (ppt) for F-gases. These are units of air pollution mixing ratios commonly used to describe ambient air pollution concentrations (1 ppm = 1,000 ppb = 1,000,000 ppt).

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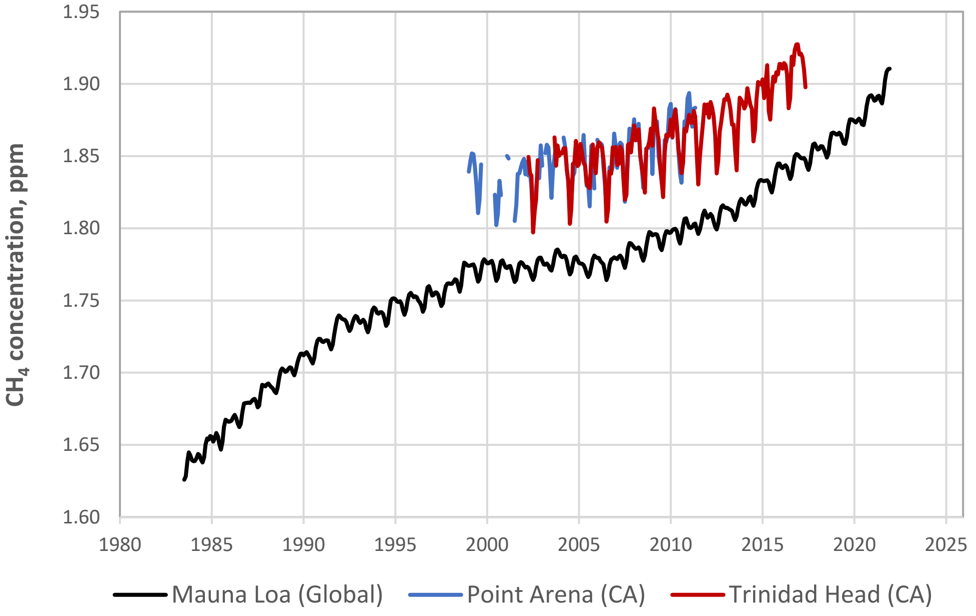
[*] Based on data retrieved in June 2022; the last year of data are considered preliminary.

Figure 1 shows the CO_2 measurements at Mauna Loa, and three coastal sites in California (La Jolla, Point Arena and, Trinidad Head). Measurements at Mauna Loa first began in 1958. In over six decades, the annual average CO_2 concentrations have increased from 315 ppm in 1958 to 416 ppm in 2021. Annual CO_2 concentrations have increased by an average rate of 1.6 ppm per year over the past decades, accelerating in the last five years to about 2.4 ppm per year (NOAA, 2022a). At all these sites, CO_2 displays a seasonal trend with increasing CO_2 observed from autumn through late winter and decreasing CO_2 from spring through late summer. This is due to seasonal biosphere-atmosphere interactions – that is, plants take up CO_2 in spring and summer, then decay and release CO_2 in fall and winter) along with subtle seasonal changes in anthropogenic fossil fuel use. In the northern hemisphere, CO_2 concentrations tend to increase as one moves north from the equator, largely a result of global population centers (and hence, sources of CO_2) being located at higher latitudes. Thus, CO_2 levels at the California sites tend to be slightly higher than those at Mauna Loa, and levels at the two Northern California sites (Trinidad Head and Point Arena) tend to be slightly higher than those at the Southern California site (La Jolla). For example, annual average CO_2 at La Jolla has been 1.2 ppm higher than Mauna Loa over the past ten years. The California sites also tend to have higher variability than the Mauna Loa site, primarily due to their location on a major continent with large population centers and forested regions, which act as sources and sinks of CO_2, respectively.

Figure 2. Monthly average atmospheric methane (CH_4) concentrations



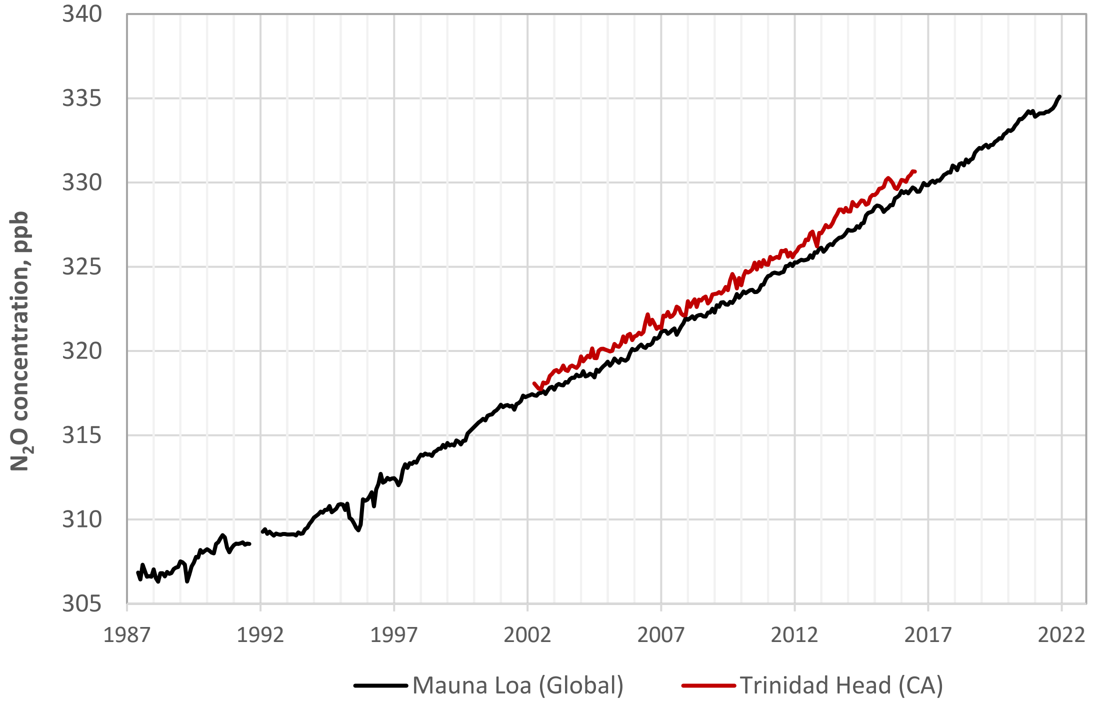
Source: NOAA 2022b (Dlugokencky, NOAA/GML)

Note: Measurements at Point Arena are from 1999 to 2011; at Trinidad Head, 2002 to 2017.

Figure 2 shows the atmospheric measurements of CH_4 at Mauna Loa since 1983, and at the California coastal sites, namely Point Arena and Trinidad Head, since 1999 and

2002, respectively. Global CH_4 levels have increased since 1983, except for a brief period between 1999 and 2006 when they were relatively constant before increasing again starting in 2007. CH_4 concentrations in the pre-industrial era (i.e., pre-1750) were approximately 0.7 ppm (IPCC, 2013). By contrast, today's atmospheric CH_4 concentrations exceed 1.9 ppm at Mauna Loa and the California sites – an increase of over 150 percent (NOAA, 2022b). Similar to, but to a greater extent than, CO_2, the CH_4 concentrations at the California regional background sites are higher than those observed at Mauna Loa. This is due to a strong latitudinal gradient that promotes elevated CH_4 concentrations in the northern latitudes, where there are more human activities that lead to greater emissions (Frankenberg et al., 2005).

Figure 3. Monthly average nitrous oxide (N_2O) concentrations

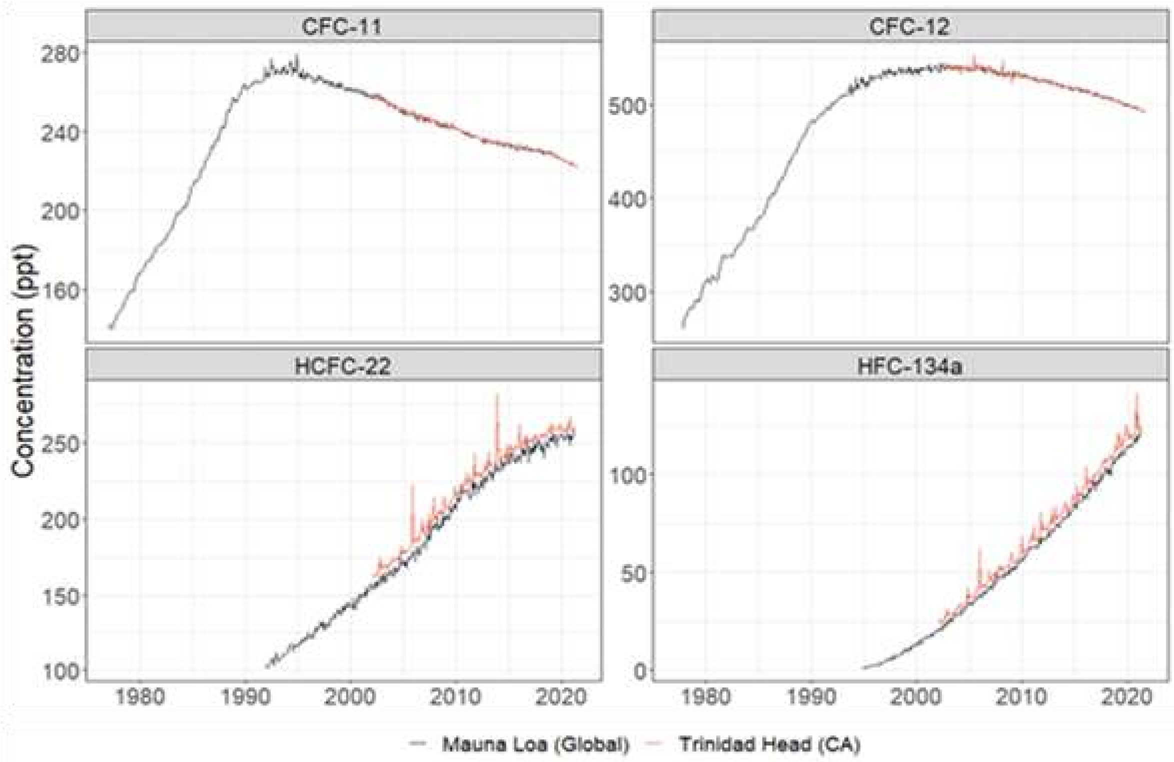


Source: NOAA 2022c (Dlugokencky, NOAA/GML)

Note: Measurements at Trinidad Head are from 2002 to 2017.

Figure 3 shows the atmospheric concentrations of N_2O at Mauna Loa, which are available from 1987 to present, and Trinidad Head, which are available from 2002 to 2017. Global N_2O concentrations have been increasing at a rate of approximately 0.7 ppb per year over the past few decades, and are now approximately 24 percent greater than the pre-industrial levels of 270 ppb (NOAA, 2022c). Unlike CO_2 and CH_4, global N_2O concentration trends do not display a strong seasonal cycle in the lower atmosphere.

Figure 4. Monthly average F-gas concentrations



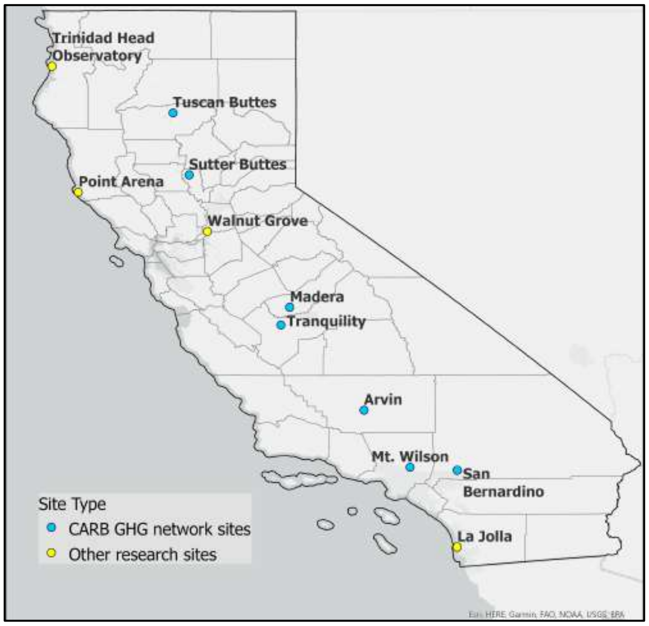
Source: NOAA, 2022a,d

Figure 4 shows the atmospheric concentrations at Mauna Loa and Trinidad Head of select F-gases, which are a class of synthetic chemicals that includes chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). The figure shows the four most prevalent F-gases at Mauna Loa: trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), chlorodifluoromethane (HCFC-22), and 1,1,1,2-tetrafluoroethane (HFC-134a). F-gases began to appear in the atmosphere in the 20th century as a result of their usage as refrigerants and propellants; pre-industrial F-gas concentrations are assumed to be zero.

While F-gases are potent GHGs with global warming potentials that can be hundreds to thousands of times stronger than CO_2, interest in atmospheric measurements of F-gases first began in the 1970’s when they were linked to the destruction of stratospheric ozone (i.e., the “ozone hole”) (Molina and Rowland, 1974). CFCs are strongly ozone-depleting, and their production and use were halted in 1996 under the Montreal Protocol (UNEP, 2012). Consequently, their global ambient concentrations have been slowly decreasing since the mid-1990s. Although no new emissions are expected, these gases have atmospheric lifetimes of decades, that is, they remain in the atmosphere for decades after they are released. With no new emissions, CFCs are well-mixed throughout the atmosphere and there is no latitudinal gradient in atmospheric CFC concentrations. Thus, Mauna Loa and Trinidad Head have nearly identical CFC levels.

HCFCs were an interim replacement for CFCs. While not as destructive towards stratospheric ozone as CFCs, HCFCs still have considerable ozone depletion potential, and are also being phased out globally. Although banned in the US and European Union, HCFC-22 still has limited use and production in developing countries. HCFC-22 has a latitudinal gradient that closely follows human population centers (i.e., higher levels in the mid-latitudes), thus levels are higher at Trinidad Head than at Mauna Loa. Ambient monitoring indicates an increasing HCFC-22 trend since the 1990s, although the concentrations have begun to plateau in recent years as global phase-outs have ramped up. HFCs are modern refrigerants, such as HFC-134a, have negligible ozone depletion potential and thus have been widely used across the world since their introduction in the mid-1990s, despite their high global warming potential. First detected in the atmosphere in the 1990s, HFC-134a concentrations have been increasing since it was first detected in the atmosphere in the 1990s. Unlike CFCs and HCFCs, HFC-134a concentrations have not begun to plateau or decrease, instead maintaining a growth rate of approximately 5 ppt per year since 2005. Like HCFCs, HFC-134a levels follow population centers and display a latitudinal trend, whereby Trinidad Head typically experiences higher levels than Mauna Loa.

Figure 5. Greenhouse gas monitoring locations in California



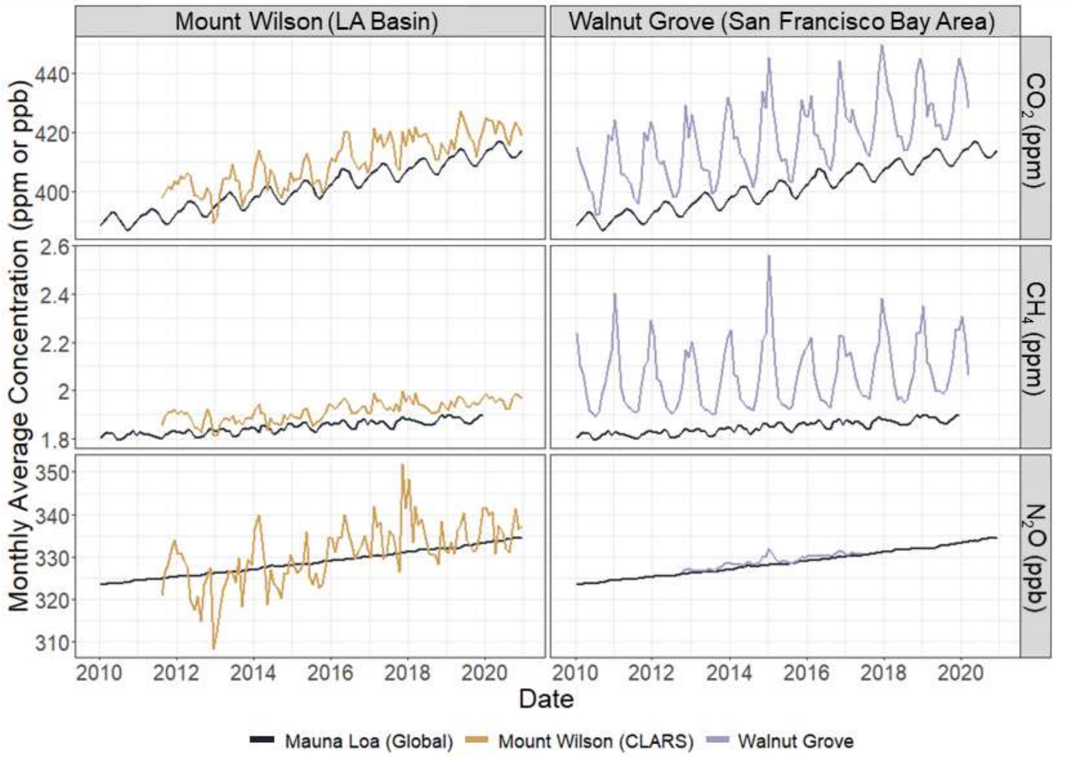
Source: CARB, 2021

California has undertaken additional efforts to track the changes in ambient GHG concentrations at several monitoring sites located throughout the state. Figure 5 shows the seven GHG monitoring network sites operated by the California Air Resources Board (CARB), a research monitoring site operated by the Lawrence Berkeley National Laboratory at Walnut Grove, and the three coastal background sites operated by NOAA (NOAA, 2021a). These stations measure well-mixed regional air, providing monitoring data which can be used to understand how GHG concentrations are changing in California relative to the global trends. For example, the Walnut Grove station, an inland tower located near Sacramento, provides the signature of regional emissions from portions of Northern and Central California; the Mount Wilson site integrates remote sensing measurements (similar to the data products from satellites) at 33 locations across the

Los Angeles (LA) air basin to yield basin-wide concentrations (see “Technical considerations” section).

Figure 6 shows monthly averaged CO_2, CH_4, and N_2O concentrations measured at Mount Wilson representing the LA basin, along with in-situ observations from the Walnut Grove site. As a global background reference, observations from NOAA’s Mauna Loa Observatory are also included in each graph.

Figure 6. Comparison of monthly average atmospheric GHG concentrations at a global background site and two regional background sites



Sources: Zhao and Sander, 2021 (Mount Wilson);
Fischer and Jeong, 2016 (Walnut Grove);
NOAA 2022a (Mauna Loa)

CO_2 observations from Mount Wilson track the global background well, albeit with larger variabilities and higher monthly average concentrations as a result of local emissions from the LA basin (Figure 6, top left panel). The average CO_2 concentration in the LA basin increased from roughly 400 ppm in 2011 to over 420 ppm by 2020. Similarly, the CO_2 concentrations at the Walnut Grove site were also higher than at Mauna Loa for a given year but had considerably larger inter- and intra-annual variability than the Mount Wilson observations. As noted above, the measurements at Mount Wilson represent a “basin average” number, while the Walnut Grove measurements reflect CO_2 at one location and are more sensitive to local emission sources. The more pronounced seasonal pattern at the Walnut Grove site can also be attributed to its location as a receptor site for upwind sources from the Bay Area, as well as seasonal changes in mixed layer depths, which trap air pollution emissions closer to the ground during cooler months.

Observations from Mount Wilson and Walnut Grove also show higher CH_4 values and larger variabilities relative to the Mauna Loa background, which is due to the impact of local emissions in their respective regions (i.e., the LA basin and the San Francisco Bay Area). Similar to CO_2, larger inter- and intra-annual variability in CH_4 is observed at Walnut Grove. This is likely due to fundamental differences between the CLARS remote sensing technique used at Mount Wilson and the in-situ measurement technique used at Walnut Grove, and the proximity of the latter site to local CH_4 emission sources.

Annual N_2O concentration trends measured by the CLARS remote sensing instrument show a similar trend in the LA basin as those measured at Mauna Loa, but with larger interannual variability. By contrast, the trend in N_2O concentrations at Walnut Grove closely mirrors the global trend, which are both increasing by approximately 1 ppb per year.

Why is this indicator important?

Global temperatures are directly linked to GHG levels in the atmosphere (IPCC, 2021). The 2015 Paris Agreement aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C above pre-industrial levels (UNFCCC, 2016). GHG emissions reduction targets have been established to prevent atmospheric concentrations from reaching levels at which catastrophic and irreversible impacts occur (see *Greenhouse gas emissions indicator).* Atmospheric GHG concentrations help track changes in the emissions of anthropogenic drivers of climate change and their accumulation in, and removal from the atmosphere.

CO_2 is a long-lived GHG responsible for roughly 65 percent of the total warming effect caused by GHGs globally. It contributes to over 84 percent of the current GHG emission inventory in California on a 100-year timescale (CARB, 2020a; WMO, 2016). Since CO_2 is typically well-mixed in the atmosphere, measurements at remote sites can provide integrated global background levels. The first and the longest continuous measurements of global atmospheric CO_2 levels were initiated by Charles D. Keeling in 1958 at Mauna Loa. For the first time, these measurements documented that atmospheric CO_2 levels were increasing globally. In the 1980s and the 1990s, it was recognized that greater coverage of CO_2 measurements was required to provide the basis for estimating the emission impacts of sources and sinks of atmospheric CO_2 over land as well as ocean regions. Since CO_2 remains in the atmosphere for many centuries, its atmospheric levels can continue to increase even if its emissions are significantly reduced.

Atmospheric CH_4, N_2O, and F-gases contribute roughly 17 percent, 6 percent, and 12 percent, respectively, of the warming (referred to as radiative forcing”) caused by globally well-mixed GHGs (IPCC, 2013; WMO, 2016). These pollutants could play an even more important role owing to their greater 100-year global warming potentials (100-year GWP) as compared to that of CO_2 (GWP = 1). Despite a much shorter lifetime than that of CO_2, these can cause significant climate impact in the near term, and are called short-lived climate pollutants (SLCPs). For instance, CH_4 has a 100-year GWP of about 28, and remains in the atmosphere for about 12 years before removal, whereas F-gases such as HCFC-22 and HFC-134a have GWPs of over 1,000, and can remain in the atmosphere for one to two decades. On the other hand, N_2O has a GWP of 273 and remains in the atmosphere for roughly 120 years, which can result in long-term climate impacts (IPCC, 2021).

High-precision measurements, such as those presented in this indicator report, are essential for understanding GHG emissions from various sources – including human activities, atmospheric processes, plants, soils, and oceans. Tracking the life cycles of these GHGs provides information necessary for formulating mitigation strategies. Data on atmospheric GHG levels, in particular, are needed to project future climate change associated with various emission scenarios, and to establish and revise emission reduction targets (IPCC, 2013).

In California, regional GHG emission sources may contribute to enhancements in the concentrations of GHGs above global background levels. In addition to the monitoring and measurement efforts undertaken by various researchers, CARB has also funded several studies to utilize the atmospheric measurements from regional GHG monitoring sites to infer the most likely distribution and strength of regional CO_2, CH_4, and N_2O emission sources in California (Fischer and Jeong, 2016; Zhao et al., 2009, Cui et al., 2019).

What factors influence this indicator?

The concentrations of CO_2, CH_4, N_2O, and F-gases in the atmosphere reflect the difference between their rates of emission and their rates of removal. The majority of the changes observed in the global and regional GHG trends are directly related to human activities such as fossil fuel combustion, biomass burning, industrial processes, agricultural practices, and deforestation (IPCC, 2013). Additional discussion of factors affecting the emission of these GHGs in California is presented in the *Greenhouse gas emissions* indicator.

CO_2 is continuously exchanged between the land, oceans, and the atmosphere through physical, chemical, and biological processes (IPCC, 2021). Prior to 1750, the global background CO_2 concentration was estimated to be less than 280 ppm (WMO, 2016). During this period, the amount of CO_2 released by natural processes (e.g., respiration and decomposition) was almost exactly in balance with the amount absorbed by plants during photosynthesis and other removal processes (WMO, 2016). The increase in the CO_2 concentration today derives primarily from emissions related to fossil fuel combustion and biomass burning. It is also directly related to changes in agricultural practices and deforestation (IPCC, 2021). While more than half of emitted CO_2 is removed through natural processes within a century, about 20 percent remains in the atmosphere for many millennia (Archer et al., 2009). Consequently, atmospheric CO_2 will continue to increase in the atmosphere even if annual CO_2 emissions are substantially reduced from present levels. It should be noted that, while increasing levels of atmospheric CO_2 are affecting climate, changes in climate are likewise affecting the processes that lead to CO_2 uptake from, and release into, the atmosphere (IPCC, 2021). For example, warming temperatures increase plant photosynthesis and thus CO_2 removal from the atmosphere, and wildfires release carbon stored by plants back into the atmosphere.

Atmospheric CO_2 concentrations reflect regional, as well as seasonal and inter-annual influences. Due to its higher fossil fuel emissions, the Northern Hemisphere has higher CO_2 concentrations than the Southern Hemisphere. Seasonal variations are attributed to seasonal patterns of plant growth and decay. Inter-annual variations have been attributed to El Niño and La Niña climate conditions; generally, higher-than-average increases in CO_2 correspond to El Niño conditions, and lower-than-average increases correspond to La Niña conditions (IPCC, 2021).

Atmospheric CH_4 originates from both natural and anthropogenic sources. CH_4 is emitted naturally from wetlands, oceans, termites, and geological sources. Anthropogenic sources of methane include rice agriculture, livestock, landfills, waste treatment, biomass burning, and fossil fuel and natural gas exploitation (i.e., extraction, transmission, distribution, and use). The production of CH_4 by many of these sources is influenced by anaerobic fermentation processes and climate variables (notably temperature and moisture). Atmospheric removal of CH_4, on the other hand, is driven by oxidation processes, a process likewise affected by climate variables.

Atmospheric N_2O is naturally present in the atmosphere as part of the Earth's nitrogen cycle. Its primary driver is the breakdown of nitrogen by microorganisms that live in soil and water (Anderson et al., 2010). Human activities such as agriculture, fossil fuel combustion, wastewater management, and industrial processes account for 40 percent of total N_2O emissions globally (US EPA, 2021). In California, N_2O is emitted in large part from agricultural activities such as soil and manure management. In 2018, these contributed to roughly 54 percent of total statewide N_2O emissions (CARB, 2020a). Most of the remaining 46 percent were attributed to the transportation, industrial, commercial, and residential sectors. Commercial and residential application of synthetic fertilizers over soil and lawn, in particular, plays a significant role in the nitrogen cycle; the release of N_2O from such fertilizers has been shown to vary based on their rate of application and watering events.

N_2O from fossil fuel combustion can vary significantly based on the technology, maintenance, and operation of combustion equipment (Graham et al., 2009; Huai et al., 2004). N_2O is prevalent in the tail-pipe exhaust of motor vehicles when their engines and catalytic converters are operating at sub-optimal conditions. N_2O is also typically generated as a by-product of synthetic fertilizer and other synthetic nitrogen production processes. On the other hand, N_2O is removed from the atmosphere through bacterial activities and through photochemical reactions (US EPA, 2021).

F-gases do not exist in the natural environment; they are only emitted from anthropogenic sources and are only removed through photochemical reactions in the upper atmosphere. F-gases have been used primarily as refrigerants in a variety of applications, including stationary refrigeration and air conditioning, industrial production and manufacturing processes, the transmission and distribution of electricity, and vehicle air conditioning systems. CFC-11, CFC-12, HCFC-22, and HFC-134a emissions derive largely from fugitive leaks, venting during the maintenance and servicing of equipment, leaks from improperly maintained or damaged equipment, and the improper disposal of equipment (Gallagher et al., 2014).

International, national, and state regulations affect the use, emission, and eventual atmospheric concentrations of these substances. As noted above, pursuant to the Montreal Protocol of 1987, CFCs were phased out and banned in the United States in 1996. Most of the HCFCs were phased out of new production and consumption as of January 1, 2020. Driven by the phase-out of these ozone-depleting substances and by increased demand for refrigeration and air conditioning, HFCs became the fastest growing sources of GHG emissions in California and globally. They are now subject to a production and consumption phasedown under the Kigali Amendment (to the Montreal Protocol) starting in 2019 in ratified developed countries. The first group of developing countries ratified in the amendment will begin the phasedown in 2029. The second group of developing countries will have until 2032 to begin a phasedown. It is important to note that the Kigali Amendment has yet to be ratified by the United States. However, on December 27, 2020, U.S. Congress enacted the American Innovation and Manufacturing (AIM) Act of 2020. The AIM Act directs the U.S. Environmental Protection Agency (US EPA) to address HFCs by providing new authorities in three main areas: to phase down the production and consumption of listed HFCs, manage these HFCs and their substitutes, and facilitate the transition to next-generation technologies.

California Senate Bill 1383 (Statutes of 2016) requires statewide reduction of HFC emissions to 40 percent below 2013 levels by 2030 (CARB, 2017). In March 2018, California adopted high global warming HFC prohibitions in certain stationary refrigeration and foam end uses that were originally subject to the US EPA Significant New Alternatives Policy program (SNAP) rules which were partially vacated by a court case in 2017. Later in 2018, Senate Bill 1013 adopted the federal SNAP program in its entirety, which included a provision for an incentive program to increase the adoption of low global warming refrigerant technologies. Several other states that are part of U.S. Climate Alliance followed California in adopting similar rules in their respective jurisdictions. Despite existing measures, additional HFC emissions reductions are needed to meet California's 2030 statutory targets. In December 2020, CARB approved additional HFC measures (previously identified in CARB's short lived climate strategy plan), including strict GWP limits on new refrigeration and air-conditioning equipment, company-wide reduction targets for retail food refrigeration facilities, and a first of its kind program requiring the use of reclaimed refrigerant known as the Refrigerant Recovery Reclaim and Reuse or the R4 Program. In addition to national and international measures, California is currently evaluating further HFC reduction measures that will be needed to meet the Senate Bill 1383 target and long-term carbon neutrality goals.

Technical considerations

Data characteristics

The CO_2 data presented above are a combination of data from the Scripps Institution of Oceanography (SIO), the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA-ESRL), Lawrence Berkeley National Laboratory (LBNL), and CARB. In particular, NOAA-ESRL leads the Carbon Cycle Cooperative Global Air Sampling Network, an international effort which utilizes regular discrete samples from baseline observatories, cooperative fixed sites, and commercial ships (NOAA, 2021a). Air samples are collected weekly in glass flasks and CO_2 is measured by a non-dispersive infrared absorption technique (Keeling et al., 2001). The measurements at Mauna Loa were initiated by Charles D. Keeling of SIO, and date back to March 1958 (Conway et al., 2007). Monitoring at Point Arena was conducted from 1999 through 2011, and at Trinidad Head from 2002 through 2017. At the SIO La Jolla Pier, roughly one sample is collected each month during the period of record.

The Mount Wilson data shown here are from the California Laboratory for Atmospheric Remote Sensing (CLARS) Fourier Transform Infrared Spectrometer (CLARS-FTS) which measures the signatures of GHGs and pollutants from spectra of sunlight scattered from the land surface. CLARS-FTS measures the total number of trace gas molecules in the total optical path. Built by NASA's Jet Propulsion Laboratory, CLARS measures GHG emissions from sources across the Los Angeles (LA) air basin through remote sensing measurements at 33 locations. The CLARS facility has been measuring CO_2 and CH_4 continuously since September 2011 and N_2O since May 2013, thus providing the longest available remote sensing data record that covers the entire LA basin (Zhao and Sander, 2021). The CLARS instrument builds up maps of GHG distributions from remote sensing measurements at 33 locations in the LA basin, similar to the data products from satellites. CLARS data presented here are representative of average basin-wide concentrations. This is quite different from in-situ ("tower") stations which bring a local air sample into the instrument for analysis. CLARS-FTS is similar to certain satellite instruments that measure trace gases (Fu et al., 2014; Wong et al., 2015).

Data collection at Walnut Grove tower began in 2007 through collaboration between researchers at LBNL and NOAA, with support from NOAA, the U.S. Department of Energy (DOE), California Energy Commission (CEC), and CARB. The site was equipped with an automated flask sampling system and real-time analyzers. These provide measurements of a suite of GHGs as well as other compounds including the radiocarbon of CO_2. The Walnut Grove site is the first tall tower site in the world with continuous CH_4 measurements (under NOAA-ESRL's Global Monitoring Division).

Ambient CH_4 concentration data presented in this report were obtained from the NOAA-ESRL, LBNL, and CARB networks. NOAA-ESRL collected ambient air samples in evacuated flasks to detect CH_4 using a flame ionization detector (FID) integrated with a gas chromatograph (GC) system. LBNL and CARB network sites collect continuous air measurements of CH_4 using high-precision cavity ring-down spectroscopy (CRDS) with the same collection frequency and quality control protocols. CH_4 monitoring at Mauna

Loa began in 1983, Point Arena in 1999, and Trinidad Head in 2002; monitoring was discontinued at the California sites on 2011 and 2017, respectively.

Ambient N_2O concentration data presented in this report were obtained from the NOAA-ESRL, LBNL, and CARB networks. NOAA-ESRL collected ambient air samples in evacuated flasks and utilized *in situ* systems to measure N_2O. LBNL and CARB network sites use off-axis integrated cavity output spectroscopy to continuously measure N_2O concentrations. Quality control protocols similar to those applied for CH_4 and CO_2 measurements are instituted to obtain high-precision N_2O measurements.

Ambient F-gas concentration data presented in this report were obtained from the NOAA-ESRL network. NOAA-ESRL utilizes evacuated flasks to collect ambient air at Mauna Loa and analyzes samples using GC systems integrated with an electron-capture detector (ECD) and a mass spectrometer (MS). Data collection began in 2002 in Trinidad Head.

Strengths and limitations of the data

Measurement data from NOAA-ESRL undergo critical evaluation for quality control (NOAA, 2021b). The long-term record at La Jolla, particularly when compared with the longer-term data at Mauna Loa, presents valuable time-series information for tracking GHG trends over the past half century (SIO, 2012). These data are useful for characterizing seasonal variations and provide information about the coastal air that travels into California. Although the La Jolla Pier at SIO extends considerably into the ocean, the site can receive some air currents polluted with urban GHG emissions from the Los Angeles area that mix with the oceanic and San Diego atmosphere. Likewise, the Point Arena location, although coastal, occasionally captures onshore GHG emissions. The Trinidad Head monitor sits on a peninsula extending into the ocean with a tower, however, the air coming from the Pacific Ocean can back up on the nearby coastal range mountains and backflow to the site, thus impacting the measurements of GHG in the onshore air.

CARB's Ambient GHG Monitoring Network and the Walnut Grove tower provide very useful data to study regional GHG emissions trends throughout California and to evaluate regional and statewide inventories in support of California's climate program (CARB, 2021b). These efforts rely heavily on highly accurate and precise measurements of ambient GHGs analyzed using state-of-the-science instruments. This inland network is comprised of eight monitoring stations located throughout California, and CARB and LBNL have equipped these stations with highly accurate and precise analyzers used to measure crucial climate influencers such as CO_2, CH_4, N_2O, and black carbon (BC). Data from this network are used in several research studies. They also form the basis of a series of comprehensive statewide inverse receptor-oriented modeling efforts (Fischer and Jeong, 2016, Cui et al, 2019), as well as various trend analysis studies used to verify and inform the statewide GHG emission inventory in California.

Similarly, the CLARS instrument measures and tracks the GHG emissions from sources across the LA air basin. Unlike individual in situ monitoring stations, the CLARS instrument has the unique capability to scan a large region multiple times a day through remote sensing. CLARS measurements are less sensitive to the height of the mixed layer and local sources, and unlike the in-situ monitors, CLARS data for some species must also be corrected for light scattering by aerosols.

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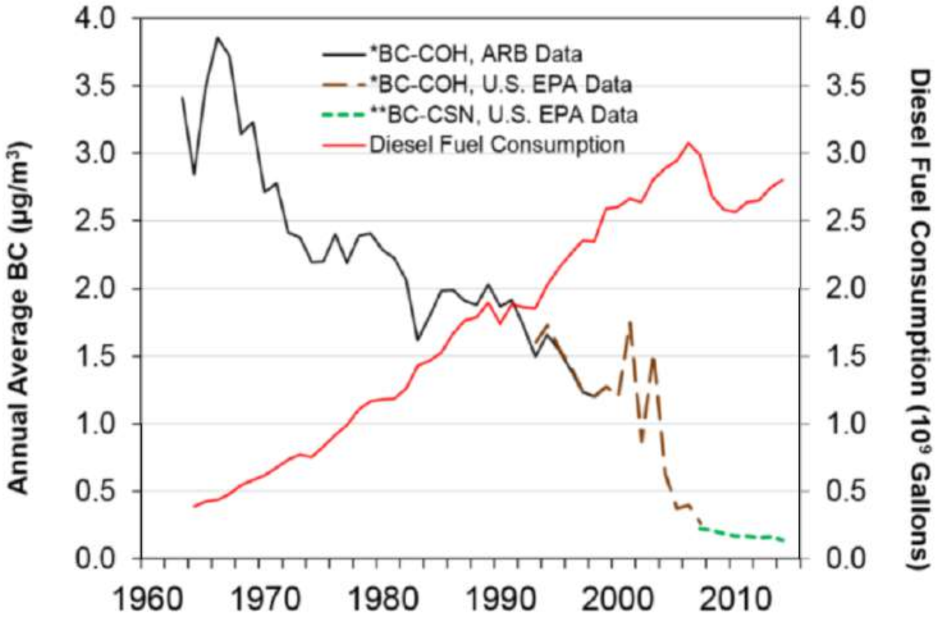
ATMOSPHERIC BLACK CARBON CONCENTRATIONS (NO UPDATE)

Atmospheric levels of black carbon, a major short-lived climate pollutant, have decreased dramatically in California since the 1960s.

Figure 1. Statewide annual average concentrations of black carbon and diesel fuel consumption



Source: CARB, 2015a

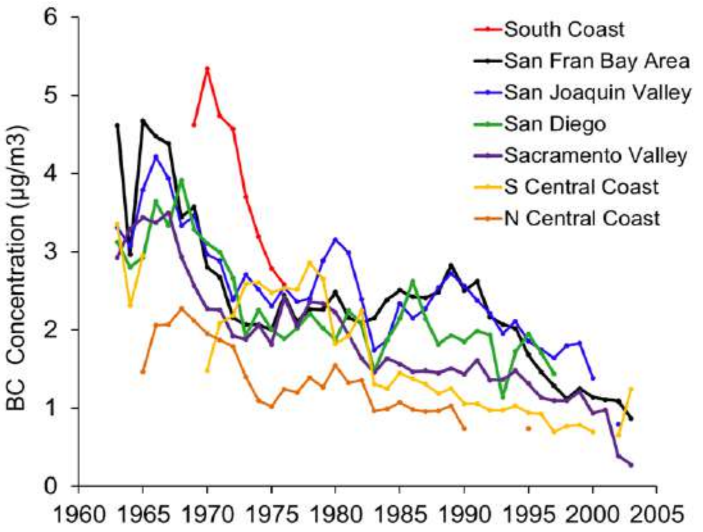
** BC-COH – black carbon, coefficient of haze*
***BC-CSN – black carbon, chemical speciation network*
Note: Data after 2000 are based on a small number of monitors and may not be representative of statewide concentrations.

What does the indicator show?

Long-term data show that ambient black carbon (BC) concentrations in California have declined steadily (Figure 1). Annual average BC concentrations have dropped by more than 90 percent over the past 50 years, from an average of 3.4 micrograms per cubic meter (µg/m^3) in the 1960s to 0.14 µg/m^3 since 2010. This dramatic decline in BC concentrations in the last five decades occurred despite a seven-fold increase in statewide diesel fuel consumption — the largest anthropogenic source of BC emissions in California. New emission standards and restrictions on diesel engines and biomass burning have significantly reduced atmospheric BC concentrations across the state (Kirchstetter et al., 2017).

Archived records of coefficient of haze (COH) were used to reconstruct historical BC concentrations. COH was one of the first measures of particulate matter (PM) pollution used by regulatory agencies and was determined to be a strong proxy for BC. (Please see *Technical Considerations* for a discussion of the data presented).

Figure 2. Estimated annual average black carbon concentrations by air basin



Source: Ramanathan et al., 2013

Although there is considerable variation, BC concentrations by air basin generally followed the decreasing statewide average trend. As shown in Figure 2, downward trends occur across all of the State's major air basins from the mid-1960s to the early 2000s. BC concentrations were considerably higher in the South Coast Air Basin than in the rest of California, at least until the mid-1970s; the lowest BC concentrations were in the North Central Coast Air Basin.

Why is this indicator important?

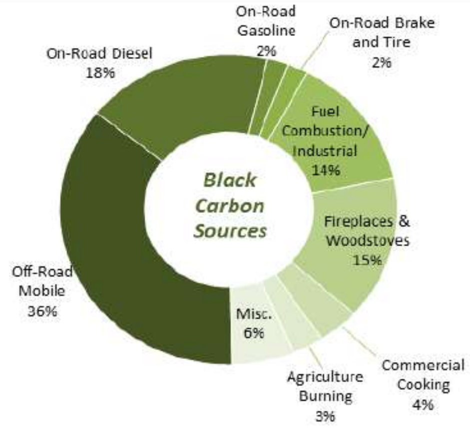
Black carbon is a light-absorbing particle in the air, commonly known as soot. Scientists recently determined that BC may be the second most important contributor to global warming after carbon dioxide (CO_2) (Bond et al., 2013). However, it behaves very differently than long-lived greenhouse gases such as CO_2 do. While greenhouse gases trap heat from the Earth's surface, BC contributes to climate warming by absorbing sunlight directly and releasing heat energy in the atmosphere. CO_2 remains in the atmosphere for hundreds of years, while BC particles are removed from the atmosphere by rain and by deposition after a few days or weeks. However, although BC has a shorter lifespan, it is a much more powerful warming agent than CO_2. For example, one ton of BC has a warming effect equal to 900 tons of CO_2 over a 100-year period. Over 20 years, one ton of BC has the warming impact of 3,200 tons of CO_2 (Bond et al., 2013). Hence, it is considered a critical short-lived climate pollutant.

Black carbon influences the climate in several complex ways. In addition to its direct warming effects, BC particles can deposit on snow, glaciers, and sea ice. This darkens these light, frozen surfaces and reduces their reflectivity. Darker surfaces absorb more solar energy, causing snow and ice to melt more quickly (Hadley et al., 2010; Hadley and Kirchstetter, 2012). This early melting could significantly affect California's summer water supplies, which rely heavily on snowmelt runoff from the Sierra Nevada. Less snowmelt runoff during the spring months, combined with warmer temperatures over already dry areas, increases wildfire risks — which can in turn release more BC particles.

Black carbon can also change the reflectivity, stability, and duration of clouds. Its effects are different depending on how much of it is in the air and where it occurs in the atmosphere. Black carbon particles in a cloud layer can absorb solar radiation, heating the air in it, and leading to cloud evaporation and reduction. However, quantification of this indirect impact on the climate system is imprecise (Koch and Del Genio, 2010).

Reducing emissions of BC presents an opportunity to slow the rate of global warming in the near term. Black carbon is also a component of $PM_{2.5}$ air pollution (fine particulate matter that is 2.5 microns or less in diameter). $PM_{2.5}$ has been linked to respiratory and cardiovascular disease (US EPA, 2009). Hence, reduced BC emissions also provide public health benefits. Control measures are projected to lead to substantial reductions in BC emissions from mobile sources, preventing an estimated 5,000 premature deaths in the State each year (CARB, 2016). These reductions are especially beneficial to disadvantaged communities. For example, diesel particulate matter concentrations are highest along freight corridors and near ports and rail yards where disadvantaged communities are often located. Regardless of net climate forcing or other climatic effects, all BC mitigation options bring health benefits through reduced particulate matter exposure. A worldwide program along the lines of what is being done in California would avoid hundreds of thousands of premature deaths annually (Anenberg et al., 2011).

Figure 3. 2013 California black carbon emissions



Source: CARB, 2015b

What factors influence this indicator?

In California, the major anthropogenic sources of BC in 2013 include a diesel-fueled mobile sources, fuel combustion and industrial processes, and residential fireplaces and woodstoves. Off-road mobile emissions account for over a third of statewide BC emissions. On-road mobile sources account for nearly a quarter of emissions, primarily from on-road diesel combustion, which contributes approximately 18 percent to California's BC emissions. On-road gasoline, as well as brake wear and tire wear emissions of BC are relatively small. Residential fireplaces and woodstoves currently account for approximately 15 percent of BC emissions, with another 14 percent attributable to fuel combustion and industrial processes.

Other anthropogenic sources include dust, waste disposal, residential natural gas combustion, and unplanned structure and car fires. These sources and the ambient concentrations of BC vary geographically and temporally. Emissions standards and restrictions implemented on diesel engines and biomass burning activities have had a significant effect on decreasing ambient air BC concentrations across the State. In 2013, total anthropogenic BC emissions were about 38 million metric tons of carbon dioxide equivalent (MMTCO_2e), using the 20-year Global Warming Potential (GWP) value of 3,200 from the IPCC Fifth Assessment Report (IPCC, 2013).

Anthropogenic BC emissions do not include forest-related sources (i.e., wildfires and prescribed burning). Wildfire is the largest source of BC emissions in California, contributing an estimated 87 MMTCO_2e annually (calculated as a ten-year annual average); prescribed fires, an important tool for forest managers, emit an estimated 4 MMTCO_2e. (To provide a more representative view of emissions without large year-to-year variability driven by natural forces, forestry emissions are calculated as a ten-year average) (CARB, 2017).

As shown in Figure 1, the largest decline in BC concentrations occurred in the years before 1975, coinciding with the adoption of state and federal air quality regulations. These include tailpipe emission limits established by California in the mid-1960s, federal emission standards for stationary sources and motor vehicles adopted in the mid-1960s, and diesel emission controls introduced nationally in 1970. Between 1975 and 1990, BC levels declined more gradually, likely due to the replacement of older, more polluting diesel vehicles as a result of on-road heavy-duty diesel particulate matter emission standards adopted in 1973 by California. BC concentrations decreased more rapidly after 1990, despite intermittent increases in the early 2000s (Kirchstetter et al., 2008). Retrofitting of urban transit buses with oxidation catalysts, limits on sulfur content in diesel fuel, changes in diesel engine technology, and restrictions on agricultural burning and residential wood combustion, among other measures, contributed to the reductions.

Existing regulatory programs, including ongoing efforts to reduce tailpipe emissions from trucks and buses, will continue to reduce BC emissions. For example, further reductions are expected from stricter diesel engine emission standards implemented by the state in 2007 and the complementary low-sulfur fuel introduced nationally in 2006. To comply with federal air quality standards, control measures that reduce $PM_{2.5}$ pollution (including BC and other constituents) are projected to decrease BC emissions from mobile sources in California by 75 percent between 2000 and 2020 (CARB, 2016). Senate Bill 1383 (Chapter 395, Statutes of 2016) sets a target to reduce BC emissions by 50 percent below 2013 levels by 2030, with a focus on disadvantaged communities.

Technical Considerations

Data Characteristics

Because of their short residence time in the atmosphere and their strong dependence on local sources, particles exhibit high spatial and temporal variation, requiring frequent measurements at numerous sites to reliably track trends. However, few extensive records of particle concentrations are available. One of the first measures of PM pollution used by regulatory agencies, the coefficient of haze (COH), was determined to be a strong proxy for BC, based on co-located field measurements of BC and COH. Archived records of COH, a now-retired measure of light-absorbing PM, were used to reconstruct historical BC concentrations. BC concentrations were inferred from COH data based on a relationship determined from statistical analyses (see Chapter 2.0 of Ramanathan et al., 2013). Statewide average BC concentrations were computed separately using data from CARB (1963 to 2000), and US EPA (1993 to 2007).

Where the US EPA and CARB datasets overlap, agreement is very good. The location and number of COH monitors operating in California has varied over time. From the mid-1970s to 2000, 30 or more COH monitors were in operation for the majority of the year, but these dropped to 15 by mid-2000 (mainly in the US EPA dataset). Hence, the data after 2000 are based on a smaller number of monitors, and may not be as representative of statewide concentrations.

Data from 2007 to 2017 are from the US EPA's Chemical Speciation Network (CSN). Since early 2000, about 17 CSN sites have been providing information on $PM_{2.5}$ concentrations in California's ambient air. Samplers operate on a 24-hour schedule from midnight to midnight, generally sampling every third day or every sixth day. CSN must meet all federal and state requirements for monitoring methodology and quality assurance. CSN is designed to track the progress of $PM_{2.5}$ emission reduction strategies through the characterization of trends of individual $PM_{2.5}$ species, including BC. Although the CSN network has been collecting BC data since 2000, the collection and analysis methods were different during the first few years of the program (Chow et al., 2007). The differences were significant enough to affect the trends, therefore data from the CSN network prior to 2007 are not presented in Figure 1.

Strengths and Limitations of the Data

For the purposes of climate change study, BC is defined as the carbon component of PM that absorbs light. A significant advantage of monitoring BC by an optical method is that it delivers results in real time with a high time resolution (in minutes). However, BC as a component of PM is difficult to measure. Methods that measure light absorption in PM assume that BC is the only light-absorbing component present. However, some components of organic carbon can also be light-absorbing. The impact of BC on climate forcing is well established, but the magnitude and wavelength dependence of absorption by organic carbon (often called brown carbon, a by-product of the biomass burning) is poorly constrained. Existing methods, such as using an enhanced thermal/optical carbon analyzer with multi-wavelength capabilities, can add value to current PM monitoring programs by providing a complete identification and quantitation of the carbonaceous component of ambient aerosols in near-real time.

Emissions inventories for climate change studies have focused primarily on greenhouse gases. Most of the important sources of greenhouse gases are also important sources of health-related pollutants. Likewise, BC is emitted primarily from combustion sources which are also important sources of health-related pollutants. California's BC inventory relies on PM inventories coupled with speciation profiles that define the fraction of PM that is BC. However, it is a challenge to estimate statewide BC emissions, and to define speciation profiles for all sources. Hence, improved emissions inventory methodologies and tools developed for health-related pollutants can also provide opportunities for improving climate change emission inventories (and vice versa).

OEHHA acknowledges the expert contribution of the following to this report:

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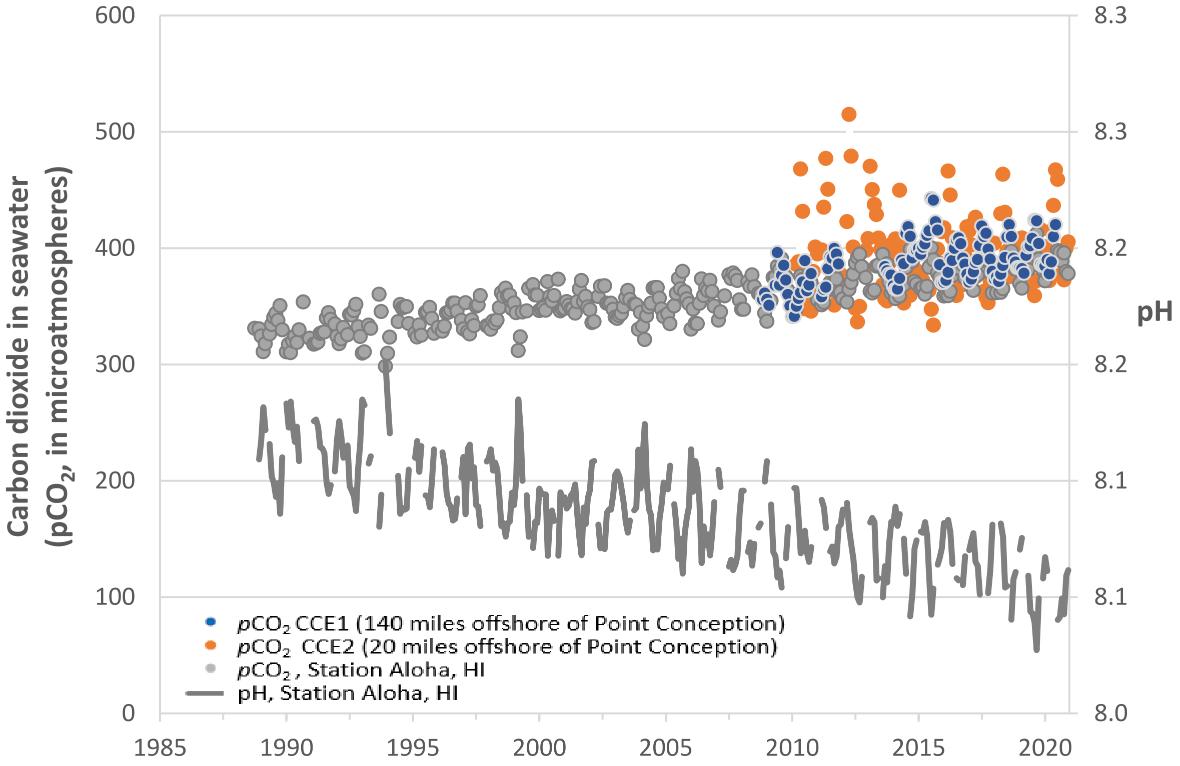
ACIDIFICATION OF COASTAL WATERS

As atmospheric concentrations of carbon dioxide increase, so do levels in the ocean, part of a process known as "ocean acidification." While long-term data for California waters are limited, carbon dioxide measurements at one offshore location near Point Conception are similar to those from monitoring off Hawaii. They show increases in seawater carbon dioxide levels accompanied by increasing acidity (measured as pH). This phenomenon has been observed at multiple sites in the world's oceans.

Figure 1. Seawater carbon dioxide and pH off Hawaii and Point Conception, CA



Source: Hawaii Ocean Time-Series 2022, Dore et al. 2009; NOAA NCEI 2022, Sutton et al., 2012 and 2016

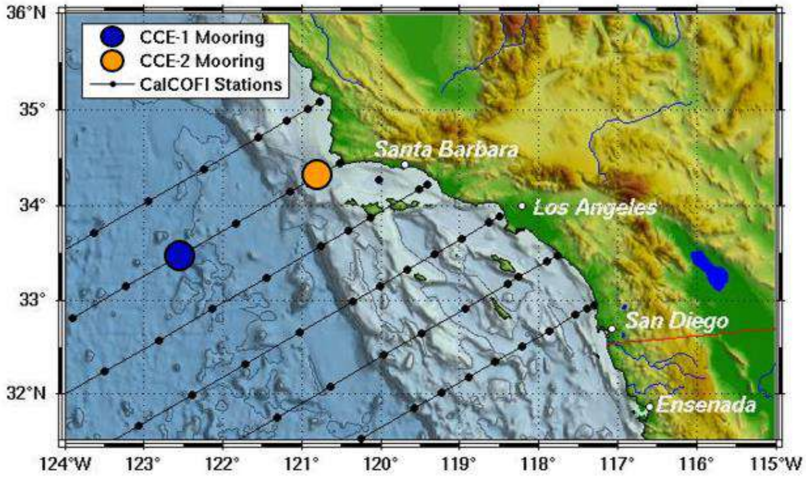
Carbon dioxide (measured as the partial pressure of CO_2 in seawater) from the Hawaii Ocean Time-Series (HOT) site (grey) and two offshore California sites (CCE1 blue, and CCE2, orange). Records of pH are from HOT.

What does the indicator show?

This indicator shows that the oceans are becoming more acidic. This is clear in levels of carbon dioxide (CO_2) and pH (a measure of acidity) in seawater off the coast of Hawaii, as shown in Figure 1. Levels of CO_2 are expressed as the partial pressure of carbon dioxide, or pCO_2 (which refers to the pressure that CO_2 contributes to the total pressure of the mixture of gases present in seawater). Off the coast of California, the levels of CO_2 measured since 2008 at "CCE1" located 140 miles off Point Conception near Santa Barbara are generally similar to those measured at similar time points at Station Aloha off Hawaii, also shown in Figure 1. At CCE2, a second location 20 miles from Point Conception, levels show greater variability (values range from 330 to 520 microatmospheres (µatm)). This is likely due to its location closer to shore, where concentrations are influenced by seasonal changes in upwelling (Sutton et al., 2019; also see *Coastal ocean temperature* indicator). Upwelling is the wind-driven movement of deep, cool, carbon- and nutrient-rich ocean water to the surface, replacing the warmer, usually nutrient-depleted surface water.

Measurements at CCE1, which began in September 2010, provide the longest-running publicly available data on CO_2 levels in seawater in California (there is a 21-month gap in measurements at CCE2). The record at both California locations are not long enough to discern trends. Figure 2 shows where sites CCE1 and CCE2 are located.

Figure 2. Location of CO_2 monitoring sites



Source: Modified from SIO, 2017

At Station Aloha, $p$$CO_2$ levels have increased steadily at the rate of about 1.8 µatm/year, and the pH has decreased at the rate of 0.002 unit per year over this time period. At seven long-term monitoring sites around the globe, measurements of $p$$CO_2$ and pH show similar changes over the last three decades: $p$$CO_2$ has increased by 1.29 to 2.95 µatm/year, and pH has decreased by 0.0013 to 0.0025 unit/year (Bates et al., 2014). Monitoring at Station Aloha off Hawaii provides the longest-running measurements of ocean acidity in the North Pacific Ocean.

Why is this indicator important?

CO_2 is considered to be the largest and most important anthropogenic driver of climate change. It is continuously exchanged between land, the atmosphere, and the ocean through physical, chemical, and biological processes. Since the mid-1980s the ocean has absorbed approximately 20 to 30 percent of the CO_2 released into the atmosphere by human activities (Bindoff et al., 2019; Canadell, et al., 2021; Friedlingstein et al., 2022); this process has significantly reduced the CO_2 concentrations in the atmosphere and minimized some of the impacts of global warming (Rhein et al., 2013). As atmospheric CO_2 concentrations continue to increase, so do CO_2 concentrations in the ocean, changing the carbonate chemistry of seawater — a process termed “ocean acidification” (Caldeira and Wickett, 2003; Doney et al., 2009). The net result of adding CO_2 to seawater is an increase in hydrogen ions (H+) — which increases seawater acidity and lowers seawater pH — along with a decrease in carbonate ion, a fundamental ‘building block’ for organisms known as “calcifiers,” that forming shells or skeletons. The concentration of carbonate ions in seawater is commonly measured using the saturation state of aragonite, a soluble form of calcium carbonate used by calcifiers, expressed as the term Ω. When Ω is less than 1, exposed calcium carbonate structures begin to dissolve (Pershing et al., 2018). Global marine ecosystems face serious threats from ocean acidification, deoxygenation (see *Dissolved oxygen in coastal waters* indicator) and ocean warming (see *Coastal ocean temperature* indicator).

Tracking anthropogenic emissions of CO_2 and the distribution among the atmosphere, land, and ocean provides a better understanding of the global carbon cycle and informs the development of climate policies (Friedlingstein et al., 2022). Future scenarios project that the ocean and land will be less effective as sinks, and thus at slowing the accumulation of CO_2 in the atmosphere with increasing emissions (Gulev et al., 2021). Nevertheless, the ocean holds great potential for uptake and long-term storage of CO_2. Approaches to enhance ocean’s carbon capacity without further acidifying ocean environments are an area of intense research. The National Academies has recommended a research agenda to assess the benefits, risks, and potential for responsible scale-up of ocean-based carbon dioxide removal strategies, and to ensure that no unintended and potentially irreversible harm to natural systems and coastal communities result (NASEM, 2021). Examples include nutrient fertilization to stimulate marine phytoplankton growth, artificial upwelling and downwelling, and seaweed cultivation.

Many economically and ecologically important West Coast species (such as oysters, mussels and crabs) have been documented to show direct responses to acidification (Chan et al., 2016). Although many studies have investigated the effects of ocean acidification on marine species, establishing threshold values for pH that sufficiently capture the concentrations at which harmful responses occur is challenging. For example, thresholds in for a species can vary with endpoints, life stage and spatial and temporal exposure patterns (Bednaršek et al., 2021a, b; Bednaršek et al., 2019). Further ocean acidification, combines with deoxygenation and ocean warming in producing these effects and how this occurs is not well understood. In a review of the literature on possible “tipping points” relating to ocean acidification, the authors concluded that the lack of long-term monitoring and the complexity of ecosystem responses to ocean acidification have made the detection of such tipping points difficult (Heinze et al., 2020).

Several biological processes in marine organisms are sensitive to changes in seawater chemistry. The best-documented and most widely observed biological effects on calcifiers (including plankton, mollusks, and corals) are decreased calcification rates and/or shell dissolution due to reduced carbonate ion levels under reduced pH conditions (e.g., Bednaršek et al., 2014; Bednaršek et al., 2021a, b; Bednaršek et al., 2019; Feely et al., 2018; Gaylord et al., 2011; Hodgson et al., 2018; Lord et al., 2019; Mekkes et al., 2021; Osborne et al., 2020; Rose et al., 2020; Swezey et al., 2020). Controlled laboratory experiments and field observations have documented decreased shell size/thickness in shellfish and elucidated these processes (Barton et al., 2012;

Gaylord et al., 2011; Hettinger et al., 2012 and 2013; Miller et al., 2009; Waldbusser et al., 2013). Impacts on calcifiers can be amplified across marine food webs when they affect sea snails (pteropods), single-celled amoeboid organisms (called foraminifera) and other key links in the marine food chain; can lead to the degradation of the habitat provided by corals, mussels, oysters and other structure-forming taxa; and can reduce the water filtration services provided by bivalves (e.g., Feely et al., 2016; Hollarsmith et al., 2020; Osborne et al., 2020; Mekkes et al., 2021). In Tribal listening sessions, several Tribes, including the Coastal Band of the Chumash Nation and the Santa Ynez Band of Chumash Indians have reported that they have seen a decrease in abalone (a cultural keystone species), Pismo clams and Olivella shells due to ocean acidification (Pala Band of Mission Indians and Santa Ynez Band of Chumash Indians, 2021).

In lower pH ocean waters, organisms face greater challenges in maintaining internal acid-base balance, leading to effects on the physiology and behavior of marine species (e.g., Somero et al., 2016; Hodgson et al. 2018; Jellison et al., 2016; Gaylord et al., 2018; Contolini et al., 2020; Rose et al., 2020). Other potential effects of ocean acidification result from changes in the ionic form of marine nutrients and potentially harmful substances (such as metals); increased photosynthetic rates in carbon-fixing organisms; altered reproduction and survival in organisms; and reduced olfaction (sense of smell) in fish. Broader ecological consequences include trophic mismatch (Kroeker et al., 2021) and altered predator-prey and other species interactions, such as herbivory and competition (e.g., Ferrari et al., 2011; Kroeker et al., 2014; Sanford et al., 2014; Gaylord et al., 2018; Magel et al., 2020; Hodgson et al., 2018; Contolini et al., 2020; Lord et al., 2019).

Regional biological indicators can help improve the understanding of impacts of ocean acidification and other stressors on California's varied smaller-scale ocean ecosystems (Duncan et al., 2019; Duncan et al., 2013). A comprehensive review and analysis of biological responses to ocean acidification has identified possible indicator species and variables to consider in selecting indicators of ocean acidification (Kroeker et al., 2013). Among the most important traits of candidate indicator species are sensitivity to the environmental factor of interest, ecological value, presence over a wide geographic extent, and accessibility and familiarity to local communities (Gaylord et al., 2018). Some potential indicators of the biological impacts of ocean acidification in California waters are:

- The California mussel (*Mytilus californianus),* a familiar and well-recognized intertidal organism throughout the US West Coast. It is a classic "foundation species" that dramatically influences community structure both through its dominant status and its role in providing habitat (mussel beds) for hundreds of other species (Suchanek, 1992; Duncan et al., 2019; Rose et al., 2020). The distribution of *M. californianus* spans the entire west coast of the US (Morris et al., 1980; Rose et al., 2020), including most of the state's shoreline Marine Protected Areas. Life history can play a critical role in mussel response to ocean acidification: newly settled *M. californianus* retain larval shells which have been shown to be smaller when larval stages occurred in lower pH seawater; further, overall health is reduced when lower pH conditions are combined with warmed waters (Gaylord et al., 2018; Rose et al., 2020). Not only are California mussels affected by changes in seawater chemistry, they are accessible on shore when tides recede. *M. californianus* has already been identified as an indicator species by two National Marine Sanctuaries in California (Gaylord et al., 2018).

- Krill, a fundamental and important component of the marine food web. Krill have been shown to be sensitive to ocean acidification, with responses that include reductions in growth rates and increased mortality (e.g., Cooper et al., 2017; McLaskey et al., 2016).
- Pelagic snails (pteropods), that have delicate shells subject to severe dissolution when exposed to low pH seawater (Duncan et al., 2019; Engström-Öst et al., 2019; Mekkes et al., 2021). Dissolution of shells of *Limacina helicina*, the most dominant pteropod within the California Current Large Marine Ecosystem, have been demonstrated to occur in waters with low levels of aragonite (the form of calcium carbonate used by marine calcifiers), thus underscoring the species' susceptibility to ocean acidification (Bednaršek et al., 2014; Bednaršek et al. 2018; Busch et al., 2014; Mekkes et al., 2021) (see Figure 3). Pteropods are ecologically important as prey for commercial fish species.

Figure 3. Dissolution of pelagic snail shells exposed to corrosive seawater

Source: Figure 7, Busch et al., 2014

Images of *Limacina helicina*, a pelagic snail, after week-long incubation in Puget Sound waters at the following levels of aragonite (a form of calcium carbonate, Ω_a) levels: [A] Ω_a ~ 1.59, corresponding to current summer surface conditions; [B] Ω_a ~0.56, current deep water or surface conditions during upwelling; and [C] Ω_a ~0.28, future deep water or surface conditions during upwelling. Corrosion is evident on the ribs of the shell in [B], and [C] shows shell perforations.

The Fourth California Climate Assessment noted that "ocean acidification presents a significant and well-established threat to commercial fisheries and farmed shellfish, and therefore human coastal communities" (Sievanen et al., 2018). This supports a growing body of literature that explores the connections between ocean acidification, coastal economies, and human communities (e.g., Doney et al., 2020).

What factors influence the indicator?

The Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report, concluded that the uptake of anthropogenic CO_2 emissions is the main driver for the global decline in ocean water pH over the last 40 years (Gulev et al., 2021). The air-sea exchange of carbon dioxide is determined largely by the difference in the partial pressure of CO_2 between the atmosphere and the ocean; as the partial pressure of CO_2 in the atmosphere increases with increasing emissions, the ocean absorbs more of it to reach equilibrium. Long-term measurements of ocean carbon content at seven monitoring sites around the globe (including the Hawaii Ocean Time Series presented in Figure 1) collectively show consistent and coherent changes in the uptake of CO_2 by the ocean. At decadal time scales, the rate of ocean acidification in these open ocean surface waters generally approximates the rate of CO_2 increase in the atmosphere (Bates et al., 2014).

The air-sea CO_2 interchange – which is driven by differences in the amount of CO_2 in air compared to water -- is influenced by biologically-mediated reactions (photosynthesis, respiration, and precipitation and dissolution of calcium carbonate). Photosynthesis and respiration remove and add CO_2 to seawater, respectively. In coastal habitats, kelp forests and seagrass meadows can locally ameliorate high CO_2 concentrations by removal of CO_2 via photosynthesis; these effects, however, are temporary (Hirsh et al., 2020; Ricart et al., 2020). Shell formation by marine calcifiers also affects the carbonate chemistry of surrounding seawater by locally reducing buffering capacity and increasing pCO_2.

While biological processes play an especially key role in determining shorter-term (daily to seasonal) variability in pH and pCO_2 in seawater (Wootton et al., 2008; Hoffman et al., 2011), air-sea exchange processes dominate the longer-term interannual-to-decadal trends. Along the West Coast, ocean acidification adds to the already naturally high values of carbon dioxide in upwelled waters. The unique oceanography of the California Current Large Marine Ecosystem may provide early indication of the impacts of ocean acidification and decreasing dissolved oxygen; California's coastal waters are experiencing more acidified and lower oxygen conditions well earlier than most other regions (e.g., Feely et al., 2008; Hauri et al., 2009; Gaylord et al., 2018; Hodgson et al., 2018; Osborne et al., 2020). The interactions between upwelling, hypoxia, and ocean acidification are well explored (e.g., Cheresh and Fiechter, 2020).

In addition to seasonal patterns in ocean chemistry tied to upwelling processes, changes associated with large-scale climate oscillations such as El Niño and the Pacific Decadal Oscillation can alter the ability of oceanic waters to serve as either a sink or a source of CO_2. This can occur through seawater temperature changes as well as through ecosystem variations that occur via complex physical-biological interactions (Chavez et al., 2007). For example, during El Niño, upwelling of high CO_2 waters is dramatically reduced along central California so that flux out of the ocean is reduced; at the same time, ocean uptake of CO_2 is also reduced because of lower photosynthetic activity, as nutrients that would have been carried to the surface by upwelled waters are less available. Modeled estimates of pH and *aragonite saturation state* (a measure of whether calcifying organisms will be able to form shells, or if shells are more likely to dissolve) along the southern California coast from 1985 to 2014 suggest a persistent shift in ocean acidification-related seawater conditions from the decade prior to the strong 1997–1998 El Niño event to the decade after it (McClatchie et al., 2016). In the southern California Current System, subdecadal (2005–2011) estimates for pH and related parameters reveal a pronounced seasonal cycle and inter-annual variability in the upper water column (15–500 meters depth) (Alin et al., 2012). Changes in the local biogeochemistry, carbon chemistry, and saturation state were also documented during the 2014-2016 heat wave event on the California coast (Lilly et al., 2019).

The variability in the data of $p\mathrm{CO_2}$ levels in Figure 1 (CCE2 location) compared to open ocean waters (CCE1 location) reflects the more complex acid-base chemistry dynamic of coastal waters (NAS, 2010). In addition to upwelling and other climate-related processes, coastal waters can be affected by localized freshwater and atmospheric inputs, organic matter and nutrients from land, and processes in the underlying sediments. The seasonal, monthly, and daily variability that can occur from biological and oceanographic processes has been observed at other monitoring stations along the California coast (e.g., M1 mooring in Monterey, Hog Island Oyster Company store station, Carlsbad Aquafarm shore station) (CenCOOS (Monterey), 2021; IPACOA (shore stations), 2021; see references for URLs to access data from these stations). Knowledge of short-term variability of CO_2 in seawater is important to interpret any changes attributed to anthropogenic processes at a given location. An analysis of $p\mathrm{CO_2}$ and pH data collected at 40 monitoring stations (in four ocean basins, representing a range of ocean, coastal and coral reef locations) estimated the length of the record needed to distinguish anthropogenic trends from natural variability to be 8 to 15 years at open ocean sites (such as CCE1, estimated at 12 years) and 16 to 41 years at coastal sites (such as CCE2, estimated at 24 years) (Sutton et al., 2019).

Despite the global nature and the widespread implications of ocean acidification, a unified policy response analogous to international efforts to limit greenhouse gas emissions has yet to be developed (Collins et al., 2019). Since it takes decades to millennia for the ocean subsurface to respond to changes at the surface, the ocean is already "committed" to changes resulting from current atmospheric greenhouse gas levels, even after concentrations stabilize; thus, ocean acidification is irreversible on timescales relevant to human societies and ecosystems (IPCC 2019).

Technical considerations

Data characteristics

Monitoring along the California coast includes moorings with carbon dioxide and pH sensors, regular measurements of inorganic carbon species on oceanographic cruises, calculation of aragonite saturation state, and shore-based observations of carbon chemistry in nearshore waters. These monitoring efforts are included in large-scale monitoring programs, for example within the US Integrated Ocean Observing System (IOOS) and the National Oceanic and Atmospheric Administration (NOAA) ocean acidification observing network, all carried out in collaboration with a wide range of national, regional, and international partners. Many of these efforts can be viewed in real time through an online data portal (IPACOA, 2021).

Integrated biological, chemical, and physical oceanographic monitoring may elucidate broad-scale impacts of ocean acidification and climate change. Long-term ecological monitoring programs for intertidal and subtidal ecosystems (e.g., LiMPETS, MARINe, and PISCO), the Marine Protected Area Monitoring efforts (e.g., Ocean Science Trust), and oceanographic monitoring by the Applied California Current Ecosystem Studies (ACCESS) provide essential data to support a better understanding and interpretation of the impacts of ocean acidification for California.

The CCE1 mooring (140 miles southwest of Point Conception) was deployed in November 2008 as part of a multi-investigator, multi-disciplinary project by NOAA's Pacific Marine Environmental Laboratory. The project expanded to include the CCE2 mooring, at the shelf break closer to Point Conception, in 2010. Sensors on these moorings measure aspects of biological, chemical, and physical oceanography as well as meteorology; data are collected every three hours. This project is closely coordinated with other projects off of Southern California such as the California Cooperative Oceanic Fisheries Investigations, and the California Current Ecosystem Long Term Ecological Research, and the Consortium on the Ocean's Role in Climate.

Figure 1 features data from the Hawaii Ocean Time-series (HOT) program for comparison. This program has been making repeated observations of the chemistry, and biology of the water column at a station north of Oahu, Hawaii, since October 1988. Cruises are made approximately once per month to the deep-water Station Aloha located 62 miles north of Oahu, Hawaii. Calculated values of pH and $p\text{CO}_2$ are obtained from measured parameters; direct measurements of pH are also made at sea.

Despite the central importance of data for detecting long-term changes in the ocean's carbon system, coordinated observing networks in the US coastal and estuarine waters did not exist until the early 2010s, following the establishment of NOAA's Ocean Acidification program (NOAA, 2021). Historically, assessments of changes to the carbonate system relied on a handful of data records worldwide (none of which operated in California waters, and the longest of which began only in the early 1980's) (Bates et al., 2014). Recent studies have focused on ways in which to build monitoring frameworks and identify gaps (e.g., Turk et al., 2019; Taylor-Burns et al., 2020).

Strengths and limitations of the data

Given that pH and/or $p\text{CO}_2$ of seawater are variable in many of California's marine ecosystems, datasets of these carbonate chemistry parameters will need to be of sufficient length before trends beyond natural variability can be detected (Sutton et al., 2019). Hence, a limitation of the ability to detect long-term trends in carbonate chemistry off California's coast is that the monitoring sites have not been continuously operated, due to funding limitations, and many focused on ocean acidification were more recently initiated. Measurements of pH, in addition to $p\text{CO}_2$, will allow a more accurate and precise evaluation of the changes associated with ocean acidification. Future expansion and extension of the current monitoring network for ocean acidification was a major recommendation of the West Coast Ocean Acidification and Hypoxia Panel (Chan et al., 2016). Ideally this will take shape via a robust, integrated monitoring system for ocean acidification and hypoxia that is integrated with biological monitoring.

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Changes in Climate

Climate, which is generally defined as “average weather,” is described in terms of the mean and variability of temperature, precipitation, and wind over a long period of time.

Warming of the climate is unequivocal, and the dominant effect of human activities in driving this change is clear (IPCC, 2021). Global surface temperatures during 2011-2020 were 0.95 to 1.20°C (1.71 to 2.16°F) warmer compared to 1850–1900 (IPCC, 2021). Each of the last four decades has been successively warmer than any preceding decade, with temperatures increasing at a faster rate since 1970 than in any other 50-year period over the past 2000 years.

Warming trends in the United States and California – including the acceleration of warming trends – are consistent with global changes. The average surface temperature for the contiguous 48 states has risen by about 0.16°F per decade since 1901; eight of the top ten warmest years on record have occurred since 1998, with 2012 and 2016 being the warmest (US EPA, 2021). Similarly, in California the past decade included eight of the warmest years; record high temperatures occurred in 2014 and 2015. As expected in a warming climate, temperatures at night – which generally correspond to minimum temperatures – increased faster than daytime temperatures. Warmer nights can impact public health, especially for certain sensitive groups, and can affect fruit and nut tree production in the state’s agricultural regions. Extreme heat events have become more frequent since 1950, especially in the last 30 years. These warming trends have been accompanied by an increase in “cooling degree days,” a temperature-based metric that indicates a greater need for energy to cool homes and buildings.

In California, precipitation has become more variable in recent decades, with very dry years interspersed with very wet years. This variability has been influenced by “atmospheric rivers,” long, narrow bands that transport most of the water vapor originating from the tropics to the poles (NOAA, 2017).

With warmer temperatures and lower precipitation volumes, drought conditions continue in the state. In fact, years 2000 to 2021 have been the driest 22-year period in the last millennium in California and the rest of the southwestern United States—part of what scientists are now calling an emerging “megadrought” era (Williams, et al., 2022).

Climate change is already making many weather and climate extremes such as heatwaves, heavy precipitation, and droughts even more extreme in every region across the globe (IPCC, 2022). In 2021, an unprecedented number of devastating extreme events occurred across the United States, costing an unprecedented $152.6 billion. In the past five years, such weather events are estimated to have cost more than

$14.2 billion/year in California – more expensive than in any other time period (NOAA, 2022).

INDICATORS: CHANGES IN CLIMATE

Air temperature *(updated)*
Extreme heat events *(updated)*
Winter chill *(updated)*
Cooling and heating degree days *(updated)*
Precipitation *(updated)*
Drought *(updated)*

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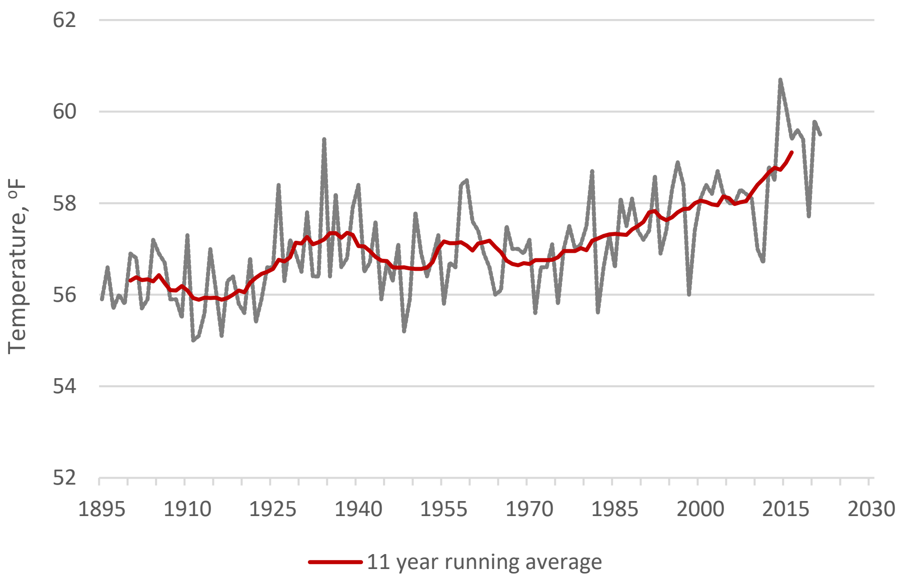
AIR TEMPERATURE

Air temperatures have increased over the past century, driven mainly by changes in nighttime temperatures.

Figure 1. Statewide annual average temperatures



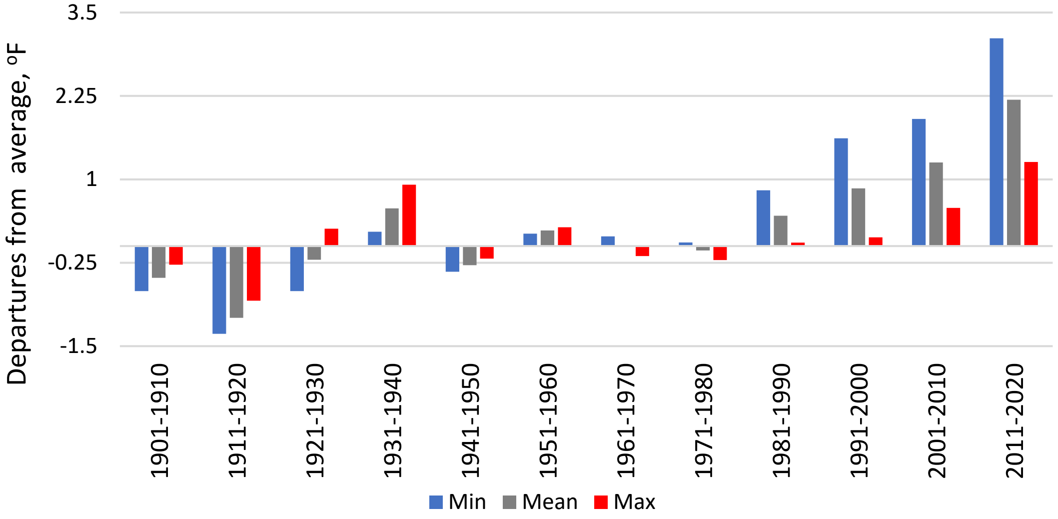
Source: WRCC, 2022

What does the indicator show?

Statewide air temperatures show a warming trend consistent with that found globally (IPCC, 2021; also see the globalwarmingindex). They have been recorded since 1895. Figure 1 presents annual average temperatures statewide. Annual average temperatures have increased by about 2.5 degrees Fahrenheit (˚F) (or about 2°F per century, which is a common way of measuring long-term temperature changes). Recent years were notably warm, with 2014 being the warmest on record, followed by 2015, 2020, 2017, 2016, and 2018. Some of these warmest years coincided with some of the driest years in the instrumental record and led to exacerbated drought conditions due to increased land surface temperatures, evapotranspiration, and evaporative demand.

Figure 2 depicts “departures” by decade from a long-term average (base period of 1901 to 2000) for minimum, mean, and maximum temperatures. Departures are the difference between each decade’s value and the long-term average. Before the 1930s, temperatures were cooler than the long-term average, then hovered around the average between the 1940s and the 1970s. The last four decades showed marked warming, as temperatures increased at a faster rate. Minimum, average, and maximum temperatures have increased overall. Minimum temperatures (which reflect overnight low temperatures) have increased the fastest.

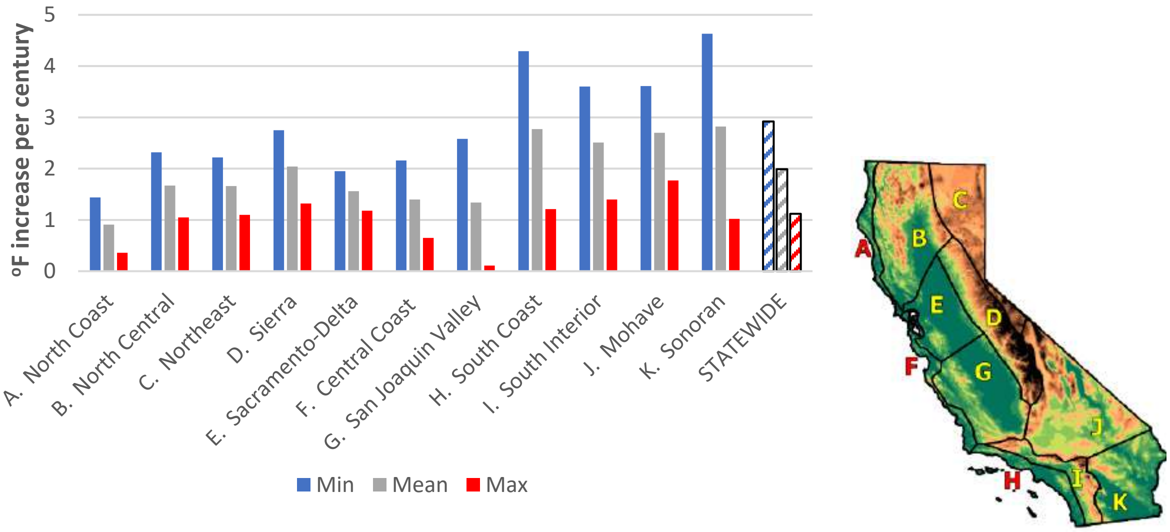
Figure 2. Statewide Temperatures, Decadal Averages (relative to the 1901-2000 long-term average*)



Source: WRCC, 2021

** Values shown for each decade are "departures" from the long-term average, 1901-2000—that is, the difference between the long-term average and the average for the decade.*

Figure 3. Regional and statewide temperature trends (1895 to 2020)



Source: WRCC, 2021

As shown in Figure 3, statewide minimum temperatures rose at a rate of 2.9°F per century. Maximum temperatures rose at 1.1°F per century. As minimum temperatures have increased the fastest, the increasing trend in the average California temperature is driven more by nighttime processes than by daytime processes.

All of California's 11 climate regions have experienced warming trends over the last century, although at varying rates (Figure 3). The greatest increases are observed in the Sonoran Desert and South Coast regions. Minimum temperatures showed the greatest rate of increase in all the regions, consistent with statewide trends.

Why is this indicator important?

Temperature is a basic physical factor that affects many natural processes and human activities. Warmer air temperatures alter precipitation and runoff patterns, influencing the availability of freshwater supplies. Increased temperature leads to a wide range of impacts on ecosystems — including changes in species' geographic distribution, in the timing of life cycle events, and in their abundance — as well as on human health and well-being. In addition, warming temperatures affect energy needed for cooling and heating, which in turn influences the types of energy generation, infrastructure, and management policies needed to meet these demands. Temperature changes can also increase the risk of severe weather events such as heatwaves and intense storms. Understanding observed temperature trends is important for refining future climate projections for climate-sensitive sectors and natural resources within the state (Cordero et al., 2011).

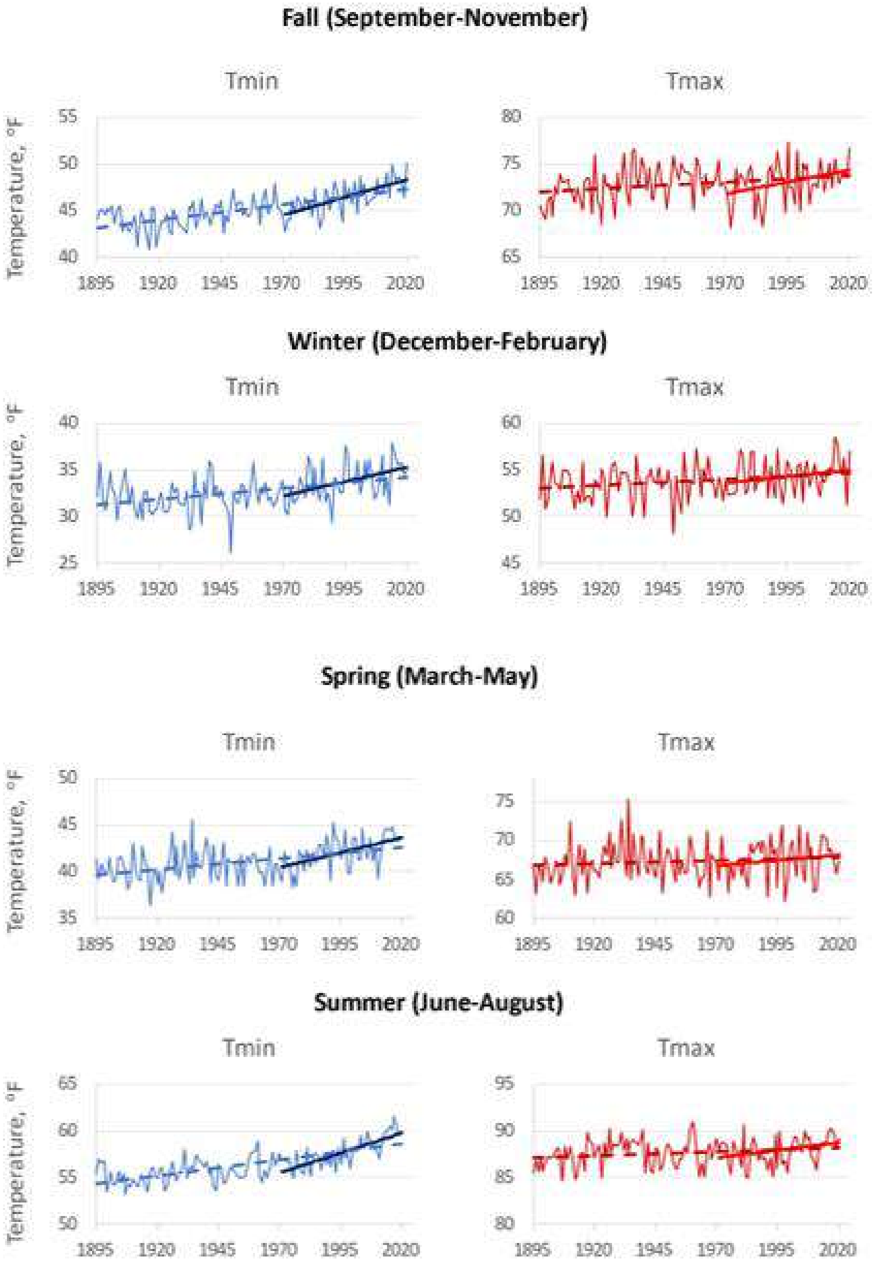
What factors influence this indicator?

Carbon dioxide and other greenhouse gas emissions into the atmosphere since the Industrial Revolution in the mid-1700s have driven unprecedented warming worldwide. (IPCC, 2021). Emissions of these greenhouse gases intensify the natural greenhouse effect, causing surface temperatures to rise. Greenhouse gases absorb heat radiated from the Earth's surface and lower atmosphere and reflect much of the energy back toward the surface.

Temperatures are influenced by local topography, elevation, proximity to the ocean, and global and regional atmospheric and oceanic circulations. As previously mentioned, Figure 3 illustrates geographic differences in warming trends (WRCC, 2021). Regional information can be obtained from the California Climate Tracker. Climate patterns can vary widely from year to year and from decade to decade, in accordance with large-scale circulation changes around the Earth. The Pacific Ocean has a major effect on California temperatures all year along the coast, especially summer, and farther inland in winter. In addition to topography, local influences on temperature include changes in land surface and land use. For example, urbanization of rural areas is generally known to have a warming effect, due in large part to the heat-absorbing concrete and asphalt in building materials and roadways. Expansion of irrigation has been shown to have a cooling effect on summertime temperatures (Bonfils and Lobell, 2007).

Statewide seasonal temperature trends are shown in Figure 4. Across the seasons, minimum temperatures are increasing faster than maximum temperatures. Trends for the more recent time period (from 1971 to 2021, solid line in Figure 4) are greater than trends since 1895 (dotted line). The greatest increases in minimum temperatures occurred in the summer and fall over both time periods. For maximum temperatures, the greatest increases over the entire period of record occurred in the fall and winter; since 1971, the greatest increased occurred in the fall and summer.

Figure 4. Seasonal air temperature trends in California



Source: WRCC, 2021

Average minimum temperature (Tmin) and average maximum temperature (Tmax) for each year are presented for each season. The linear trend for the entire period is shown as solid lines, and for 1971-2021 as dashed lines.

Technical considerations

Data characteristics

The Western Regional Climate Center (WRCC)'s California Climate Tracker provides monthly temperature values in California from 1895 to the present using the PRISM Climate Mapping Program from Oregon State University. PRISM is an analytical tool that generates fine scale grid-based estimates of monthly precipitation and temperature. The "About the California Climate Tracker" page provides more information. (WRCC has updated its methodology since the previous report for determining historical temperatures, so values in the current edition of this report slightly differ from the previous edition).

Strengths and limitations of the data

The datasets used are subjected to their own separate quality control procedures, to account for potentially incorrect data reported by the observer, missing data, and to remove inconsistencies such as station relocation or instrument change.

The PRISM dataset offers complete coverage across the state for every month of the record. Limitations include the bias of station data toward populated areas and the limited ability of quality control processes in remote or high terrain areas. The dataset is constantly updated to map climate in the most difficult situations, including high mountains, rain shadows, temperature inversions, coastal regions, and associated complex climate processes.

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References:

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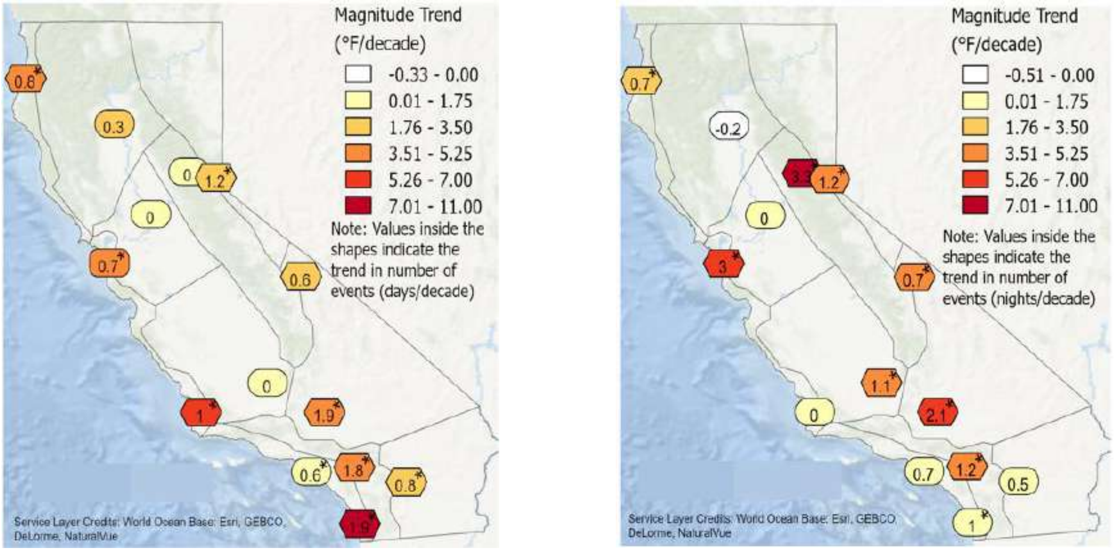
EXTREME HEAT EVENTS

Extreme heat has become more frequent in California since 1950, especially at night. Across most locations studied here, the number and magnitude of extreme heat events have significantly increased. Heat waves – two or more consecutive heat events – vary from year to year, but have become more frequent in the past decade.

Figure 1. Magnitude and frequency of extreme heat events (trend per decade, 1950-2021)



A. Daytime extreme heat events

B. Nighttime extreme heat events

Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

An extreme heat event occurs between April and October when the temperature is at or above a location-specific historical temperature threshold, set at the 95th percentile of daily maximum for daytime extreme events (Figure 1A), or of daily minimum temperatures for nighttime events (Figure 1B), during the 1960-1990 reference period.

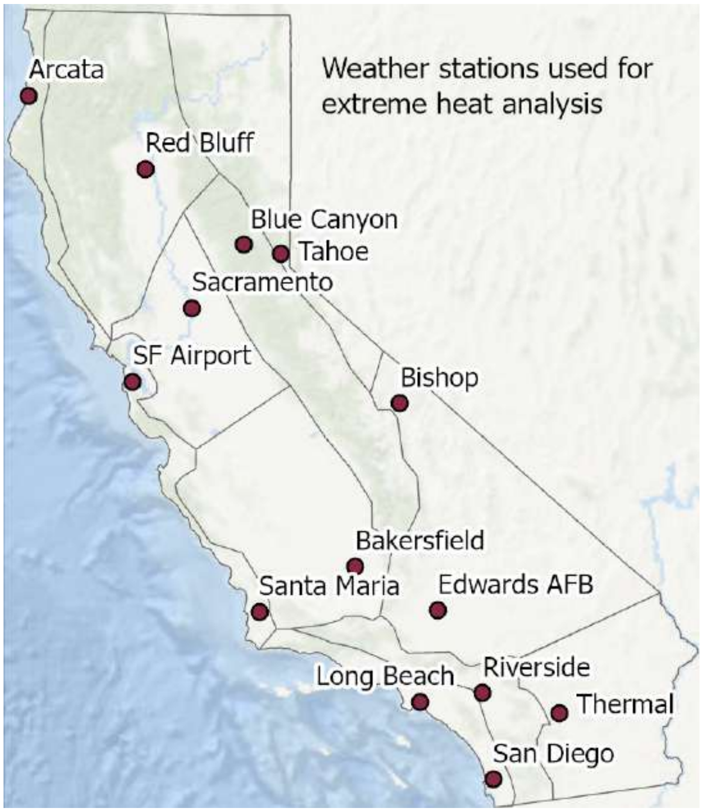
The rate of change (per decade) in ***frequency,*** *the total number of extreme heat events each year, is the value in each shape (hexagon or oval); an asterisk indicates a statistically significant trend ($p \leq 0.05$). The rate of change (per decade) in* ***magnitude****, the annual sum of daily exceedances above the historical temperature threshold, in degrees Fahrenheit (°F), is presented using the fill colors (see legend); a hexagon denotes a trend that is statistically significant ($p \leq 0.05$), while an oval is not significant. The outlines on the map show the boundaries of the eleven climate regions, as defined by the Western Regional Climate Center.*

What does the indicator show?

Since 1950, nighttime extreme heat events have increased in magnitude and frequency more than daytime heat events, as shown in Figure 1. The maps show decadal trends in the magnitude and frequency of daytime and nighttime extreme heat events during the warm months between April and October at selected locations (see Figure 2 map of weather stations).

For a given location, a daytime extreme heat event occurs when the historical threshold for daily maximum temperature is exceeded, and a nighttime extreme heat event, when the historical threshold for daily minimum temperature is exceeded. There is no standard temperature for defining an extreme heat event. Researchers often apply a threshold between the 85th and 98th percentile of historical values. Here, the threshold is set at the location-specific 95th percentile of either the daily maximum temperatures (for daytime events) or the daily minimum temperatures (for nighttime events) from April to October during the 1960-1990 reference period.

Figure 2. Selected weather stations*



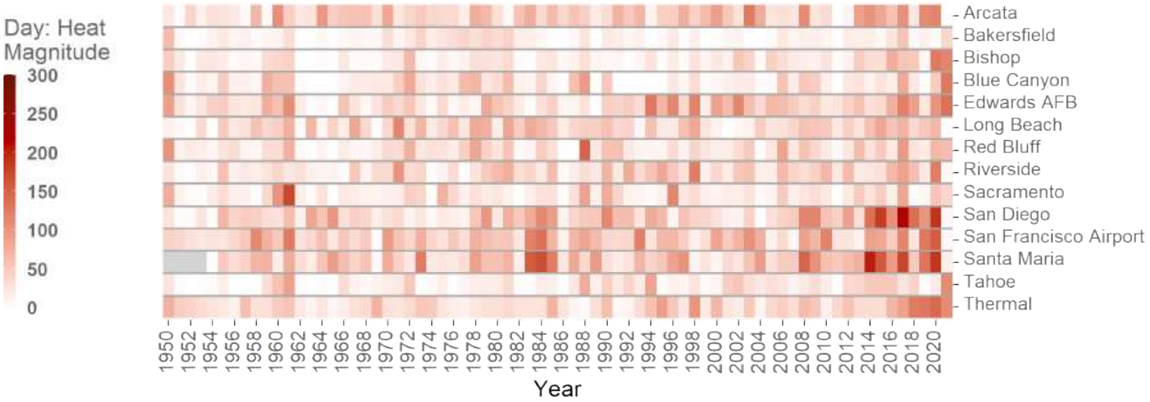
**At least one weather station is from each of California's eleven climate regions (outlined in gray; refer to map, Figure 8). Data sources are discussed in "Technical considerations."*

From 1950 to 2021, the magnitude of extreme heat events increased by at least 1.76 degrees Fahrenheit (°F) per decade during the day at 10 of the 14 stations and at night at 8 stations (stations with orange to dark red fill in Figure 1A and B, respectively). During the same period, the frequency of heat events increased by at least 1 event per decade at 5 stations for daytime events, and at 7 stations for nighttime events (values inside shapes in Figure 1A and 1B, respectively). Out of the stations analyzed, the number of daytime heat events increased the fastest in Edwards AFB and San Diego, with the latter also showing the fastest increase in magnitude (Figure 1A). Blue Canyon experienced the greatest increase in the number of nighttime heat events (with San Francisco Airport a close second) and magnitude (Figure 1B).

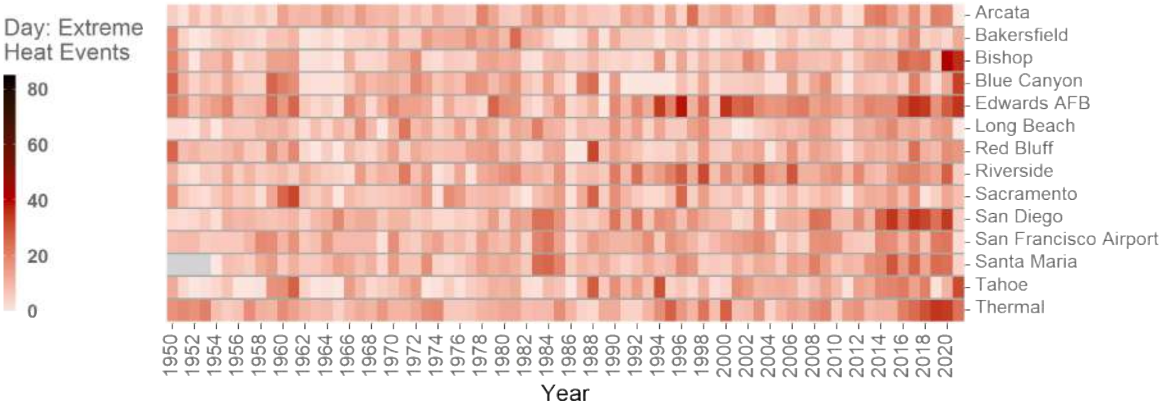
The magnitude and frequency of daytime and nighttime extreme heat events each year at the selection locations are presented in Figures 3 and 4, respectively. The magnitude shown is the sum of daily or nightly exceedances above the historic threshold in a given year at that location.

Figure 3. Annual daytime extreme heat events at the selected locations (1950-2021)

A. Daytime Extreme Heat Events: Magnitude (°F)



B. Daytime Heat Events: Frequency (days)



Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

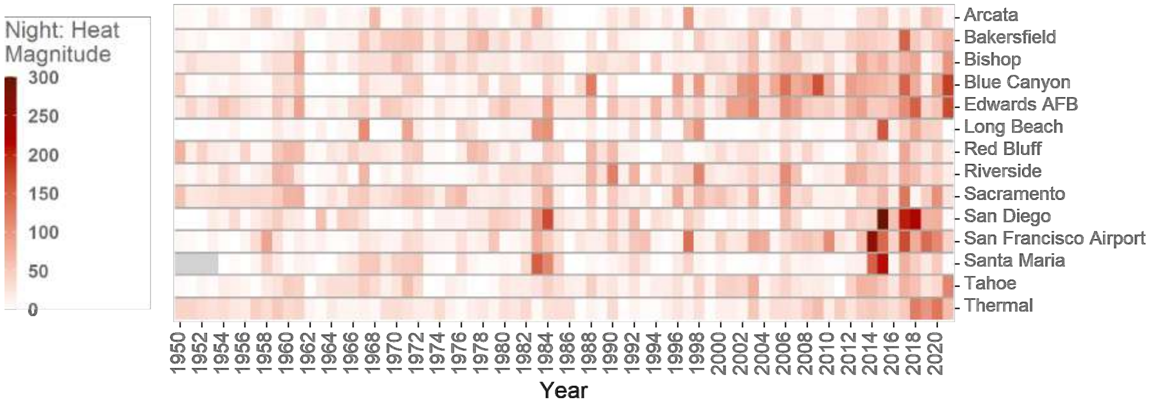
Annual values for magnitude and frequency are presented for each location. Greyed out areas mean no data are available for that timeframe. A location-specific threshold of the 95th percentile was used to determine extreme heat events.

At Edwards AFB, San Diego, San Francisco Airport, and Santa Maria, the magnitude of daytime extreme heat in the last decade is especially notable with at least one year having reached at least 150°F (Figure 3A); note that this is the annual sum of the daily exceedance above the 95th percentile. Similarly, daytime heat events have become more frequent in the last decade, notably at Bishop, Edwards AFB, San Diego, and Thermal, where at least one year having reached 35 or more events (Figure 3B).

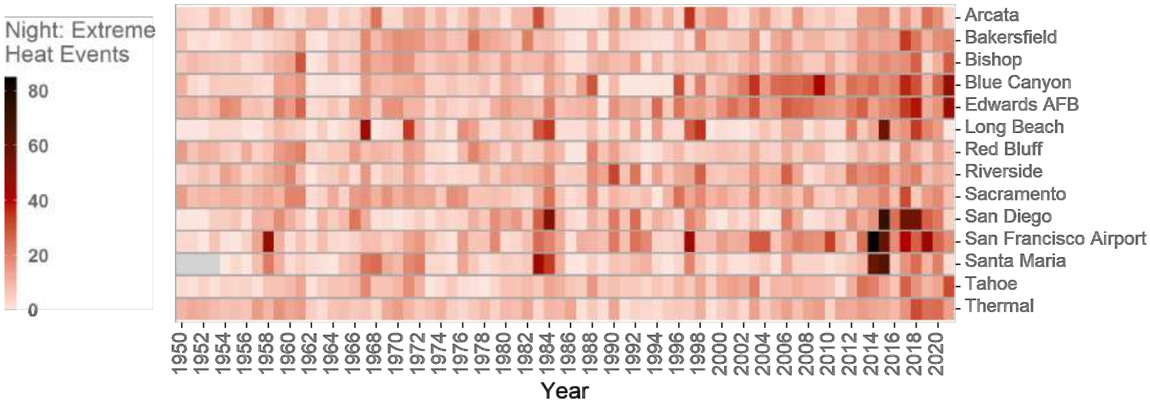
Compared to daytime heat events, nighttime events have seen greater increases in magnitude and frequency (Figure 4). Blue Canyon, Edwards AFB, Long Beach,

Figure 4. Annual nighttime extreme heat events at the selected locations (1950-2021)

A. Nighttime Heat Events: Magnitude (°F)



B. Nighttime Heat Events: Frequency (days)



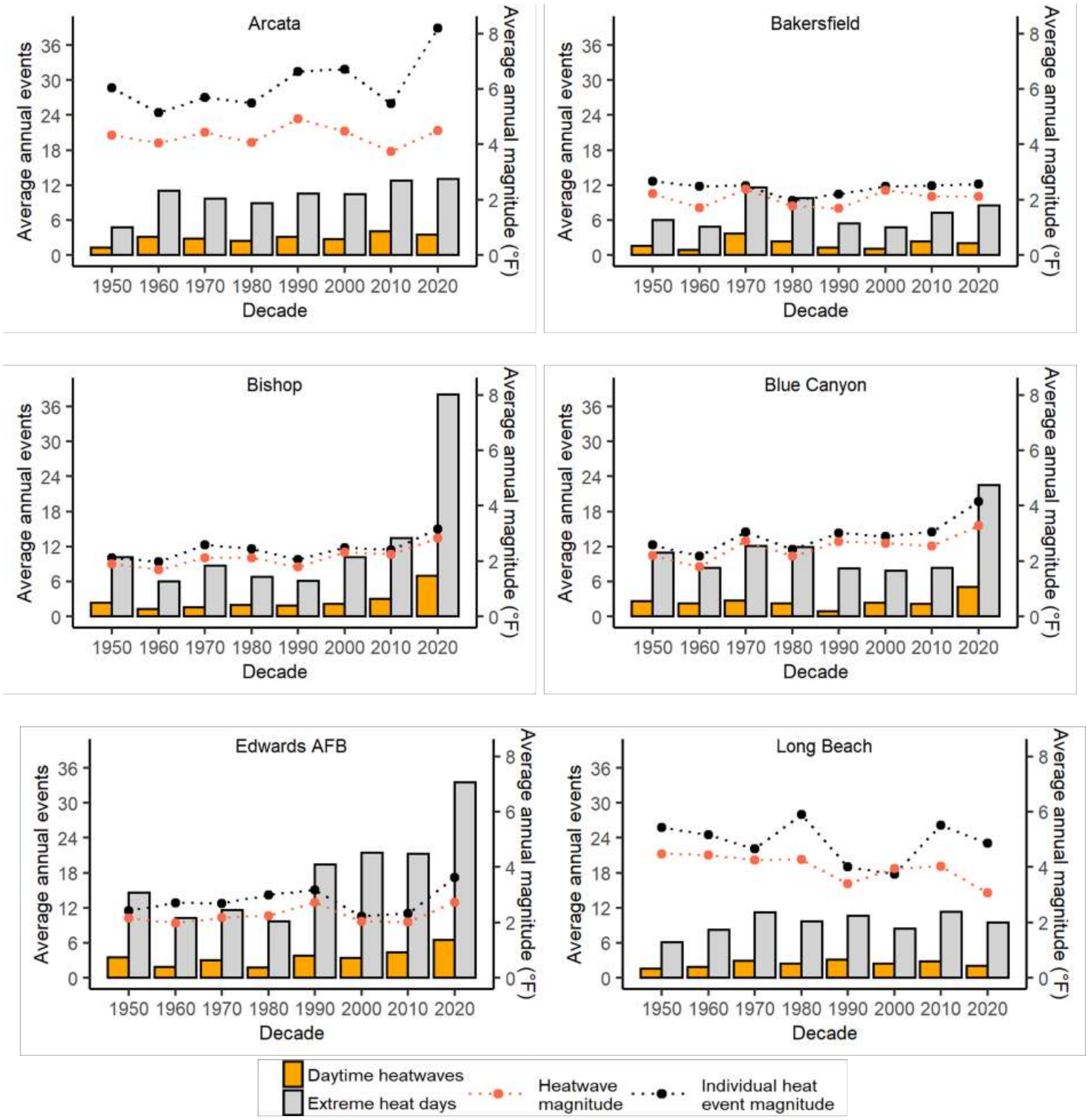
Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

Annual values for magnitude and frequency are presented for each location. Greyed out areas mean no data are available for that timeframe. A location-specific threshold of the 95th percentile was used to determine extreme heat events.

San Diego, San Francisco Airport and Santa Maria had at least one year when the magnitude of nighttime heat events reached at least above150°F; San Diego and San Francisco Airport experienced one and three year(s) above 200°F, respectively, during this period (Figure 4A). The last decade also saw the same locations reaching over 35 nighttime heat events on at least one year, with San Diego, San Francisco Airport and Santa Maria recording over 50 nighttime heat events (Figure 4B).

There is no set definition for how many consecutive events make up a heatwave. For purposes of this indicator, a heat wave consists of two or more consecutive daytime or nighttime heat events. Figures 5 and 6 present location-specific averages by decade for daytime and nighttime heatwaves, respectively; values presented for the last decade ("2020") are for 2020 and 2021 only. For comparison, the frequency and magnitude of extreme heat events are also presented.

Figure 5. Daytime heat wave and extreme heat by decade at the selected locations



The average annual values by decade for the number of daytime heatwaves and extreme heat events (bars) and their magnitude (the sum of daily exceedances above the historical threshold, in degrees Fahrenheit (°F)) (dots and lines) are presented for each station. A daytime heatwave is defined as two or more consecutive extreme heat days at a given location. Note: Values for the "2020 decade" include data from 2020 and 2021.

Figure 5, continued

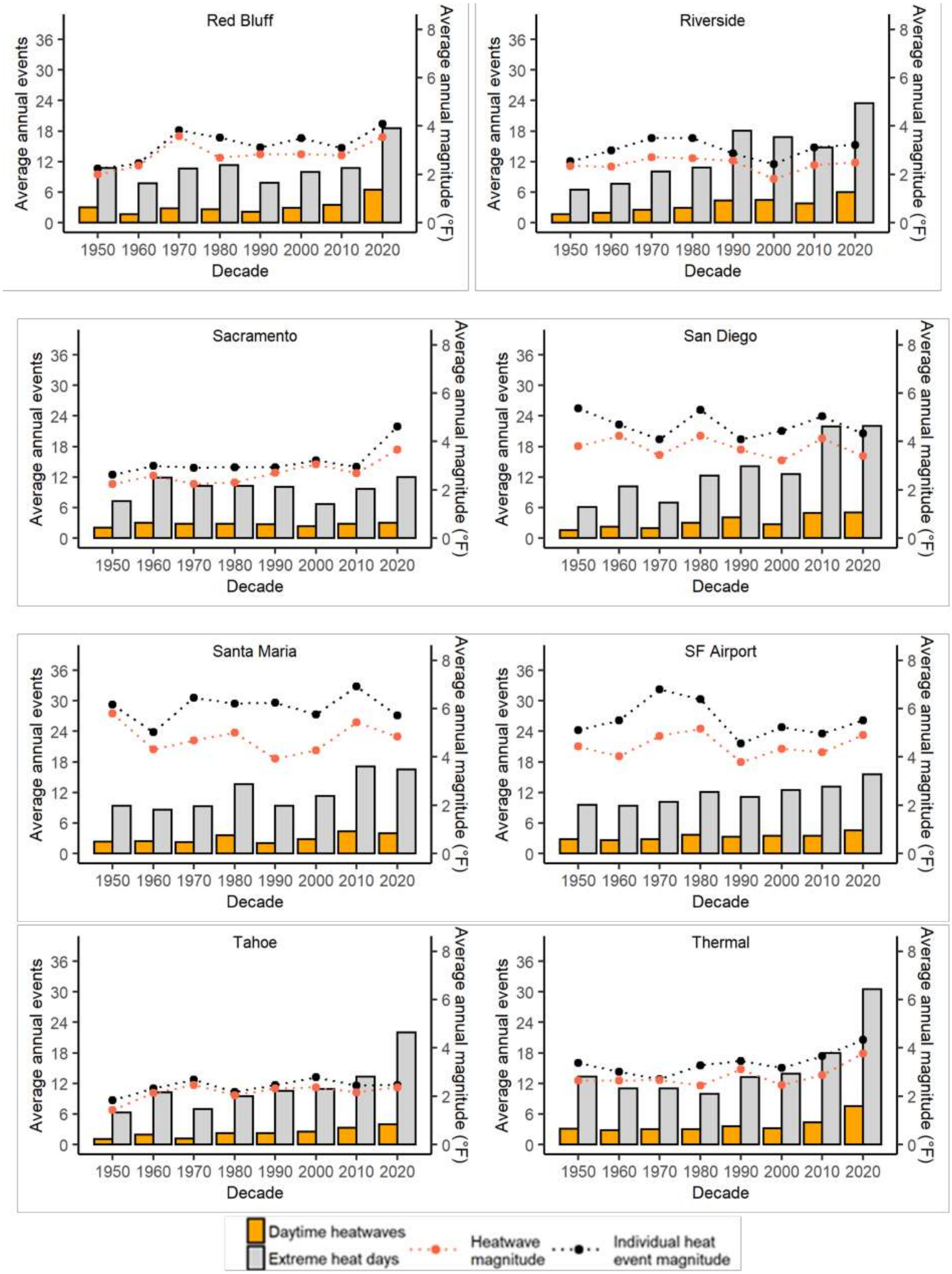
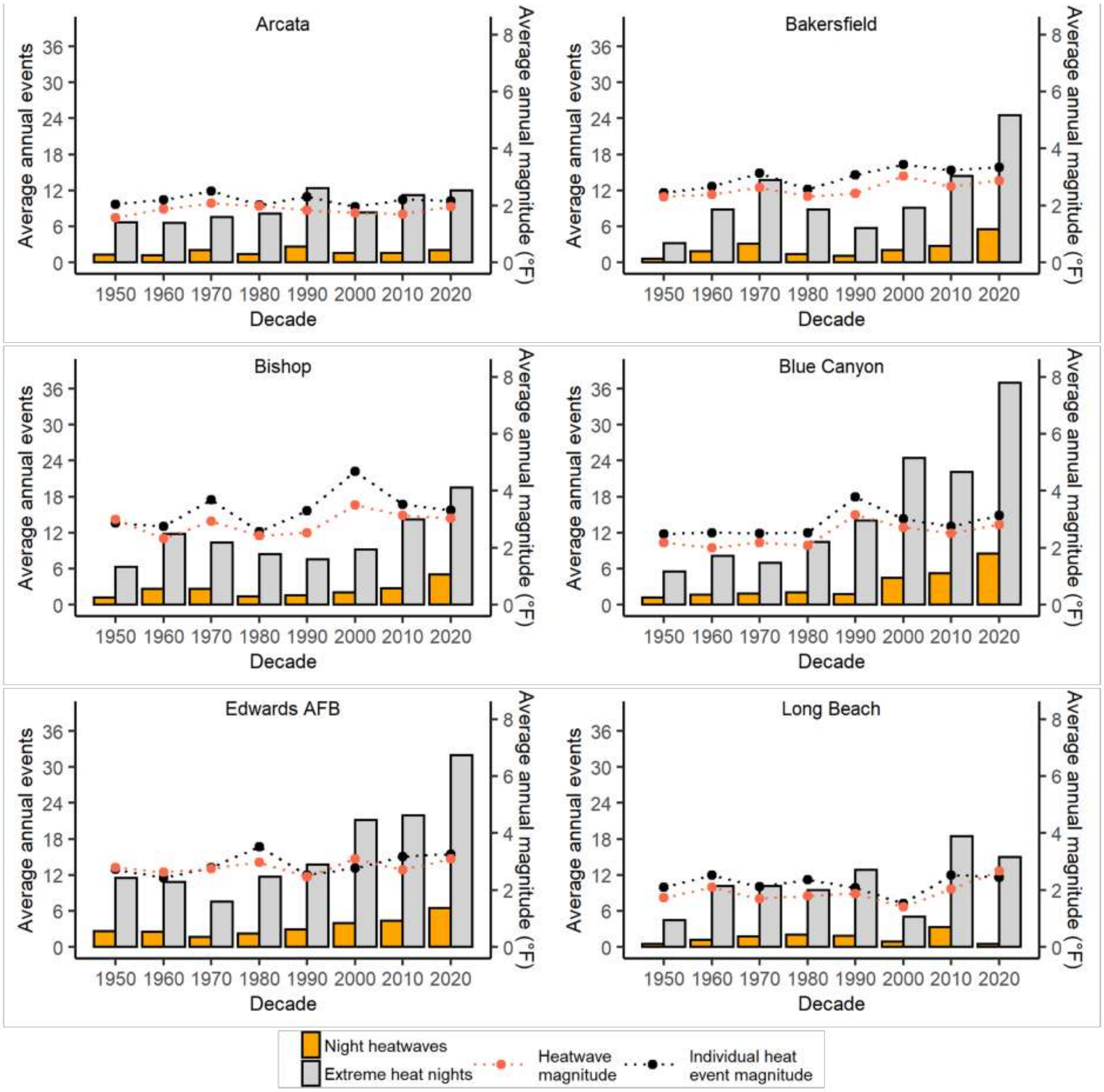
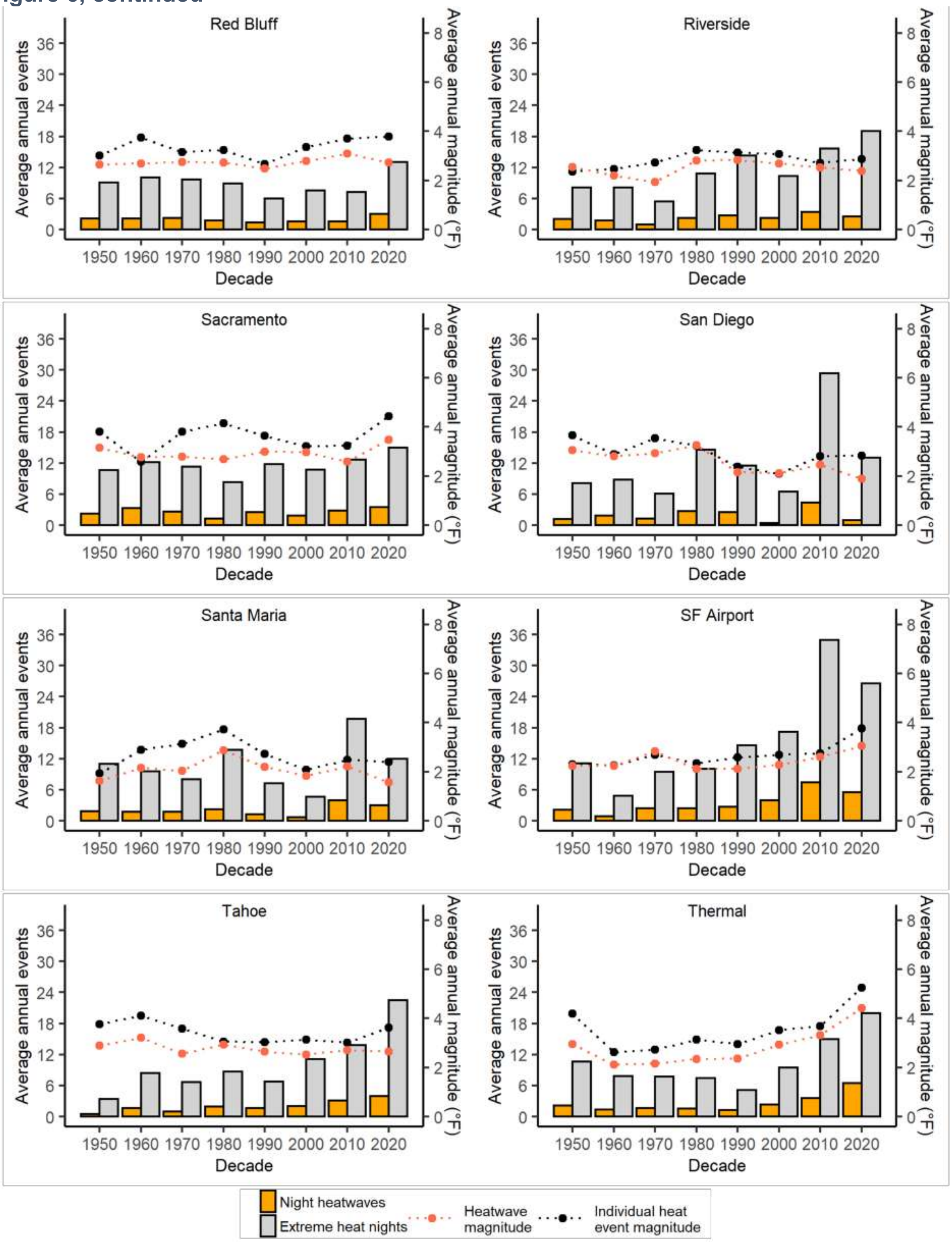


Figure 6. Nighttime extreme heat wave and extreme heat by decade at the selected locations



The average annual values for the number of nighttime heatwaves and extreme heat events (bars) and their magnitude (the sum of nightly exceedances above the historical threshold, in degrees Fahrenheit (°F)) (dots and lines) are presented for each station by decade. A nighttime heatwave is defined as two or more consecutive extreme heat nights at a given location. Note: Values for the "2020 decade" include data from 2020 and 2021.

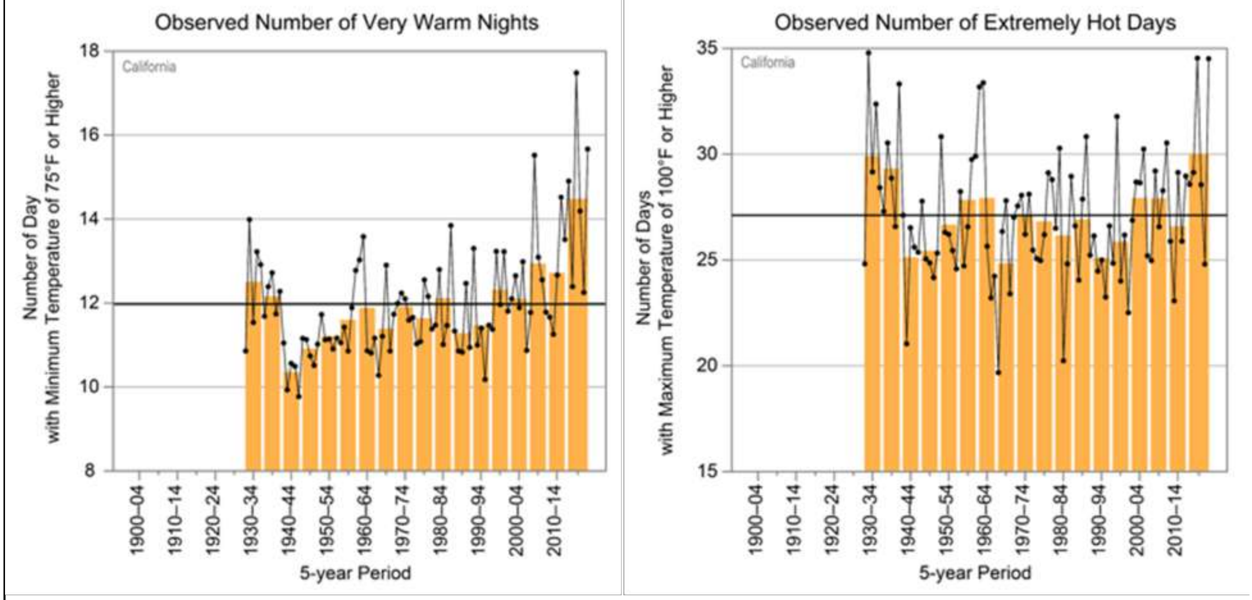
Figure 6, continued



Since 1950, the average number of daytime heatwaves per decade at each station has been relatively constant, ranging between 1 and 3 at most stations, however certain stations have experienced more frequent daytime heatwaves in the 2010s and in 2020/2021: Bishop, Blue Canyon, Edwards AFB, Red Bluff, and Thermal (Figure 5).

The magnitude of daytime heat waves shows no clear trends, although several stations experienced more intense heatwaves in 2020/2021 (Arcata, Bishop, Blue Canyon, Edwards Air Force Base, Red Bluff, Sacramento, San Francisco Airport, and Thermal). Several stations have recorded more frequent nighttime heat waves in the 2010s and in 2020/2021, including Bakersfield, Bishop, Blue Canyon, Edwards AFB, San Francisco Airport, Thermal, and Tahoe (Figure 6). Nighttime heatwave and extreme heat event magnitude are variable but appear to be increasing at San Francisco Airport and Thermal. In general, the magnitude of heat events and heatwaves are higher during the day than at night, but there are more nighttime extreme heat events and heat waves. For most of the stations, the magnitude and frequency of extreme heat events and of heatwaves are higher in the second half of the time series for both nighttime and daytime events.

Figure 7. Statewide number of extremely hot days and very warm nights



Source: Figures 2a and 3 from Frankson et al., 2022

Left: Observed annual number of extremely hot days (maximum temperature of 100°F or higher) 1930 to 2020. Right: Observed annual number of very warm nights (minimum temperature of 75°F or higher). Dots show annual values. Bars show averages over 5-year periods (last bar is a 6-year average). The horizontal black lines show the long-term (entire period) averages: 27 days and 12 nights, respectively.

Statewide, the number of extremely hot days (Figure 7, right) – defined as days on which the maximum temperature was at or above 100°F – has been variable since

1930, both in terms of annual and five-year averages; the greatest number of hot days were observed during the 2015-2020 period, followed by 1930-1934. A more pronounced increase is evident in the number of very warm nights (Figure 7, left), when minimum temperatures were at or above 75°F. As with extremely hot days, the 2015-2020 period had the greatest number of very warm nights; numbers have exceeded the long-term average on all five-year periods since 1995-1999. Figure 7 is based on statewide analyses conducted by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (Frankson et al., 2022).

Why is this indicator important?

Periods of extremely high temperatures have significant public health, ecological and economic impacts. Heat causes the most weather-related deaths in the United States (NOAA, 2021). Heat waves accompanied by high humidity are especially dangerous to human health. Humidity prevents surfaces from cooling down at night, leading to higher nighttime temperatures (Gershunov et al., 2009). People, animals (including household pets) and plants adapted to California's traditionally dry daytime heat and nighttime cooling are unable to recover from extreme heat, especially when humidity is high at night. Heat can accelerate the formation of ground-level ozone, and trap ozone, particulate matter and other harmful air pollutants (Peel et al., 2013). Temperature specifically is frequently the leading metrological driver to ozone formation (Nolte et al., 2018). Air pollution may also work in synergy with extremely high temperatures to increase adverse cardiovascular, respiratory and other health effects (Anenberg et al., 2020; see *Heat related mortality and morbidity* indicator).

Although warmer temperatures are likely to impact a range of individuals and populations, certain subgroups are at greatest risk of health impacts from extreme heat due to intrinsic factors (such as age and health status), greater likelihood of exposures, or less capacity for adaptive measures (such as access to air conditioning). These include the elderly, children, those with lower socioeconomic status, those who are socially, linguistically, or geographically isolated, or those who work in agriculture, construction, landscaping or other outdoor occupations (see *Heat related mortality and morbidity* and *Occupational heat-related illness* indicators).

Extreme heat impacts infrastructure and economies (LCI, 2021). Urban infrastructure is especially threatened by cascading effects of extreme heat stress on interdependent water, power, and transportation systems. High heat can deteriorate pavement, buckle railway tracks, and restrict aircraft operations. During hot weather, increased use of air conditioning and refrigeration increases electricity usage, thus straining the electrical grid (see *Cooling and heating degree days* indicator). Further, the increase in electricity generation to meet the demand for air conditioning during extreme heat events leads to increased emissions of nitrogen oxides (NO_x) (Abel et al., 2017; Peel et al., 2013). NO_x has been associated with decreased lung function, lung inflammation, asthma symptoms, and decreased immune response. It is also a precursor for ozone formation.

Water resources are strained during heat events due to increased domestic, industrial and agricultural demand. Extreme heat conditions can also influence tourism, such as in California's Coachella Valley, where it is projected that hotter temperatures will deter visitors and pose a major financial impact to the local economy (Yanez et al., 2020).

Agricultural systems across California and globally are experiencing the impacts of heat stress and decreased water supplies (Parker et al., 2020). Extreme heat exposure stresses plants and stunts development of agricultural crops, resulting in reduced quality and lower yields. Scientists fear that current heat adaptation practices such as enhanced irrigation and crop breeding may not be sustainable under future climate conditions. Heat stress also affects livestock by reducing weight gain or milk and egg production; in extreme cases, heat stress can lead to animal mortality (Walsh et al., 2020).

Climate scientists report that the Western United States has experienced a larger frequency of simultaneously occurring dry and hot years in recent decades (see *Drought* indicator). Multiple extreme events can amplify ecological and societal damages, as shown by the exceptionally dangerous wildfire seasons in recent years. For example, the Thomas fire in December 2017 and the Woolsey fire in November 2018, which caused tremendous devastation in four southern California counties, were both preceded by record-breaking heatwaves and extraordinarily dry autumn conditions (Hulley et al., 2020). A warming climate promotes concurrence of weather extremes, a higher risk of environmental disasters and greater reliance on emergency management and relief resources.

Heat events are projected to become more intense, more frequent, and longer lasting (IPCC, 2021). Taking action to mitigate and adapt to the impacts of extreme heat in California is critical, particularly given the largely preventable adverse effects on public health (LCI, 2021). Recognizing the need for a comprehensive, statewide approach to extreme heat, California is developing a strategic framework of state actions to adapt and build resilience to extreme heat (CNRA, 2021).

What factors influence the indicator?

The increased frequency and intensity of temperature extremes since pre-Industrial times is attributable to human-induced greenhouse gas emissions (IPCC, 2021). Some recent hot extreme events would have been extremely unlikely without human influence on the climate system. Regional patterns are influenced by feedback processes involving land-atmosphere interactions (for example, between soil moisture and evapotranspiration), local land use and land cover changes, aerosol concentrations, and El Niño-Southern Oscillation events and other large-scale modes of climate variability.

Air temperature varies according to the time of day, the season of the year, and geographic location. Urbanization can amplify the effects of global warming in cities, especially at night (the urban heat island effect). However, rural locations see comparable increases in extreme heat days and nights and all regions of California are affected by regional climate change (see *Annual Air Temperature* indicator). The asymmetric increase in nighttime California heat wave activity and extreme heat nights compared to daytime heat extremes is consistent with impacts expected under global climate change.

As air temperatures rise due to anthropogenic emissions of other greenhouse gases, the water vapor content of the atmosphere increases. Water vapor absorbs outgoing longwave terrestrial radiation and re-radiates energy back to the surface, thus impeding radiative cooling. Therefore, there is less nighttime respite from heat when specific humidity is high. Moreover, humid heat waves tend to last longer due to the stronger coupling of maximum and minimum temperatures during humid heat waves (Gershunov et al., 2009).

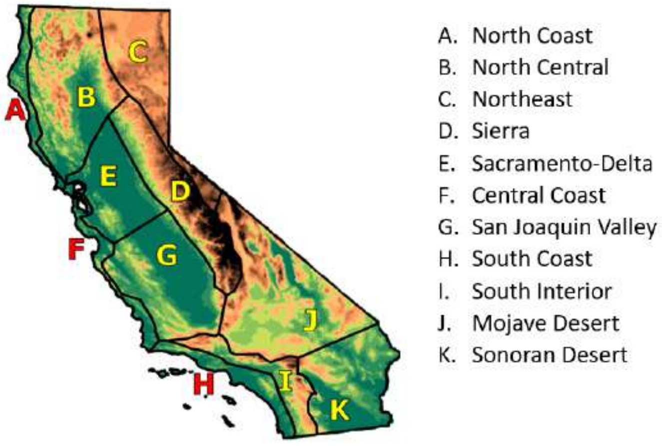
Technical considerations

Data characteristics

This indicator uses station data from Hadley Integrated Surface Dataset (HadISD) global record, hosted by CalAdapt, and station data from the National Oceanic and Atmospheric Administration's (NOAA) Regional Climate Centers (RCCs) cooperative observation network acquired from the Applied Climate Information System (ACIS). The stations using the RCC-ACIS data include: Blue Canyon, Bishop, Tahoe, and Thermal, all the other data used here are from the CalAdapt dataset. Both the RCC-ACIS and HadISD datasets have gone through quality control checks.

At least one station from each of California's climate regions, preferably those located in large urban centers, was selected for the analysis. The climate regions are shown in Figure 8. Only stations with NOAA complete records were used in the analysis. All stations have data starting from at least 1950, except for Santa Maria where data are available starting in 1954. Trends were calculated using the Mann-Kendall analysis.

Figure 8. California's Climate Regions



Source: WRCC, 2017

Strengths and limitations of the data

The datasets hosted on CalAdapt consist of hourly observed historical station datasets with at least 30 years of observations from the HadISD global record. The HadISD dataset is compiled from NOAA's Integrated Surface Database, which is a collection of highly quality-controlled weather data from various data sources. The RCC-ACIS (or SCENIC) dataset is comprised of station data containing minimum and maximum daily temperature. RCC-ACIS station data pulls weather information from various networks such as the Cooperative Observer Program (COOP) and the Weather-Bureau-Army-Navy (WBAN). The vast majority of the COOP observers are trained volunteers, and the network also includes the National Weather Service (NWS) principal climatological stations. The observing equipment used at all the stations, whether at volunteer sites or federal installations, are calibrated and maintained by NWS field representatives, Cooperative Program Managers, and Hydro-Meteorological Technicians.

The station data have received a high measure of quality control through computer and manual edits, and are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations. Station coverage is not uniformly distributed geographically, and a limited number of stations were analyzed. Recorded temperatures in urban areas can also be affected by the urban heat island effect due to land surface modification and other human activities. Since most of California's population resides in urban areas, heat impacts from urban-induced warming on health are significant. Quantification of the specific magnitudes of station-based urban heat contributions are beyond the scope of the present study but are the subject of ongoing research.

OEHHA acknowledges the expert contribution of the following to this report:

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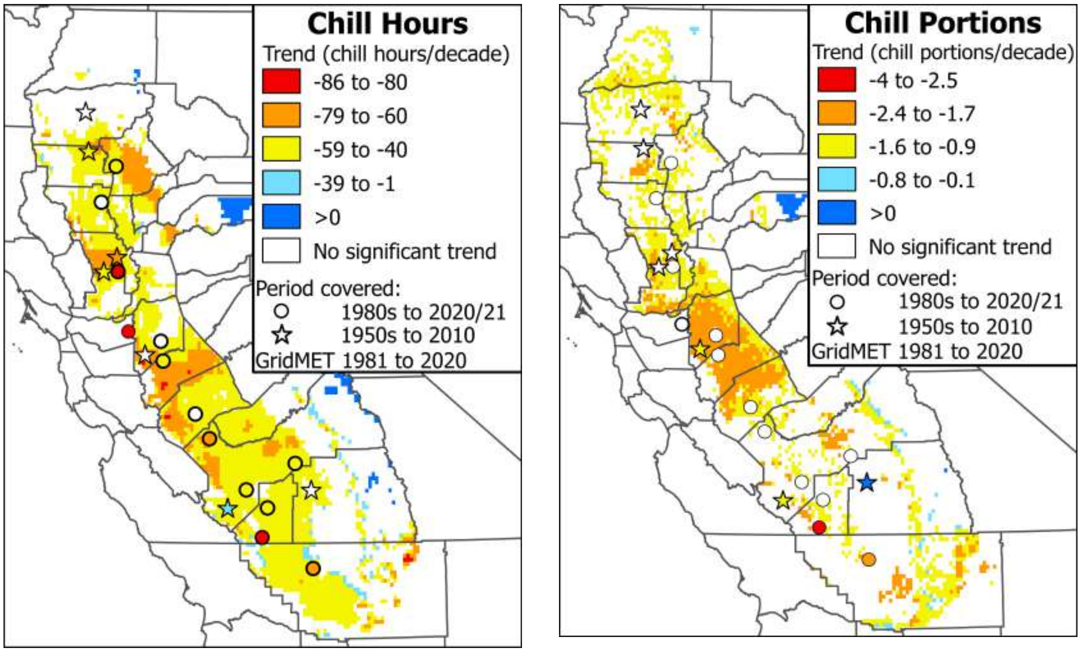
WINTER CHILL

Warming winter temperatures are reflected in declining trends in "winter chill," a measure of cold temperatures required for fruit and nut trees to produce flowers and fruits. Winter chill is tracked in two ways: "chill hours," a very sensitive and rudimentary metric used since the 1940s; and "chill portions," a biologically based metric that more closely approximates how California's agricultural trees experience winter chill. Both metrics show decreasing trends across the Central Valley over the past several decades.

Figure 1. Long-term trends in winter chill in California's Central Valley



A. Chill hours **B. Chill portions**

Source: GridMET analysis based on Zhang et al., 2021;
weather station analysis based on UC Davis, 2021

***A. Chill hours** represent the number of accumulated hours equal to or less than 45°F and above 32°F over the winter season. **B. Chill portions** accumulate most between 43° and 47°F, and progressively less at either side of this range, dropping to zero at 32°F and 54°F; periods of warm temperature can cancel this accumulation.*

Stars and circles represent trends at weather stations; coloring throughout the map represents trends derived from gridMET, a spatial data set, where white areas indicate non-significant trends ($p<0.05$). Trends for weather station sites use winter dates from November 1st to February 28th; gridMET-based trends use winter dates from November 1st to January 31st. (See Figure A-1 in the appendix for a map of weather station locations).

Figure 2. Location of weather stations analyzed for winter chill

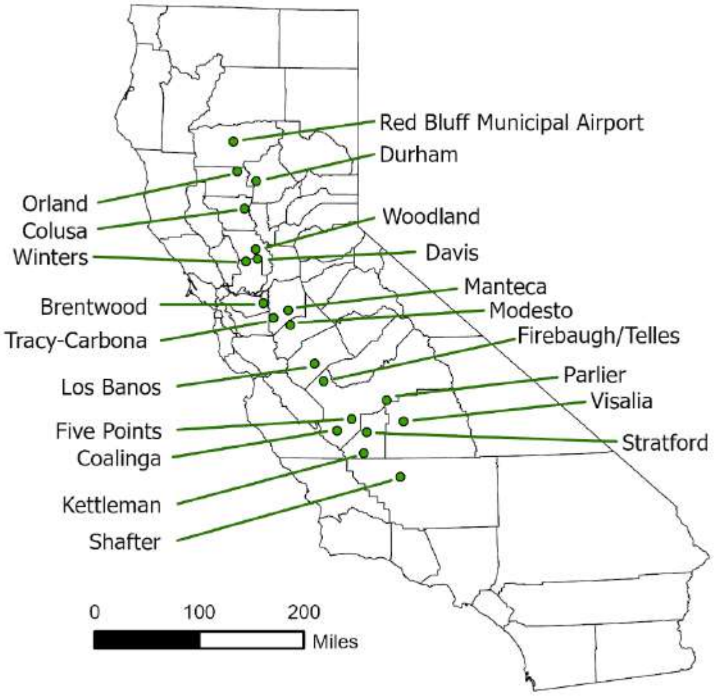


Table 1. Long-term decadal trends in winter chill at selected weather stations

Station	Years included	Chill hours trend (p-value)*	Chill portions trend (p-value)
Brentwood	1985-2019	-81.2 (0.01)*	-2.4 (0.17)
Coalinga	1952-2010	-33.9 (<0.01)*	-1.6 (<0.01)*
Colusa	1983-2016	-70.7 (0.06)	0 (0.99)
Davis	1983-2021	-85.9 (<0.01)*	-1.5 (0.14)
Durham	1983-2021	-46.8 (0.03)*	-0.9 (0.38)
Firebaugh/Telles	1983-2020	-76.0 (<0.01)*	-0.9 (0.29)
Five Points/WSFS USDA	1983-2020	-45.9 (0.03)*	-0.8 (0.38)
Kettleman	1982-2016	-106.6 (<0.01)*	-3.3 (0.02)*
Los Banos	1989-2020	-38.4 (0.21)	-1.5 (0.23)
Manteca	1988-2021	-30.1 (0.29)	-2.1 (0.07)
Modesto	1988-2021	-50.1 (0.05)	-2.0 (0.05)
Orland	1952-2010	-45.8 (<0.01)*	-0.8 (0.14)
Parlier	1984-2021	-51.0 (0.01)*	-1.1 (0.32)
Red Bluff Municipal Airport	1952-2010	-7.9 (0.60)	-0.1 (0.84)
Shafter/USDA	1983-2020	-69.6 (<0.01)*	-1.9 (0.03)*
Stratford	1983-2020	-43.6 (0.04)*	-1.3 (0.19)
Tracy-Carbona	1952-2007	-19.7 (0.23)	-1.2 (0.03)*
Visalia	1952-2010	-27.3 (0.05)	+1.2 (0.02)*
Winters	1951-2010	-43.0 (<0.01)*	-1.0 (0.07)
Woodland	1952-2010	-60.4 (<0.01)*	-0.5 (0.38)

* Statistically significant trends (where p<0.05) are indicated with an asterisk.

What does the indicator show?

Winter chill is a period of cold temperatures above freezing required for deciduous fruit and nut trees to produce flowers and fruits. Two commonly used winter chill metrics are presented in Figure 1. The first metric, chill hours (Figure 1A), represents the number of accumulated hours equal to or less than 45 degrees Fahrenheit (°F) and above 32°F over the winter season. Chill hours have been used since the 1940s. However, recent research favors the use of a more biologically based metric, chill portions (Figure 1B). Chill portions accumulate in a two-step process: (1) exposure to cold temperatures accumulate as a "chill intermediate"; this accumulation is negated by exposure to temperatures above 54°F; (2) a certain quantity of these intermediates make up a "chill portion," which cannot be reversed by high temperatures (Luedeling et al., 2009).

Figure 1 presents trends for chill hours and chill portions based on two sources: temperature observations from weather stations (stars and circles, refer to Figure 2 for locations), and modeled high-spatial resolution surface temperatures (gridMET) (colored or white areas on the map). Weather station data show that chill hours have declined at more than half of the weather stations studied (12 out of 20, $p<0.05$; at two other stations, $p=0.05$) (Figure 1A, Table 1). Chill portions show statistically significant declining trends at just four weather stations – Kettleman, Coalinga, Shafter, and Tracy-Carbona (at one other station, $p=0.05$) – and an increasing trend (also significant) at one station (Visalia; Figure 1B, Table 1). Graphs for each weather station presenting data for chill hours and chill portions are in Figure A-1.

Winter chill trends were calculated using gridMET for 19 counties within the Central Valley: Butte, Colusa, Glenn, Fresno, Kern, Kings, Madera, Merced, Placer, San Joaquin, Sacramento, Shasta, Solano, Stanislaus, Sutter, Tehama, Tulare, Yolo, and Yuba. These estimates show declining chill hours in much of the Central Valley (Figure 1A); chill portions are also declining, although at a smaller spatial extent (Figure 1B). The latter suggests that although temperatures have warmed in certain areas, they may not have warmed enough across the region to affect the accumulation of biologically based chill portions, which account for hours at a higher temperature threshold (54°F) than chill hours (32°F - 45°F).

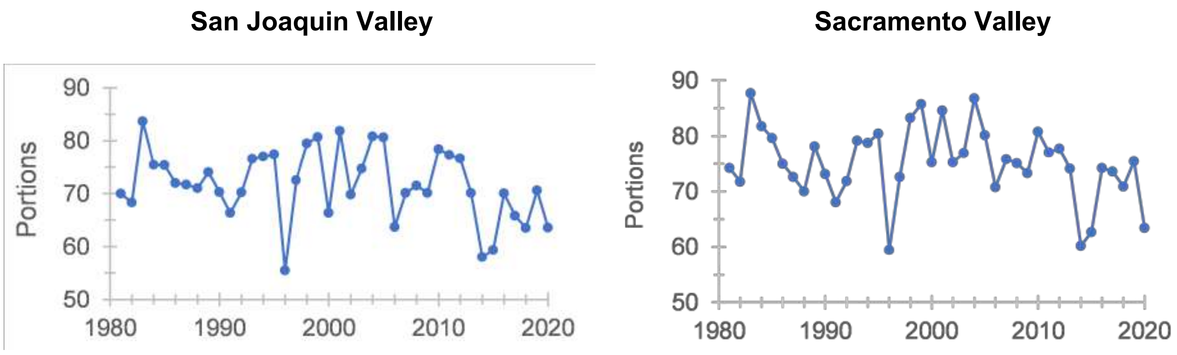
The influence of temperature on the biological processes underlying the breaking of dormancy — and the processes themselves — are poorly understood. It is known, however, that not all "chill" is effective. The chill portion metric considers this by incorporating a more biologically based theoretical framework: temperatures above 54°F —common during the winter months in California — cancel the effect of previous chill accumulation (Luedeling et al., 2009). Chill hours, which count the number of winter hours when temperatures are between the freezing point and 45°F, do not account for this canceling effect. For California's Mediterranean climate and mild winters in California's fruit and nut-growing regions, chill portions are better suited for tracking winter chill than chill hours. (See *Technical considerations* for how these metrics are calculated.) The amount of chill that is required is dependent on the type of tree; for example, almonds require 250 to 350 chill hours or 22 to 32 chill portions; apples, 1200 to 1500 chill hours or 50 chill portions; and Bing cherries, 1000 to 1300 chill hours or 65 chill portions (Erez, 2020 and Ryugo, 1988).

Why is this indicator important?

An extended period of cold temperatures above freezing and below a threshold temperature is required for fruit and nut trees to become and remain dormant and then bear fruit. As noted above, this chill requirement can vary widely from one fruit or nut to another and even across varieties of the same fruit or nut. Fruit and nut trees need 200 to 1,500 hours of temperature between 32°F and 45°F during the winter (Baldocchi and Wong, 2006), or between 13 and 75 chill portions to produce flowers and fruits (Pope et al., 2014).

The warm winter of 1998 and 2013-2014 demonstrated the importance of winter chill (Figure 3). Above-normal temperatures in January and February of 1998 meant many fruit and nut trees did not receive sufficient chilling time necessary for dormancy; revenues from almonds and cherries dropped by about 40 and 50 percent, respectively, compared to the two prior years (USDA, 2022). During 2013-2014, the Central Valley's average chill portions dropped by 25 percent. As a result, orchards for many crops showed delayed and extended bloom, poor pollinizer overlap (when the pollen-producing flowers and the fruit-producing flowers do not open simultaneously), and weak leaf-out (when fewer leaves emerge). The low chill was likely responsible for much of the unusual tree behavior and low yields. Delayed bloom can extend later into spring, when conditions may be too warm for successful pollination. Extended bloom can result in changes in fruit or nut maturation timing, which could mean a more prolonged, costly harvest and an increased risk of pests eating crops (Pope, 2014).

Figure 3. Chill portions from 1981-2020



Source: Parker et al., 2022

Annual chill portions within two regions of the Central Valley (San Joaquin Valley and Sacramento Valley)

Prolonged periods of fog during the winter in the California Central Valley provide favorable conditions to meet dormancy requirements. In an analysis of weather data and satellite imagery for the Central Valley during the years 1981-2014, scientists found the number of winter fog events decreased by 46 percent, on average, with much year-to-year variability (Baldocchi and Waller, 2014). If prolonged periods of winter fog disappear in the future, the sun hitting buds in the Central Valley will increase the internal temperature in the buds, thus reducing the number of hours below the critical temperature. Agronomists are finding methods to adapt to this, such as by applying kaolin clay to reflect sunlight or calcium carbonate to modify incoming light (Beede, 2016).

Future trend projections show that continued warming will reduce the accumulated winter chill in the Central Valley (Luedeling et al., 2009). By the middle to the end of the 21st century, projections suggest that climatic conditions will no longer support current varieties of some of the main tree crops currently grown in California. Chill hours are projected to show greater declines than chill portions, and current varieties of major tree crops may tolerate a 20 percent decline in the winter chill. This decline would jeopardize the region’s ability to sustain its production of high-value nuts and fruits like almonds, cherries, and apricots, resulting in serious economic, dietary, and social consequences. The tree crop industry will likely need to develop agricultural adaptation measures (e.g., using chill-compensating products or growing low-chill varieties) to cope with these projected changes.

What factors influence this indicator?

The indicator is derived from temperature data. As such, it is influenced by the same factors that influence air temperature; the increase in winter temperatures in the Central Valley (see *Air temperature* indicator) is reflected in the decrease in chill hours at most of the weather stations and throughout the region. In addition to regional influences such as topography and proximity to the ocean, local factors such as degree of urbanization and land use can affect temperature. Furthermore, “microclimates” exist within the same orchard, so temperature differences could occur at smaller spatial scales.

As discussed above, the choice of metric makes a difference in quantifying the magnitude of winter chill accumulation. The difference presented here between chill hours and chill portions is consistent with research that has modeled the potential impact of continued climate change. For example, one study using weather data and several greenhouse gas emissions scenarios throughout California’s Central Valley projected chill portions to decrease by 14 to 21 percent and chill hours to decrease by 29 to 39 percent between 1950 and 2050 (Luedeling et al., 2009). Projected impacts appear far more dramatic when seen through the lens of chill hours, although the chill hours model appears to be more sensitive to changes in temperature than the trees themselves.

While both metrics quantify chill accumulation, factors such as proximity of the weather station or, as noted above, the presence of microclimates introduce uncertainties in whether the temperature measurements used in deriving them are representative of what trees are experiencing.

Technical considerations

Data characteristics

The indicator presents two metrics for winter chill: chill hours and the more mathematically complex chill portions. The primary differences in the calculations for these two metrics are:

- Chill hours equally count any hour when temperatures are between 32°F and 45°F. Chill portions accumulate when temperatures are between 32°F and 54°F, with the most accumulation occurring between 43°F and 47°F.
- Chill hours only count up to 45°F. Chill portions count up to 54°F, which better approximates effective chilling for trees grown in fairly mild climates.
- Chill hours are a sum of hours between the temperatures described above, without accounting for warm hours. Chill portions accumulate in a two-step process first reaching a “chill intermediate” that can be negated by exposure to high temperatures (above 54°F); a certain quantity of chill intermediates make up a “chill portion,” which cannot be reversed by high temperatures (Leudeling et al., 2009).

Weather station-based chill hours and chill portions were calculated using “chillR," a statistical model for phenology analysis (Leudeling, 2017). The model is an extension to a commonly used statistics software, R. Weather station data for Central Valley locations listed in Baldocchi and Wong (2008) were retrieved through the chillR downloading interface. Stations for which data were not retrievable from the University of California Statewide Integrated Pest Management Program (UCIPM) archive were omitted from the analysis.

The UCIPM archive includes data from the California Irrigation Management Information System (CIMIS) and the National Weather Service Cooperative Network (NWS COOP). Hourly temperature records, which are needed to calculate chill accumulation, are available from CIMIS. However, these stations only have data back to 1982. NWS COOP has records that date back decades earlier (the earliest records used in this indicator start in 1951), but only for daily maximum and minimum temperature; hourly temperatures were estimated using an algorithm based on diurnal temperature trends and reported maximum and minimum temperature (Leudeling, 2017).

To estimate chill hours and chill portions using gridMET, daily temperature time series were downscaled to hourly and fed into chillR (Zhang et al., 2021). GridMET trends were calculated for the 19 counties within the Central Valley: Butte, Colusa, Glenn, Fresno, Kern, Kings, Madera, Merced, Placer, San Joaquin, Sacramento, Shasta, Solano, Stanislaus, Sutter, Tehama, Tulare, Yolo and Yuba.

Strengths and limitations of the data

Summary statistics that are commonly used to track temperature (such as average, minimum and maximum) generally do not provide the resolution necessary to examine climate trends relevant to agriculture. Deriving chill accumulation from temperature data for the winter months yields a more meaningful measure for tracking a change in climate that would be more predictive of fruit production. Winter chill accumulation provides an indication of whether specific fruit and nut trees are experiencing sufficient periods of dormancy.

The hourly data from CIMIS provide direct inputs into the calculation of winter chill degree hours, unlike daily minimum and maximum temperature data from NWS, which require the use of an algorithm. CIMIS weather stations are designed to monitor agricultural climate conditions. Thus, they are almost exclusively in agricultural areas, with the monitoring equipment located in a well-irrigated pasture. NWS COOP weather stations are designed with a broader use in mind. As such, they are generally located in developed, paved areas – in towns and cities, or at airports. As a result, temperatures at the NWS COOP stations in the winter are likely higher than they would be in an open field a few miles away. While this means that the chill accumulation at each NWS COOP weather station may not be precisely representative of what an orchard in that area would experience, any trends of increased or decreased chill accumulation of years and decades would likely be similar.

Historical temperature records are rarely complete. Many different approaches are used to fill in gaps in temperature records to analyze long-term trends. In this report, hourly or daily station temperatures were interpolated following Luedeling (2017). If more than 50 percent of the winter record required interpolation, that winter was not included in the analysis.

GridMET provides a daily temperature product at a 4-km spatial resolution within the USA from 1979 to the present. This allows for analyses across the entire landscape, unlike weather station data which only shows weather at one location. Since gridMET is modeled product, it may not be as accurate as station-based data. However, like weather station data, the direction of the gridMET trends is accurate.

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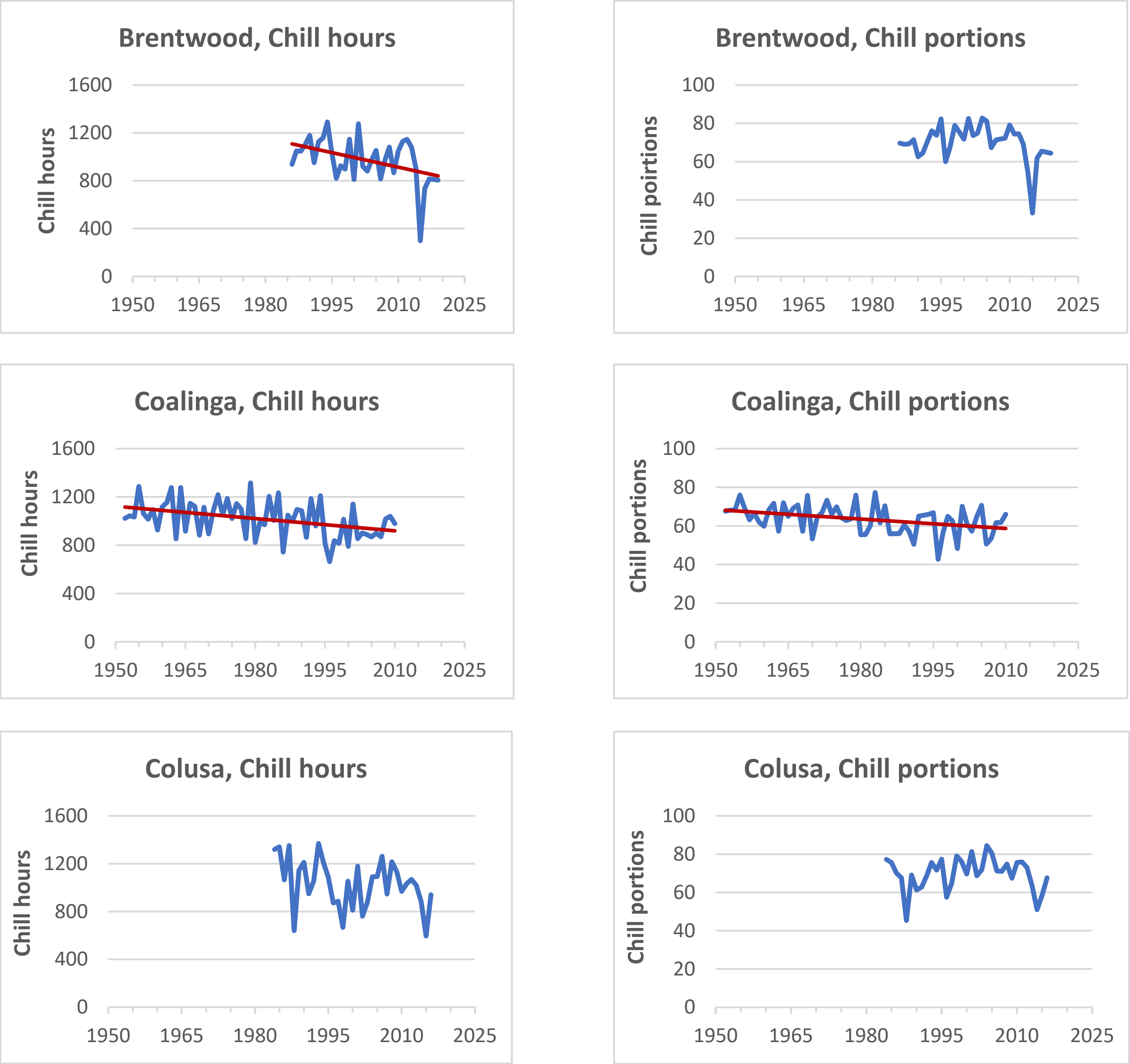
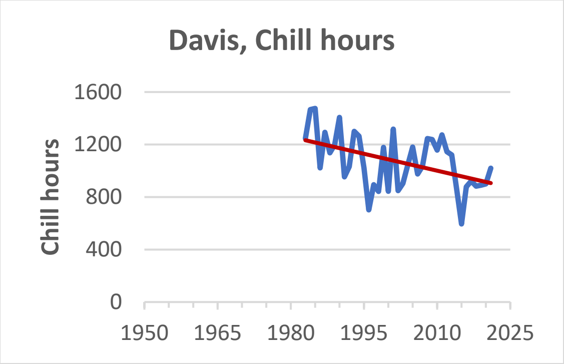
Appendix

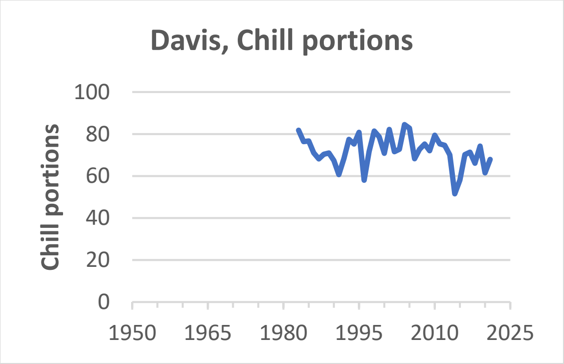
Figure A-1. Long-term trends in chill hours and chill portions, by location.

Statistically significant trends (p<0.05) are shown as red lines; no trend line is shown for non-significant trends.

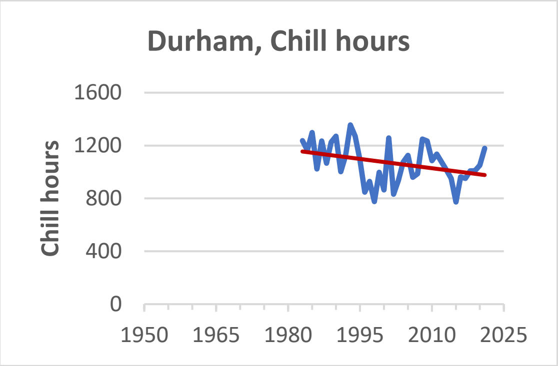




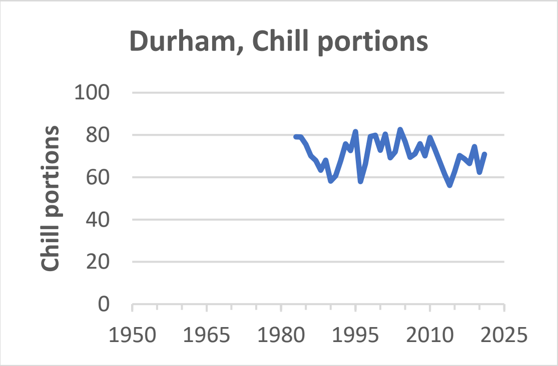
Davis, Chill hours



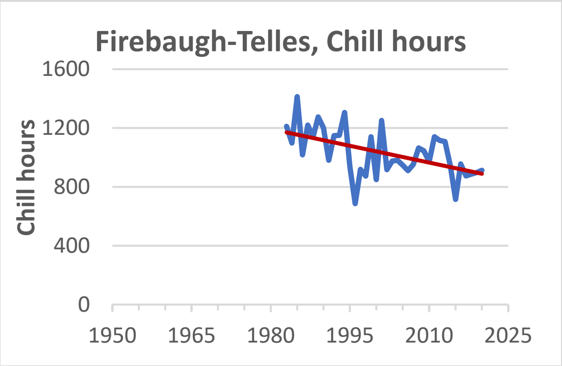
Davis, Chill portions



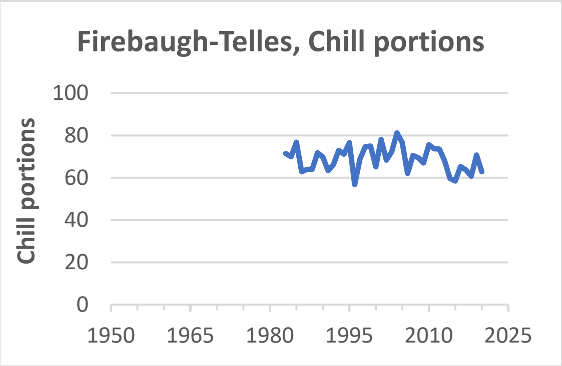
Durham, Chill hours



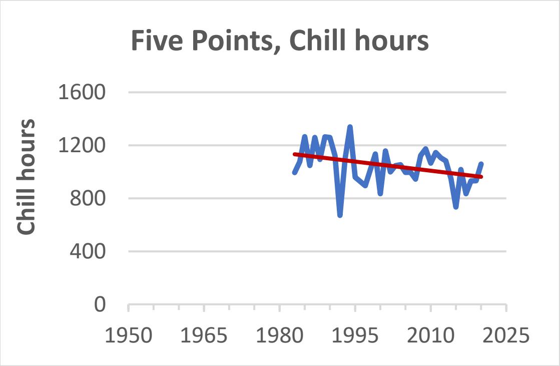
Durham, Chill portions



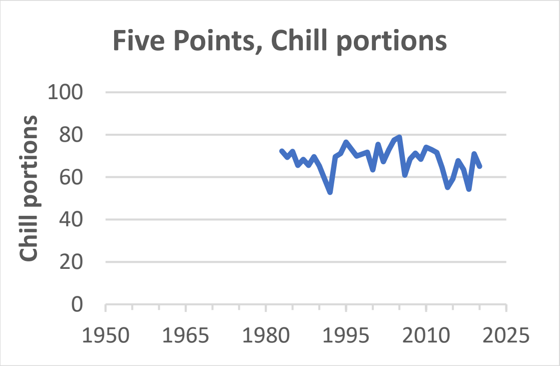
Firebaugh-Telles, Chill hours



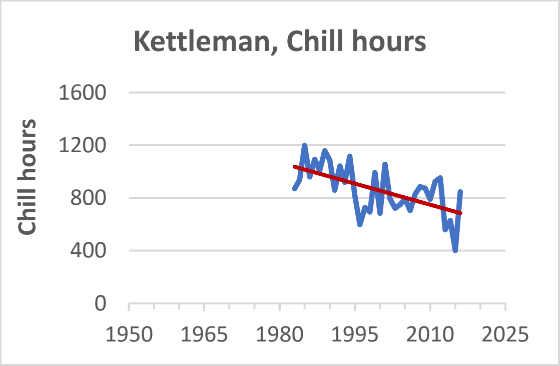
Firebaugh-Telles, Chill portions



Five Points, Chill hours



Five Points, Chill portions


Kettleman, Chill hours
Chill hours
1600
1200
800
400
0
1950
1965
1980
1995
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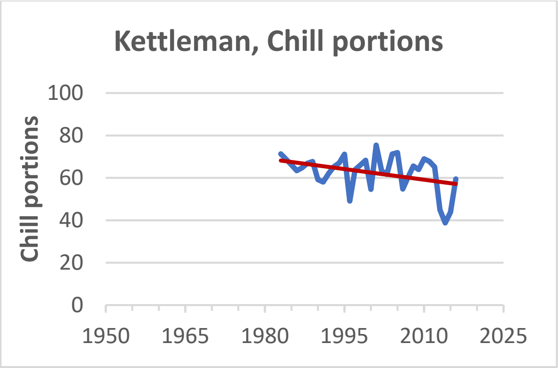
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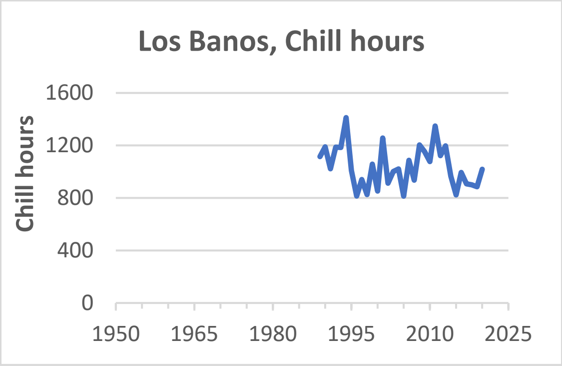
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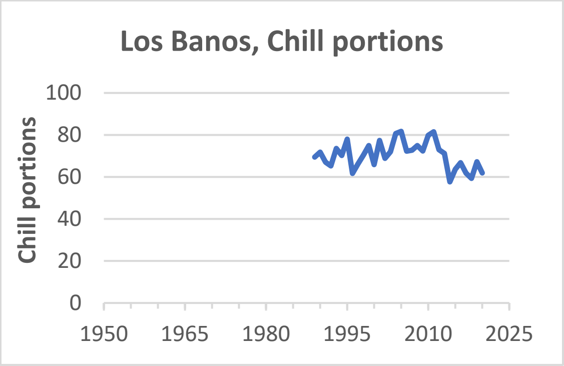
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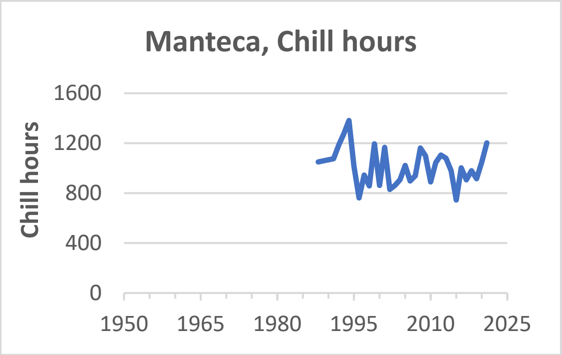
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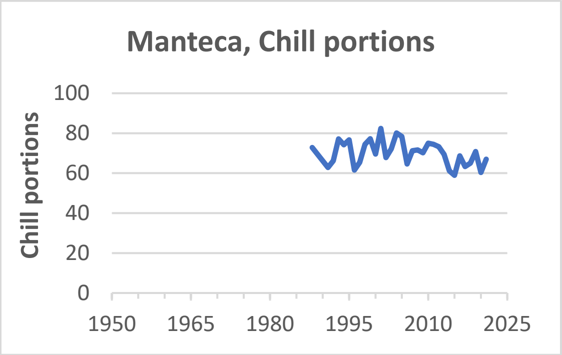
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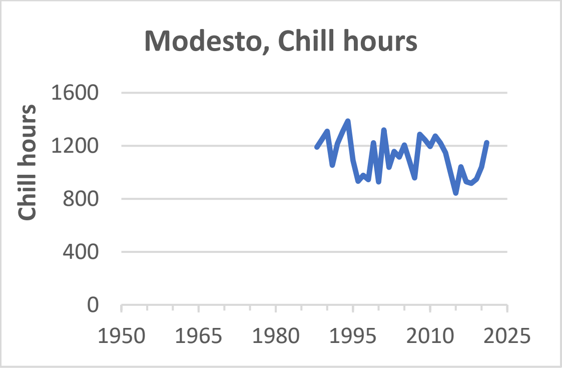
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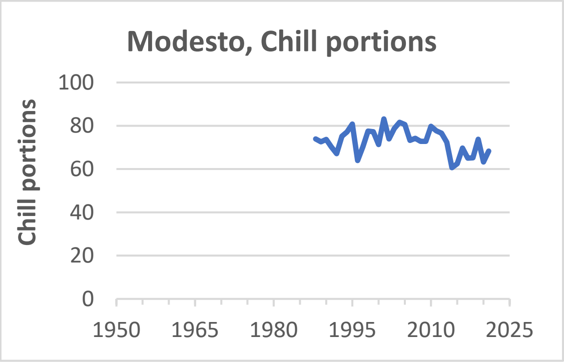
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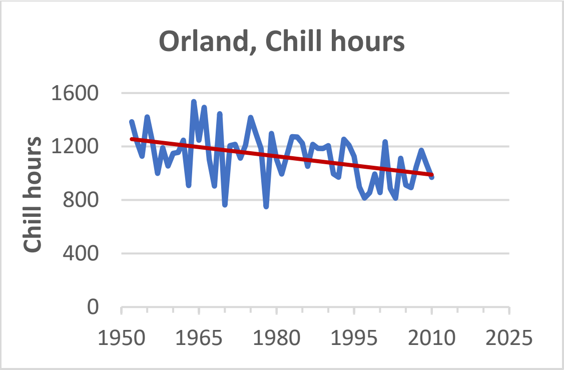
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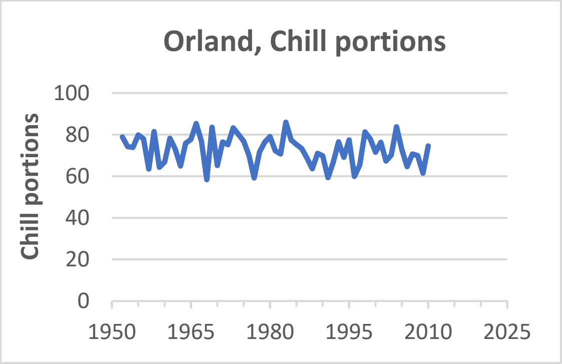
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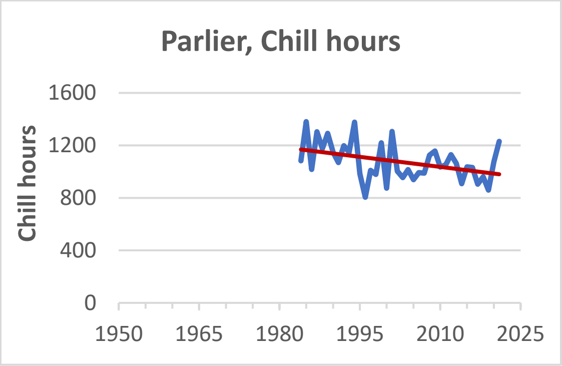
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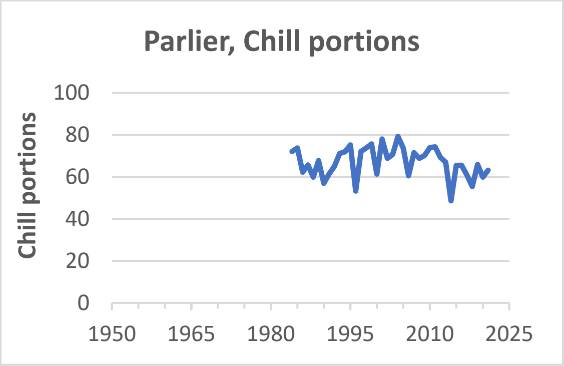
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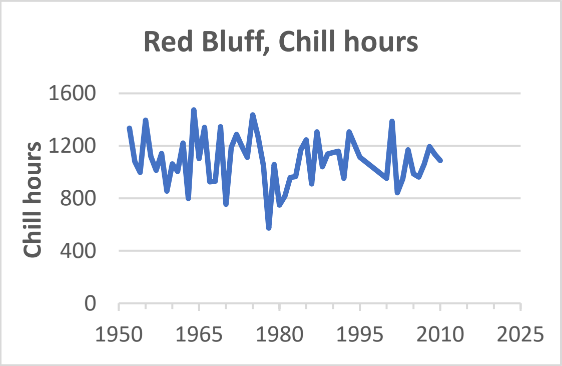
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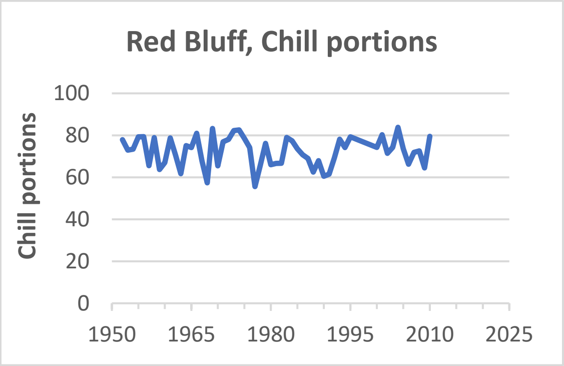
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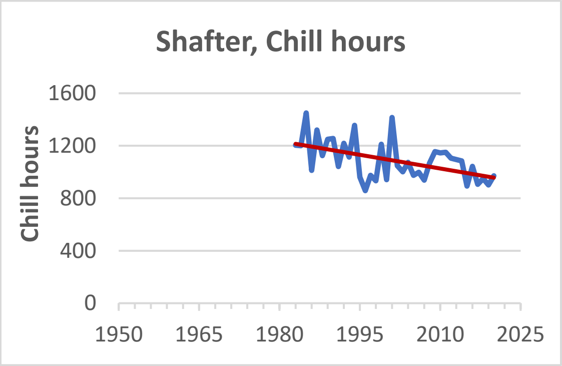
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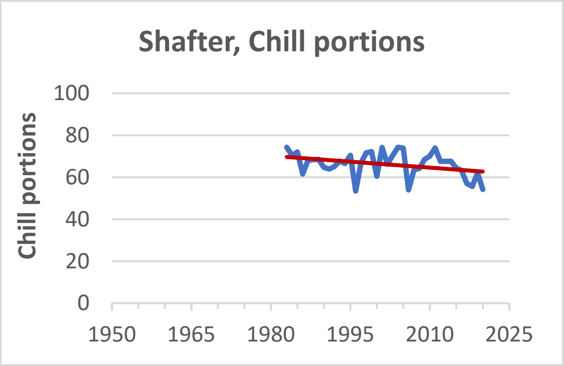
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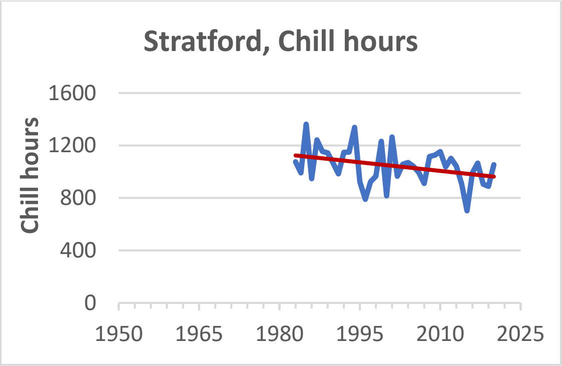
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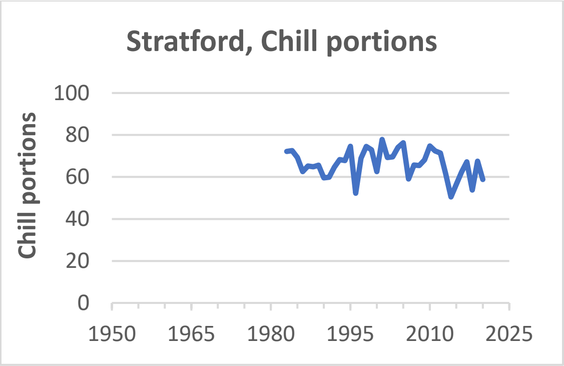
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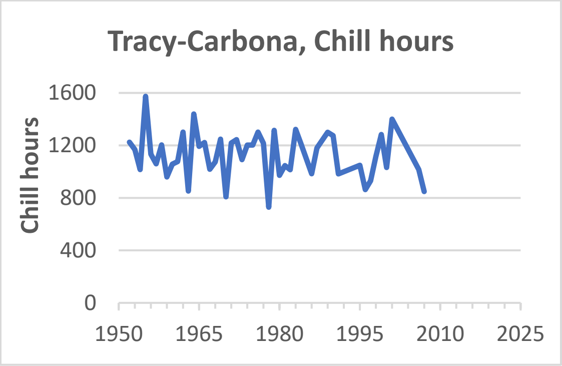
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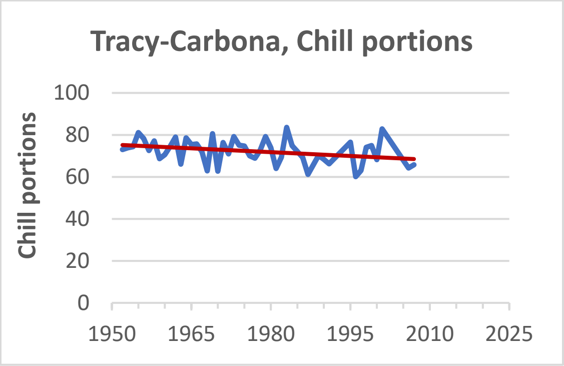
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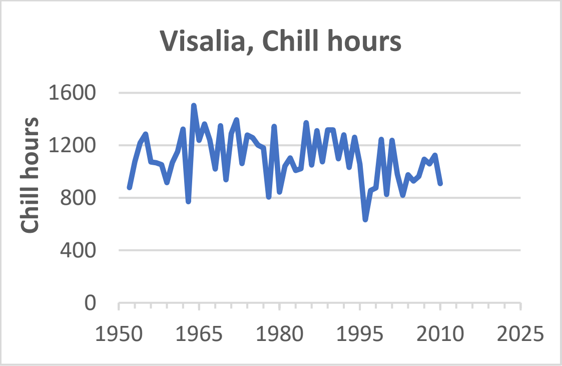
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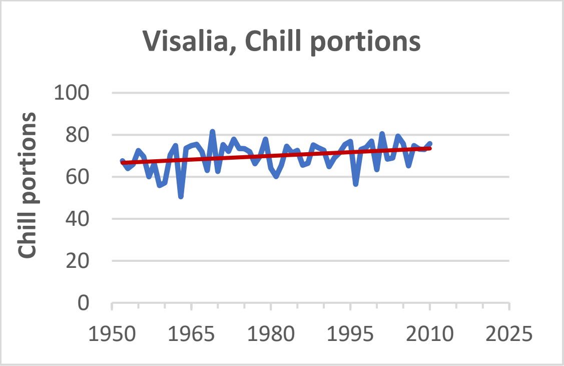
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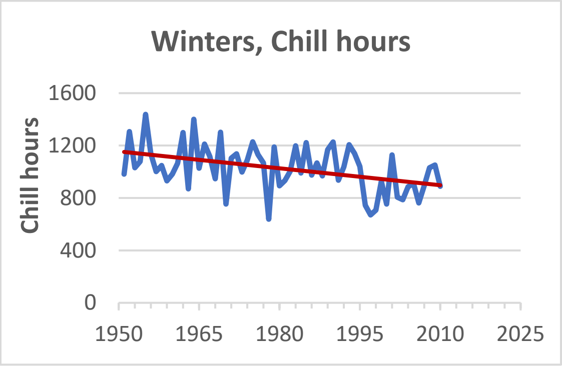
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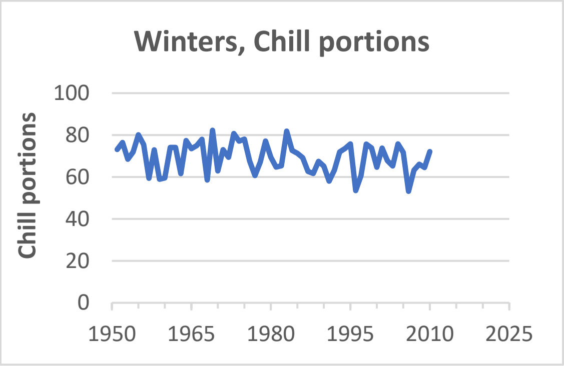
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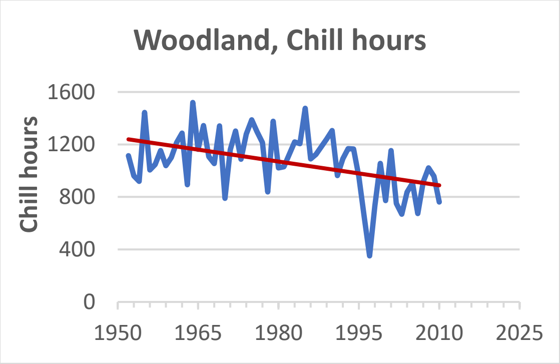
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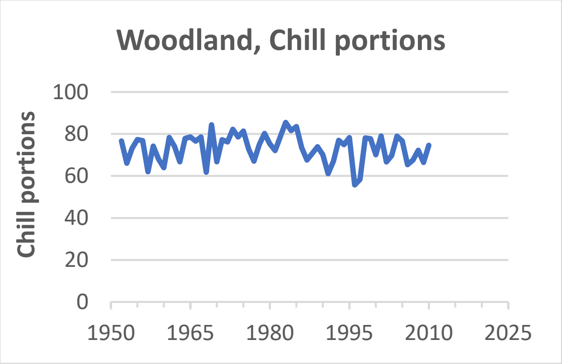
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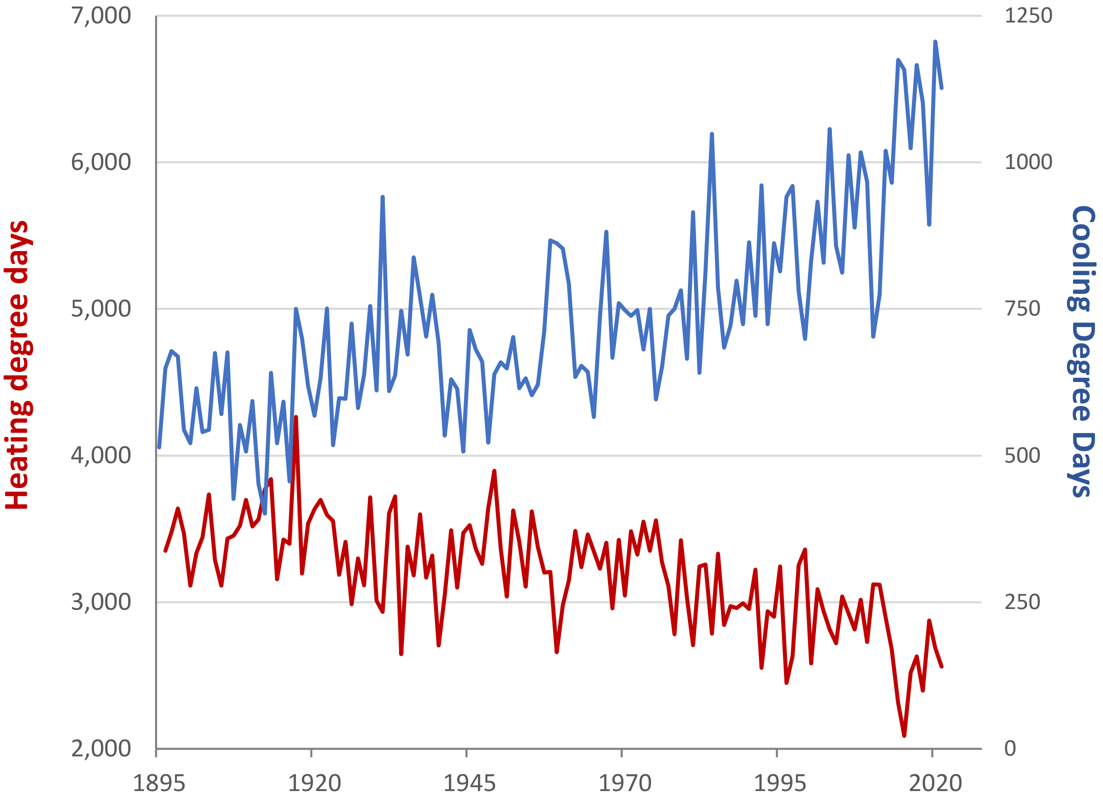
COOLING AND HEATING DEGREE DAYS

Cooling degree days and heating degree days are temperature-based metrics used to help estimate cooling and heating needs. Other things being equal, the higher the cooling degree days over a period, the more energy required to cool a building to a given temperature. Similarly, the higher the heating degree days, the less energy it takes. In California, cooling degree days have gradually increased and heating degree days have gradually decreased.

Figure 1. Cooling and Heating Degree Days Statewide



Source: NOAA 2022

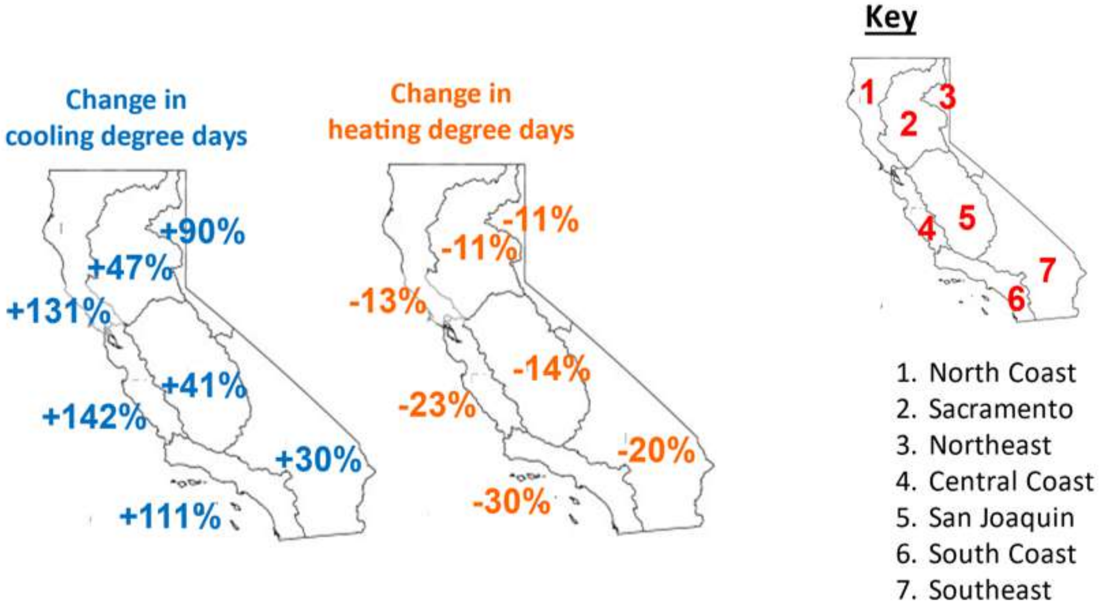
Note: Degree days measure the difference between the average daily temperature and a reference temperature, in this case, 65 degrees Fahrenheit (°F). Cooling degree days measure how much the average daily temperature is higher than 65°F; heating degree days, how much it is lower than 65°F. For example, an average statewide temperature of 75°F on one day corresponds to a cooling degree day value of 10. Average is defined as the midpoint of the hourly minimum and maximum temperature for the day. Each value shown in the graph is the sum of degree days for that year.

What does the indicator show?

Annual cooling degree days (CDD) in California increased between 1895 and 2020, while heating degree days (HDD) decreased over the same period (Figure 1). Both trends are consistent with national patterns (NOAA, 2021a) and are especially visible in the past five decades, with the past few years showing some unusually high statewide CDDs and unusually low HDDs.

California's 100 million acres encompass diverse terrains and geographies with various climates. Long-term trends in degree days show regional variations, as shown in Figures 2, 3, and 4 and Table 1 for California's seven NOAA climate divisions.[1] All seven divisions show an increase in CDD and a decrease in HDD over the last century, but to varying extents (see Figures 2-4). Coastal California shows greater percentage increases in CDD over the last century compared to inland areas of the state, partly because they had low CDDs to begin with. The Central Coast and especially the South Coast had the largest percentage declines in HDD.

Figure 2. Percent change in degree days by climate division, 1895-2021



Source: NOAA, 2022a

Table 1 presents these trends in terms of changes in annual cooling and heating degree days (base 65°F) for the seven climate divisions, expressed as a linear rate of change per decade. Trends are reported for two periods: 1895 to 1970, and 1971 to 2020. In each region, cooling degree days increased and heating degree days decreased over both periods. The regional rates of change for the most recent 50 years (1972-2021) are substantially higher than for the previous 77-year period (1895-1971).

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[1] National Oceanic and Atmospheric Administration (NOAA) climate divisions span the contiguous United States, subdividing each state into ten or fewer climate divisions; other indicators in this report are based on data from the Western Regional Climate Center, which divides California into eleven climate regions.

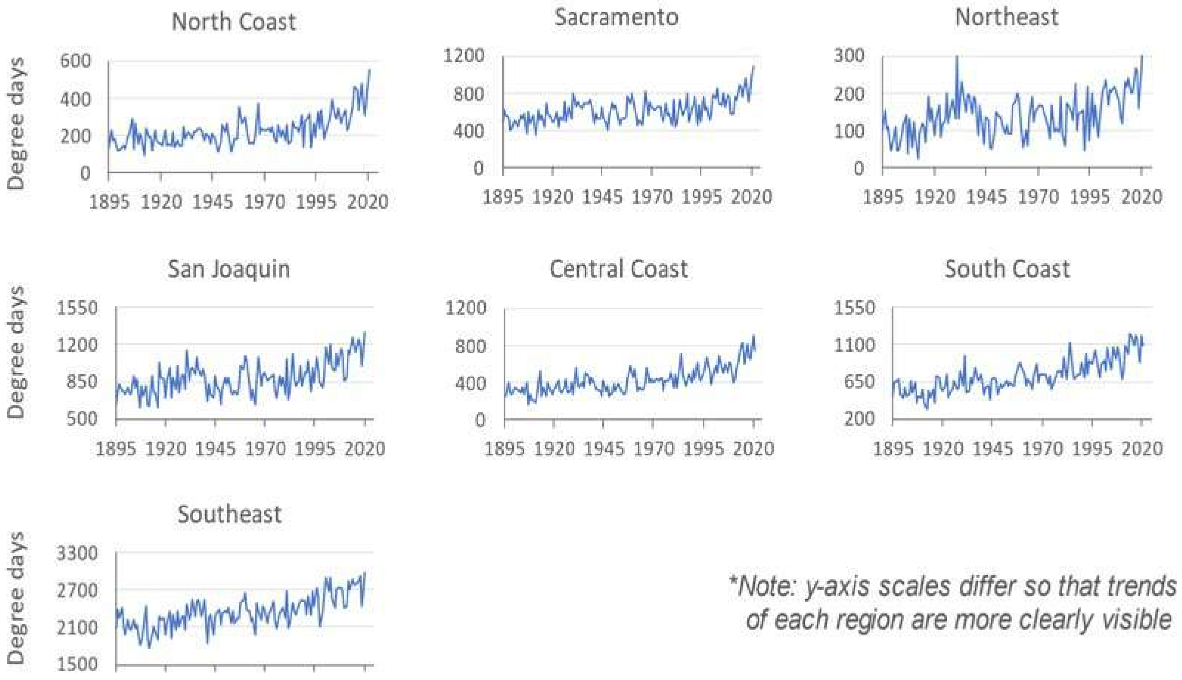
Table 1. Divisional Trends in Cooling and Heating Degree Days

Trends are presented for each of California's climate divisions. Values presented are the slope of linear trends, representing the rate of change in cooling or heating degree days per year.

Climate Division	**Trends, 1895-1971 (Degree Days per Decade)**		**Trends, 1972-2021 (Degree Days per Decade)**	
	Cooling	**Heating**	**Cooling**	**Heating**
North Coast Drainage	+8	-32	+45	-135
Sacramento Drainage	+18	-18	+62	-119
Northeast Interior Basins	+6	-68	+27	-157
Central Coast Drainage	+16	-35	+63	-138
San Joaquin Drainage	+15	-12	+82	-135
South Coast Drainage	+27	-45	+86	-147
Southeast Desert Basins	+38	-24	+111	-98

Source: NOAA, 2021a.

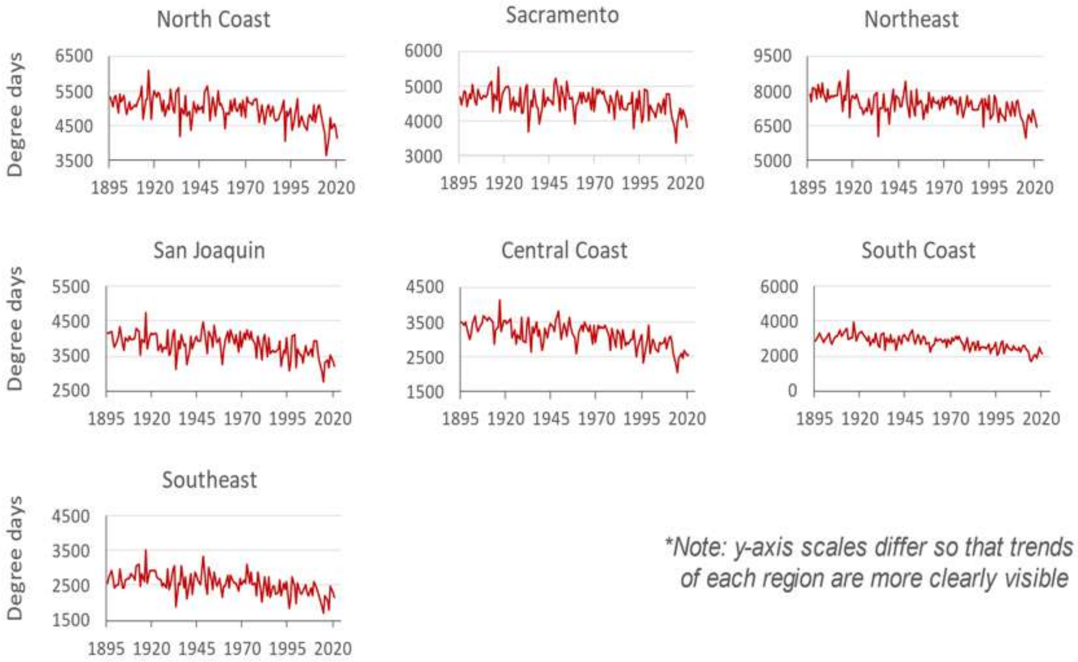
Figure 3. Cooling degree days by Division, 1895-2021*



**Note: y-axis scales differ so that trends of each region are more clearly visible*

Source: NOAA, 2021a

Figure 4. Heating degree days by Division, 1895-2021*



**Note: y-axis scales differ so that trends of each region are more clearly visible*

Source: NOAA, 2022a

Why is this indicator important?

Since the 1930s, degree days have been used as a proxy for the energy needed to cool or heat homes and buildings, to benchmark building performance, and to inform utility planning and construction decisions (Marston, 1935; Meng and Mourshed, 2017; NOAA, 2005; USGCRP, 2020), as well as in estimating changes in biological systems such as in agriculture. The relationship between degree days and building heating and cooling energy use is approximate and depends on many factors that vary by building and over time. These include building construction and thermal characteristics (such as building size, ventilation, insulation, and number, placement and energy efficiency rating of windows and doors), building type and function (single-family residential, multi-family residential and the myriad of commercial and industrial uses), the type and efficiency of cooling and heating technologies, and cooling and heating practices (for example, based on occupancy, tolerance for heat or cold, and use of heat-generating appliances and equipment) (Meng and Mourshed, 2017; US EPA, 2016). Compressor-based air conditioning was not introduced into U.S. homes until the middle of the 20th century (Cooper, 1998). Prior to that, home cooling did not use much energy; other such changes can be expected as energy use and technology evolve.

As the climate continues to warm, heating needs will likely decline, and energy consumption is expected to shift from cooler months to warmer months (CEC, 2015) due to increased cooling energy use from expanded presence of air conditioning and higher levels of use. In 2019, 58% of California households had central cooling, while in

2003 only 44% did (DNV, 2021).[2] That is, in 2019, California homes were 32% more likely to have central cooling than in 2003. Meeting a growing demand for cooling creates specific challenges for new energy generation and distribution infrastructure, including encouraging higher levels of load flexibility to manage peak demand and system reliability (CEC, 2020; US EPA, 2016). At the same time, warming temperatures, sea level rise, and wildfires can negatively impact the operation or the efficiency of power plants, transmission networks, and natural gas facilities (CEC, 2009, 2012, 2020; Patrick and Fardo, 2009; US EPA, 2016). Climate change can also affect renewable energy, given its dependence on natural resources like water, wind, biomass and available incoming solar radiation, which are all influenced by climate variations (CEC, 2009).

For lower-income households, heating and cooling costs represent a bigger fraction of household income than for higher-income households (CalEPA, 2010). The impact of increased summer heat is disproportionate across households and communities. Lower-income households are less likely to own well-functioning efficient air conditioners or even any air conditioners at all (Chen et al., 2020; Fernandez-Bou et al., 2021), which potentially makes them more vulnerable to health effects of summer heat extremes.

What factors influence this indicator?

Since heating and cooling degree days reflect trends in temperature, factors that influence temperature affect this indicator. These factors are discussed in the *Annual air temperature* indicator.

Technical considerations

Data characteristics

The values for degree days are downloaded from NOAA's Climate at a Glance website (NOAA, 2021c). They are derived by NOAA using daily temperature observations at major weather stations in the United States with NOAA's Climate Divisional Database (nClimDiv). nClimDiv uses a 5 km gridded approach to compute temperature, precipitation, and drought values for United States climate divisions. A mean daily temperature (average of daily maximum and minimum temperatures) of 65˚F serves as the reference temperature for degree day calculations for this data set. Cooling degree days are calculated by summing the positive differences between the mean daily temperature and the 65˚F reference temperature. Heating degree days are calculated by summing the negative differences between the mean daily temperature and 65˚F.

Strengths and limitations of the data

The nClimDiv dataset is an improved version of an older climate dataset from NOAA, benefitting from additional quality assurance reviews and temperature bias adjustments

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[2] This comparison pertains only to households served by California's three investor-owned utilities (Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric) or LADWP, which are the utilities surveyed in both the 2003 and 2019 Residential Appliance Saturation Surveys.

and providing more robust values than its predecessor. New methodologies include a transition to a grid-based calculation and additional stations from before the 1930s (NOAA, 2021b).

There are important limitations to keep in mind when relating degree days to energy use. First, the thermal comfort of building occupants depends on more than just indoor temperatures (Kwok and Rajkovich, 2010). Heating and cooling energy use for a given set of degree days also depends on a variety of factors beyond the technical characteristics of structures and equipment, such as social practices, occupant preferences, and thermal comfort management regimes (Deumling et al., 2019; McGilligan et al. 2011). Second, degree days cannot fully express the complexity of weather, how and where it changes, or how these changes affect indoor conditions (Azevedo et al., 2015). For example, nighttime low temperatures have increased more than daytime high temperatures in much of California, especially since 2000 (Lindsey, 2018; see the *Annual air temperature indicators*). This can reduce the contribution of nighttime temperatures to natural cooling but is scarcely captured in degree days indicators. Also, though 65˚F is the standard base temperature used for computing degree days in U.S. energy applications, different base temperatures—such as a higher base temperature for CDD (EIA,1983) — could give different results for energy predictions. Overall, since climate patterns, land use, construction, building technologies, social patterns, and modeling methods are changing, legacy computational practices using CDD and HDD might be usefully revamped as well.

OEHHA acknowledges the expert contribution of the following to this report:

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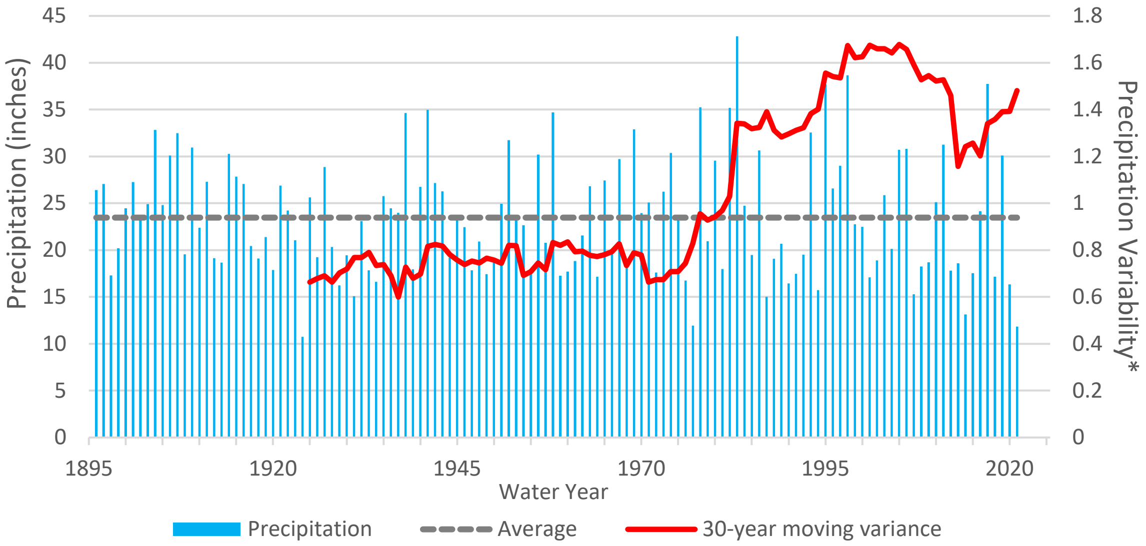
PRECIPITATION

While the amount of annual precipitation over time shows no statewide trend, year-to-year variability has increased since the 1980s. In recent years, the fraction of precipitation that falls as rain instead of snow has increased in the Sierra Nevada and Southern Cascades, reducing the water stored in the snowpack that provides most of California's water supply.

Figure 1. Statewide annual precipitation (1895-2021)



Source: WRCC, 2022

****Precipitation variability**: the value shown for each year beginning in 1925 is the ratio of the variance for the 30-year period ending in that year to the variance over the entire period (1895-2021). A ratio above 1 means precipitation was more variable; below one, less variable.*

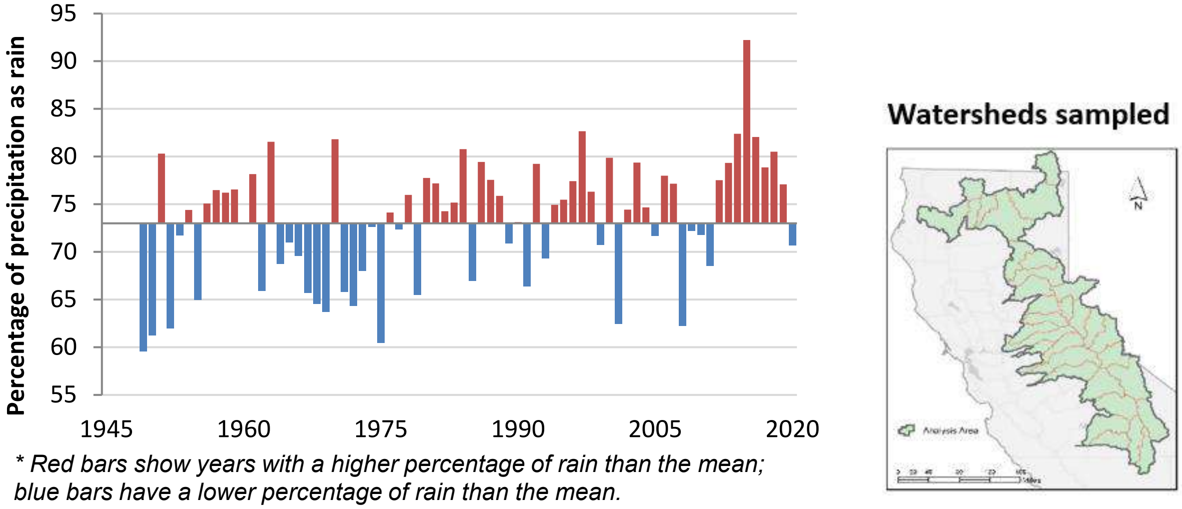
What does the indicator show?

California experiences high year-to-year variability in precipitation: some years are very wet, while others are very dry. Since the early 1980s, precipitation over the state has become more variable (Figure 1, red line). The same is true across the state's climate regions (see appendix; also He and Guatam, 2016). The past decade included the third wettest year on record (2017) and the second driest (2021). In 2017 California emerged from a severe and prolonged drought. From October 2018 to September 2019, California transitioned from a very dry fall into a very wet winter. The water year 2021 was the second driest on record, following 1924.

Precipitation totals are tracked by "water year," from the beginning of the rainy season in October through the following September, the end of the dry season. This is more useful than a calendar year in California due to its typically dry summer and wet winter ("Mediterranean") climate. On average, 75 percent of the state's annual precipitation occurs from November through March, with 50 percent occurring from December through February.

No clear trend is evident in the amount of total annual precipitation (Figure 1, blue bars). Statewide precipitation is the area-weighted average of regional precipitation values. In other words, the regional precipitation values — computed as an area-weighted average of precipitation at the climate stations in the region — are weighted by the area covered by each region, and an average is calculated as the statewide value. Since records began in 1895, statewide annual precipitation has ranged from a low of 10.75 inches in 1924 to a high of 42.82 inches in 1983. The water years spanning 2012 to 2015 set a record for the driest consecutive four-year period of statewide precipitation. The average annual precipitation varies greatly among California's eleven climate regions (as defined by the Western Regional Climate Center): from 4.7 inches in the Sonora Desert to 67.8 inches in the North Coast.

Figure 2. Rain as a percentage of total precipitation* (1949-2020)



** Red bars show years with a higher percentage of rain than the mean; blue bars have a lower percentage of rain than the mean.*

Source: DWR, 2021a

Figure 2 shows the percentage of yearly precipitation falling as rain over the 33 watersheds that provide most of the state's water supply. Each value shown represents the difference between that year's percentage of rain compared to the average of 73 percent (mean, black line) for the entire period (1949 to 2020). Red bars show years with more rain than average (and thus less snow), and blue bars show years with less rain than average. Despite high year-to-year variability, recent years clearly show a trend toward more precipitation falling as rain. The percentage of precipitation falling as rain for 8 of the last 10 years was higher than average. The 2015 water year, which had the lowest snowpack on record, also had the highest percentage of rain, at about 92 percent.

Why is this indicator important?

Precipitation, in the form of rain and snow, provides most of California's supply of water. The fraction of precipitation falling as rain significantly affects how much water is stored as snow. During warmer months, the state relies on Sierra Nevada snowmelt to meet a large fraction of its water demand (see *Snow-water content* and *Snowmelt runoff* indicators). Tracking changes in the amount and physical state of precipitation, and in the patterns of storm events gives critical information for balancing the multiple water management objectives of reservoir operations, including storage and flood protection. Historical trends help inform short- and long-term water management planning and provide the basis for future projections (Siirila-Woodburn et al. 2021; Sterle et al., 2019).

Changes in the timing of precipitation are also important to track. A comparison of historical and current precipitation (1960–1989 vs 1990–2019) averaged over the entire state shows a change in the monthly distribution of precipitation (Luković et al., 2021). This study found a progressively delayed and shorter, sharper rainy season in California. This is consistent with climate change projections (Oakley et al. 2019; Polade et al. 2014, Swain et al., 2018).

Along with providing water to people in California, precipitation also nourishes the natural environment. Changes to precipitation or water availability can manifest in ecosystems in various ways. During the 2012-2016 drought, five consecutive dry winters resulted in severe ecological impacts, including massive tree mortality, catastrophic wildfires, and steep drops in winter-run Chinook salmon fry survival and in the number of adult Coho salmon returning to spawn (DWR, 2021b).

As dry and wet extremes continue to occur more often, shifts between droughts and floods will become more frequent. Shifts between extreme dry years to extreme wet years are anticipated to happen more often in southern California (Swain et al., 2018). California’s recent rapid shift from severe drought (2012-2016) to heavy precipitation and flooding (2016-2017 winter) exemplifies what so-called precipitation “whiplash” looks like and what its impacts can be: hundreds of roads and other infrastructure throughout California were damaged by floods and mass movements such as landslides. Heavy runoff in the Feather River watershed contributed to the failure of the Oroville Dam spillway, forcing the evacuation of almost a quarter of a million people (Swain et al., 2018). A wet-to-dry whiplash promotes the growth of vegetation that later dries and serve as fuel for fires (Williams et al., 2019). Altogether, projections of climate change suggest that California will spend most of the year in a perennial drought, interrupted periodically by large storms that produce heavy precipitation (Allen and Luptowitz, 2017; Gershunov et al., 2019; Huang et al, 2020; Pottinger, 2020).

Figure 3. Heavy rainfall triggered over 500 landslides at the Tuolumne River canyon in 2018

Source: Collins,et al. 2020;
Photo credit: Wayne Hadley
(used with permission)

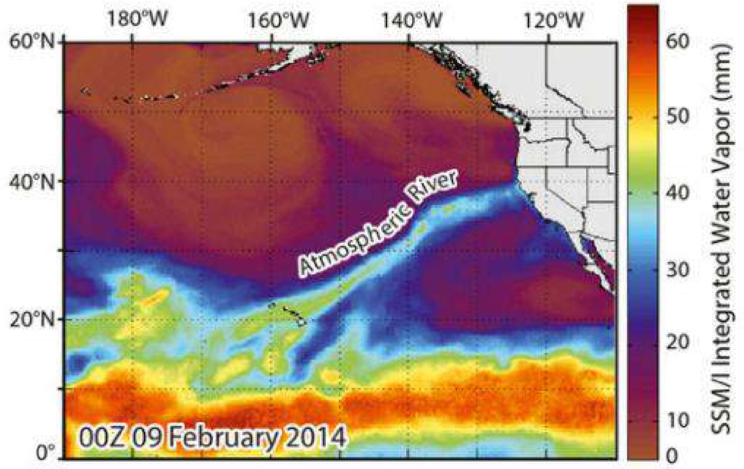
Floods, landslides, and even avalanches following heavy rainfall threaten human life and property (Collins et al., 2020; Hatchett et al., 2017 and 2020). Fast-moving, highly destructive debris flows triggered by intense rain can happen after a wildfire due to vegetation loss and soil exposure (USGS, 2021). An example of the devastating nature of post-debris flows occurred January 2018, when high intensity rainfall in southern California over an area recently burned by the Thomas Fire triggered landslides that killed 23 people, destroyed over 130 homes, severely damaged infrastructure in Montecito and Carpinteria, and caused the closure of Highway 101 for 13 days (Lukashov et al., 2019). Figure 3 shows shallow landslide and debris flow scars caused by another storm on March 22, 2018, at the Tuolumne River Canyon (near the town of Groveland, in the Sierra Nevada foothills). This storm created a flash flood that caused infrastructure damage in the tens of millions of dollars, led to more than 500 landslides, and moved more sediment in one day than the Tuolumne River would normally transport in a year (Collins et al., 2020).

The chances of an extreme 200-year flood event, last seen in the extraordinary “Great Flood” of 1861-1862, is more likely than not to occur within the next 40 years, and multiple occurrences are plausible by 2100 on a business-as-usual greenhouse gas emissions trajectory (Swain et al., 2018). During the Great Flood, flood waters remained throughout the state for months, transforming the land and making roads impassable (Jones, 2019). A storm of this magnitude today would probably lead to considerable loss of life and economic damages approaching a trillion dollars (Swain et al., 2018; USGS, 2011).

What factors influence this indicator?

High year-to-year variability in precipitation is a natural part of California’s climate: the western United States has experienced great swings between wet and dry for thousands of years (Ibarra et al., 2018; Sterle et al. 2019). During the summer, California experiences a deep “seasonal drought” as atmospheric moisture gets diverted away from the state by dense blobs of air parked over the north Pacific Ocean (also known as a “high pressure zone”). In the southeastern desert regions, however, some monsoonal activity in the summertime may bring thunderstorm precipitation (Corbosiero et al., 2009; WRCC, 2021). Precipitation deficits during the recent drought have been associated with a prominent region of high pressure nicknamed the "ridiculously resilient ridge" that diverted storm tracks northward during California's rainy season from 2012 to 2015 (Swain, 2015). During winter, the Pacific high pressure zone retreats southward, and much of California's annual precipitation falls during a few large "atmospheric river" storms (Lamjiri et al., 2018; WRCC, 2021).

Figure 4. Satellite-derived image of an atmospheric river



Source: Hatchett et al., 2017

An atmospheric river along the western United States identified using satellite-derived integrated water vapor or the amount of water vapor in the atmosphere (shown according to the color scale on the right).

Atmospheric rivers are long, narrow bands of water vapor, greater than 1,000 miles long and typically about 250 to 370 miles wide (Figure 4). A natural part of the global water cycle, they transport most of the water vapor outside of the tropics. Some atmospheric rivers originate from the Pacific Ocean near Hawaii and make landfall in California, where they can release water vapor in the form of heavy rain or snow (NASA, 2021; NOAA, 2017).

Precipitation from atmospheric rivers supplies 30 to 50 percent of California's annual precipitation and about 40 percent of the Sierra Nevada snowpack (Dettinger, 2013; Guan et al., 2010). On average, rainfall from atmospheric rivers makes up 79 percent, 76 percent, and 68 percent of all extreme-rainfall accumulations in the North Coast, northern Sierra, and Transverse Ranges of southern California, respectively (Lamjiri et al., 2018). Windward slopes of hills or mountains provide the ideal location for atmospheric rivers to produce heavy precipitation in California through a phenomenon called orographic forcing: when air gets pushed up the slope of a mountain range, the water vapor cools and condenses if the air is moist enough, forming clouds and causing heavy precipitation to fall (Ralph, 2020). Precipitation from atmospheric rivers in western North America will become more frequent, heavy, and extreme (Gershunov et al., 2019; Hagos et al., 2016; Polade et al., 2017). Although climate change will enhance the amount of precipitation delivered by landfalling atmospheric rivers along the West Coast, the overall frequency of precipitation will decrease as fewer storms not caused by atmospheric rivers are projected (Gershunov et al, 2019).

Most of the water vapor that provides the state's precipitation comes from the Pacific Ocean. Much of the variability in the state's precipitation is related to El Niño and La Niña in the tropical Pacific, which are the warm and cool phases of a recurring climate pattern called the El Niño-Southern Oscillation, or ENSO. The warm phase of

ENSO, El Niño, happens in years when warm surface waters in the ocean intensify a current of strong, high-altitude winds called the Pacific jet stream and shift it south. This causes wet winters in the southern part of the United States (including southern California) and warmer and drier conditions in the northern United States. During the cool phase of ENSO, La Niña, unusually cool surface water conditions in the ocean displace the jet stream northward, leading to drought in the southern United States and heavy rain in the Pacific Northwest. Climate change may make extreme El Niño and La Niña events become more frequent and stronger by the end of the century (NOAA, 2020).

Regarding physical state, precipitation falls as rain or snow depending on the temperature of the air and the ground, the local geography, and the characteristics of the storm itself. Warming temperatures and their influence on a rising snowline (the altitude above which snow remains on the ground) make winter precipitation more likely to fall as rain instead of snow and run off into the ocean instead of being stored in reservoirs (Gonzales et al, 2019; Hatchett et al, 2017; Huang et al, 2020, Lynn et al, 2020). This higher runoff poses a greater flood risk (Huang et al, 2020).

Modeling simulations show that greenhouse gases including carbon dioxide and methane, as well as solar forcing, can increase California wintertime precipitation. Precipitation also changes in response to aerosols: sulfate aerosol increases California wintertime precipitation, whereas black carbon reduces it. California precipitation is more sensitive to aerosols, especially regional emissions from Europe and Asia, than to greenhouse gases (Allen et al., 2020).

A climate change signal can be found in extreme precipitation events globally over the past several decades (Dong et al., 2020). Observed increases in precipitation extremes in California are consistent with projected impacts of climate change in the state (Swain et al., 2018). At the national level, projections suggest that climate change will increase the size and frequency of very heavy and rare rainfall events across the United States (Swain et al., 2020).

Technical Considerations

Data characteristics

Data for Figure 1 come from the California Climate Tracker, an operational database tracker for weather and climate monitoring information. This indicator tracks precipitation amount in a "water year" defined as October 1 to September 30. This operational product, the California Climate Tracker, is updated periodically online at the Western Regional Climate Center. Data, including historical data, is continuously monitored and updated. The data provided here is the dataset available as of April 7, 2021, from WRCC with the most up-to-date values for modeled historical data.

Precipitation data for nearly 200 climate stations in the NOAA Cooperative Network (COOP) within California were obtained from the Western Regional Climate Center database archive of quality-controlled data from the National Climatic Data Center. For this study, COOP data from 1948-2020 were utilized. Gridded climate data from Parameter-elevation Regressions on Independent Slopes Model (Daly et al., 1997) were acquired from the PRISM group at Oregon State University for the period 1895-2021. PRISM provides complete spatial coverage of the state, where the station data serve to fill in recent data, until PRISM is processed each month. Because climate stations are not evenly spaced, the PRISM data are used to provide even and complete coverage across the state. These are combined to create a time series of annual statewide precipitation dating back to 1895.

Time series datasets prior to 1981 were modeled using climatologically aided interpolation that used the long-term average pattern (i.e., the 30-year normals) as first-guess of the spatial pattern of climatic conditions for a given month or day. Data are based on monthly modeling (PRISM, 2021).

The methodology for determining the rain/snow trends presented in Figure 2 combined fine-scale gridded precipitation data with coarse-scale freezing level and precipitation data from an atmospheric reanalysis. Snowfall was estimated as a fraction of total precipitation at a high spatial resolution, with output from WRCC's North American Freezing Level Tracker (NAFLT). For more information about the methods used, see Lynn et al. (2020).

Strengths and limitations of the data

The datasets used in this work were subjected to their own separate quality control procedures, to account for potentially incorrect data reported by the observer, missing data, and to remove inconsistencies such as station relocation or instrument change. The PRISM data offer complete coverage across the state for every month of the record. Limitations include the bias of station data toward populated areas and the limited ability of quality control processes in remote or high terrain areas. The results cited here offer a hybrid using both gridded and station data, considered more robust than either data set used independently (Abatzoglou et al., 2009).

A major advantage of the rain/snow approach used by Lynn et al. (2020) is that the NAFLT can be periodically updated as higher resolution gridded data products become available. This type of analysis can play an important role in developing and implementing adaptive strategies for water management. However, the methodology used interpolations based on observational data which are sparse in mountainous regions. It also might not fully reflect snow line variability in complex terrains.

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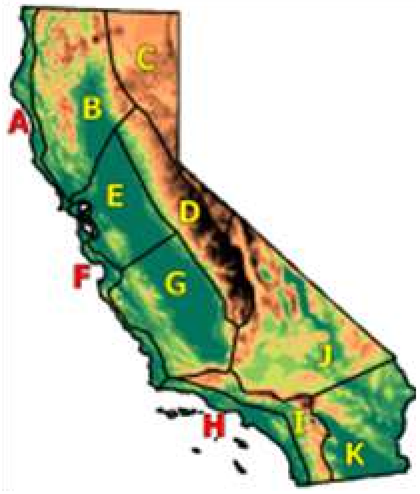
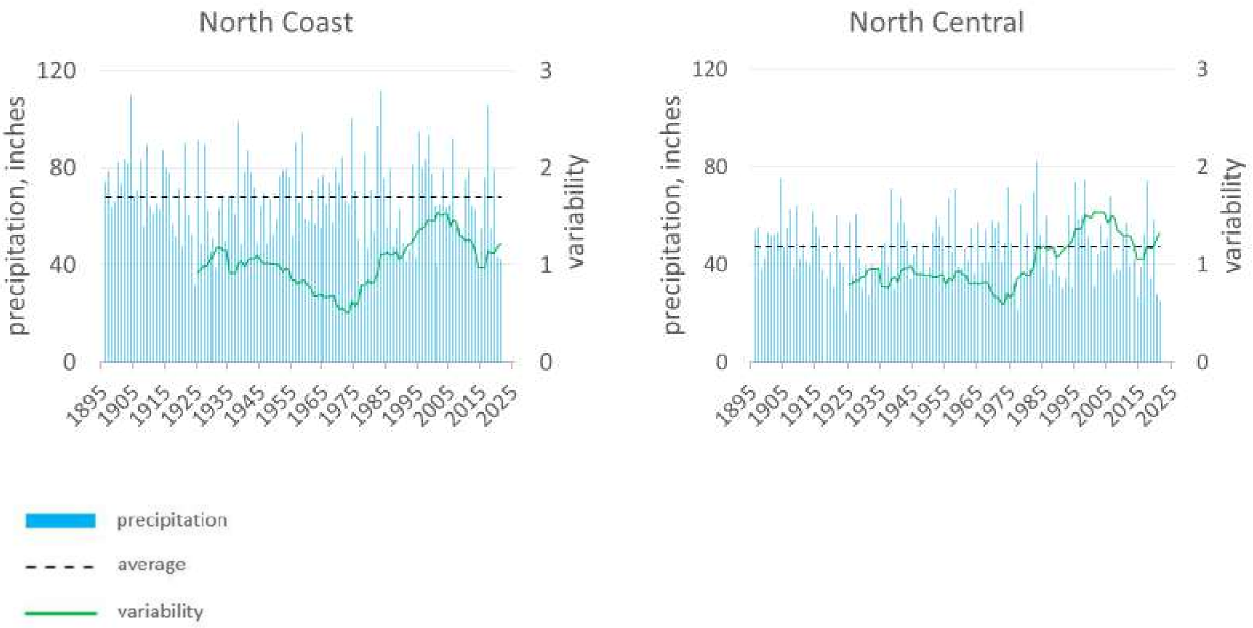
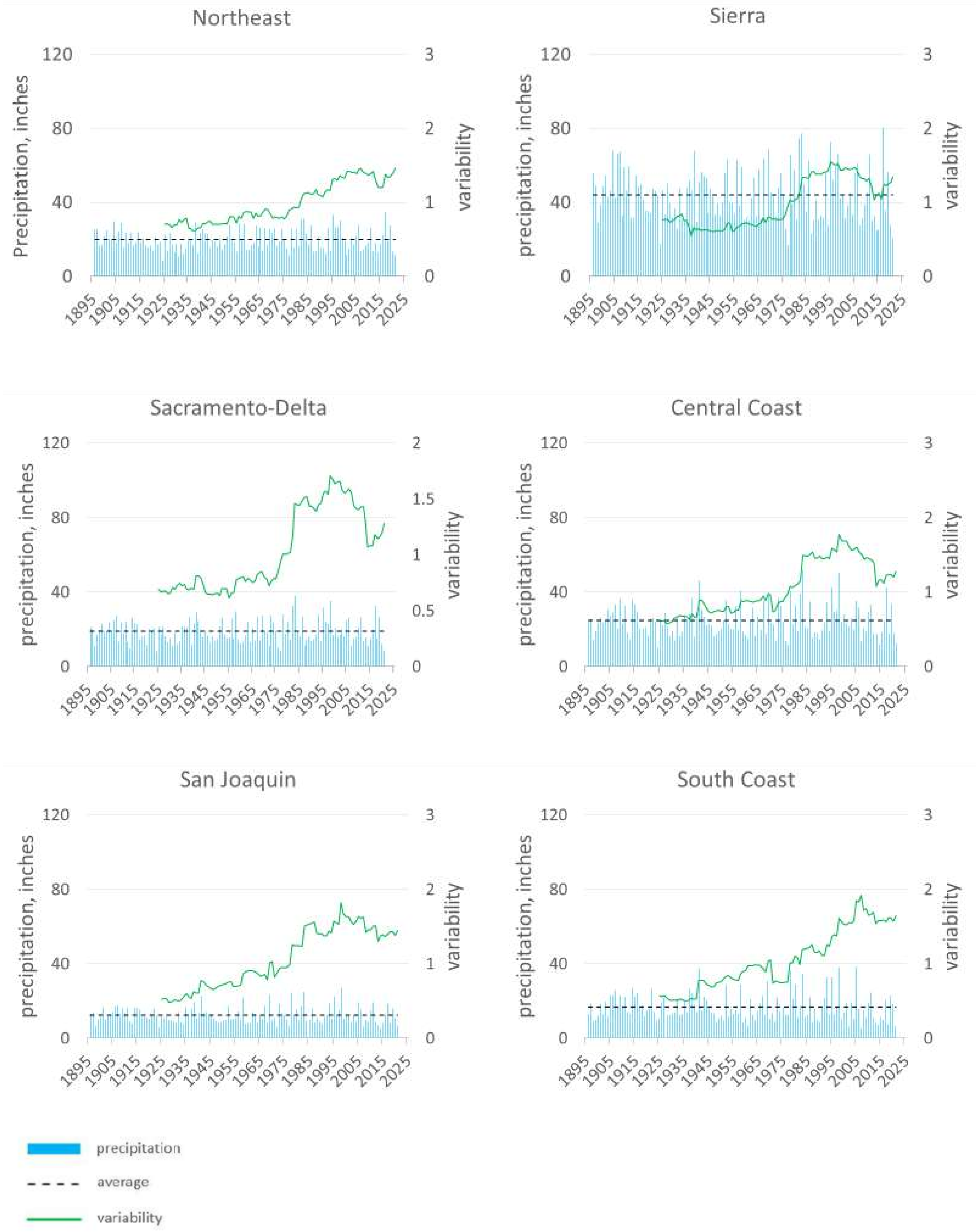
APPENDIX. Regional precipitation trends in California's climate regions (as defined by the Western Regional Climate Center)

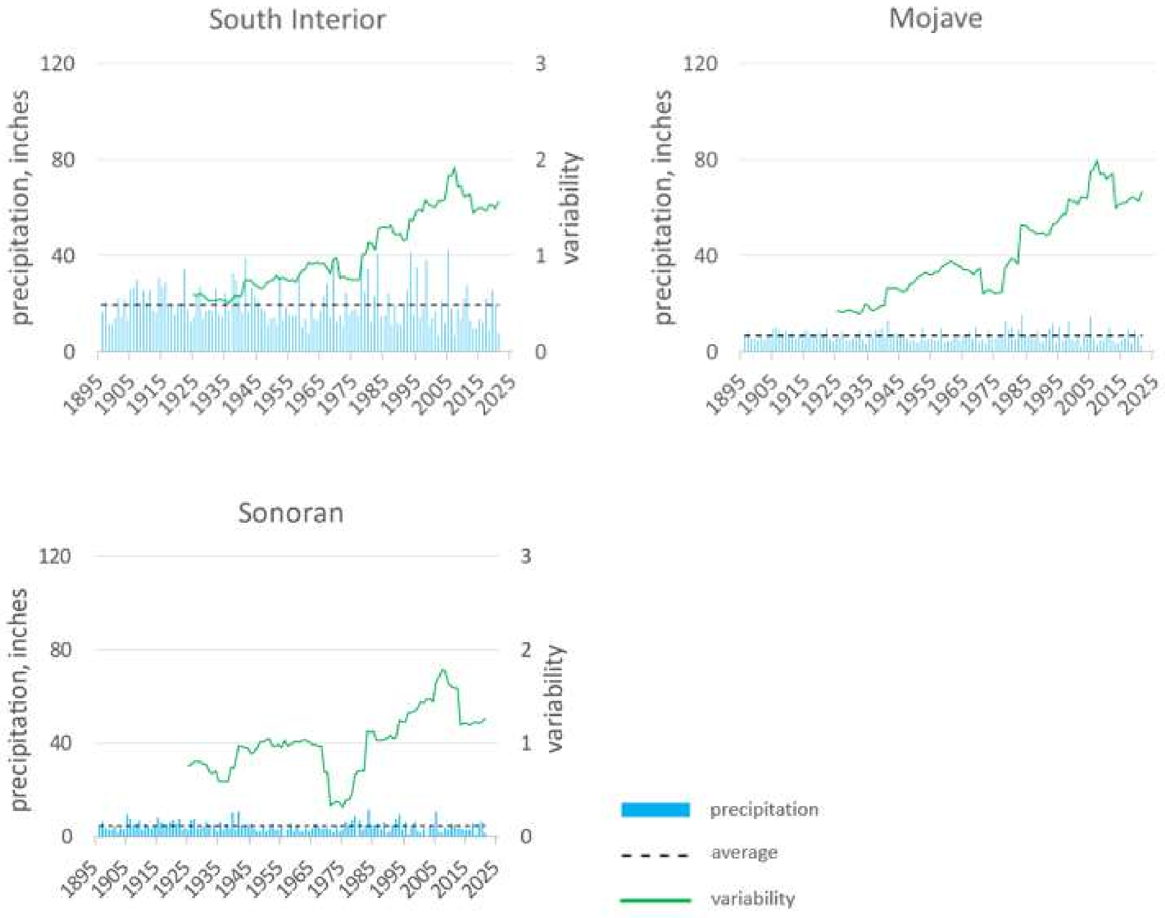


Region	Average precipitation (inches)
A. North Coast	67.9
B. North Central	49.0
C. Northeast	20.5
D. Sierra	44.9
E. Sacramento-Delta	20.3
F. Central Coast	26.4
G. San Joaquin Valley	12.9
H. South Coast	17.2
I. South Interior	19.8
J. Mojave Desert	7.0
K. Sonoran Desert	4.6
Statewide	24.2

Source: WRCC, 2021



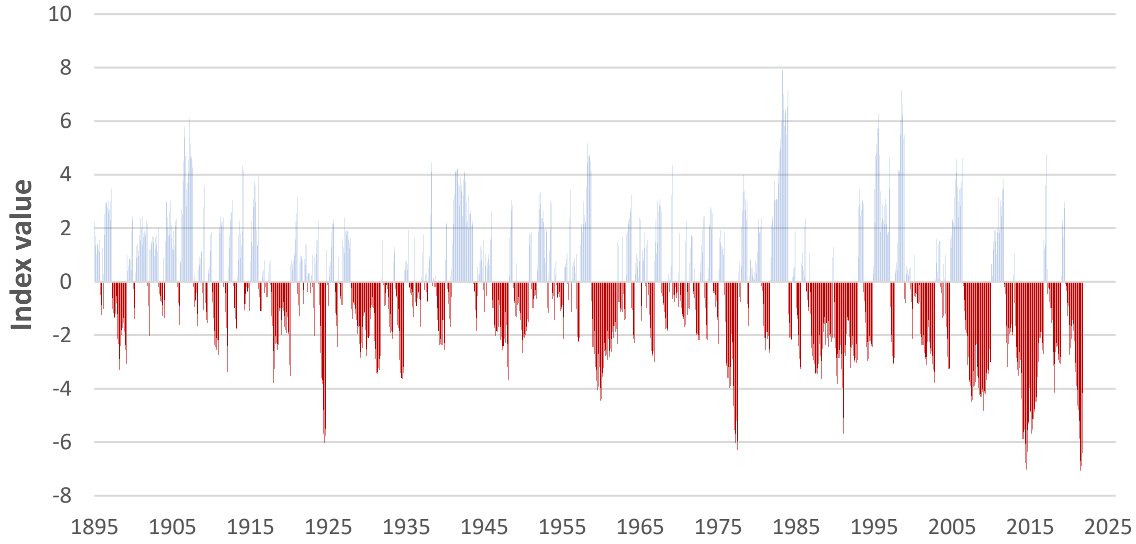

Northeast
Precipitation, inches
variability
120
80
40
0
3
2
1
0
Sierra
precipitation, inches
variability
Sacramento-Delta
precipitation, inches
variability
2
1.5
1
0.5
Central Coast
precipitation, inches
variability
San Joaquin
precipitation, inches
variability
South Coast
precipitation, inches
variability
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995
2005
2015
2025
precipitation
average
variability


South Interior
Mojave
Sonoran
precipitation, inches
variability
120
80
40
0
3
2
1
0
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
1995
2005
2015
2025
precipitation
average
variability

DROUGHT

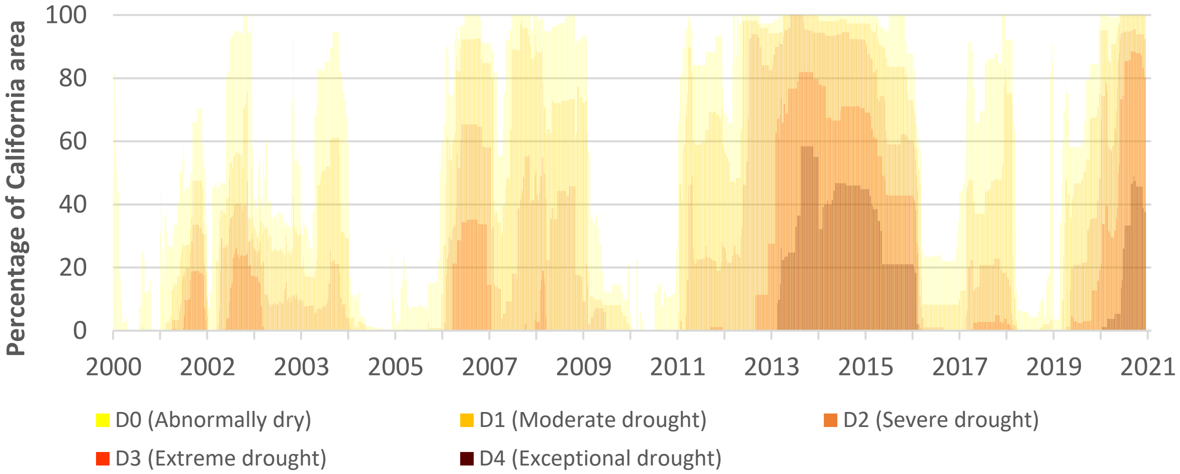
California has become increasingly dry since 1895. Statewide drought conditions by the end of the 2021 water year were comparable to those experienced during 2012 to 2016, the most severe drought since instrumental records began. The area of California land affected by extreme drought during the 2021 water year was larger compared to 2012 to 2016.

Figure 1 California Palmer Drought Severity Index (monthly, January 1895-October 2021)



Source: NOAA, 2021

Figure 2. Percentage of California land area in drought (2000 to 2021)*



Source: National Drought Mitigation Center (NDMC), 2021a

**Based on weekly assessments of drought intensity published as the U.S. Drought Monitor.*
Note: Category D0 designates abnormally dry conditions, not actual drought.

What does the indicator show?

Droughts refer to periods of unusually dry weather that last long enough to cause a shortage of water (IPCC, 2014). Figures 1 and 2 show values for two metrics of drought: the Palmer Drought Severity Index (PDSI) and the percentage of the land area designated by the U.S. Drought Monitor (USDM) in different drought categories. Developed in the 1960s, the PDSI is universally used and measures the relative dryness of a region by incorporating readily available temperature, precipitation, and soil moisture data (NDMC, 2021b; WMO and GWP, 2016). The newer USDM is a more comprehensive percentile-based drought metric that incorporates soil moisture, streamflow, and precipitation indicators, along with PDSI and local observations and experts' best judgment (NDMC, 2021a). Both the PDSI and the USDM track drought conditions in natural (unmanaged) water systems, and thus directly reflect patterns related to a changing climate. In addition, these indices have direct applicability to activities that rely on unmanaged water supplies, such as dryland farming and livestock grazing.

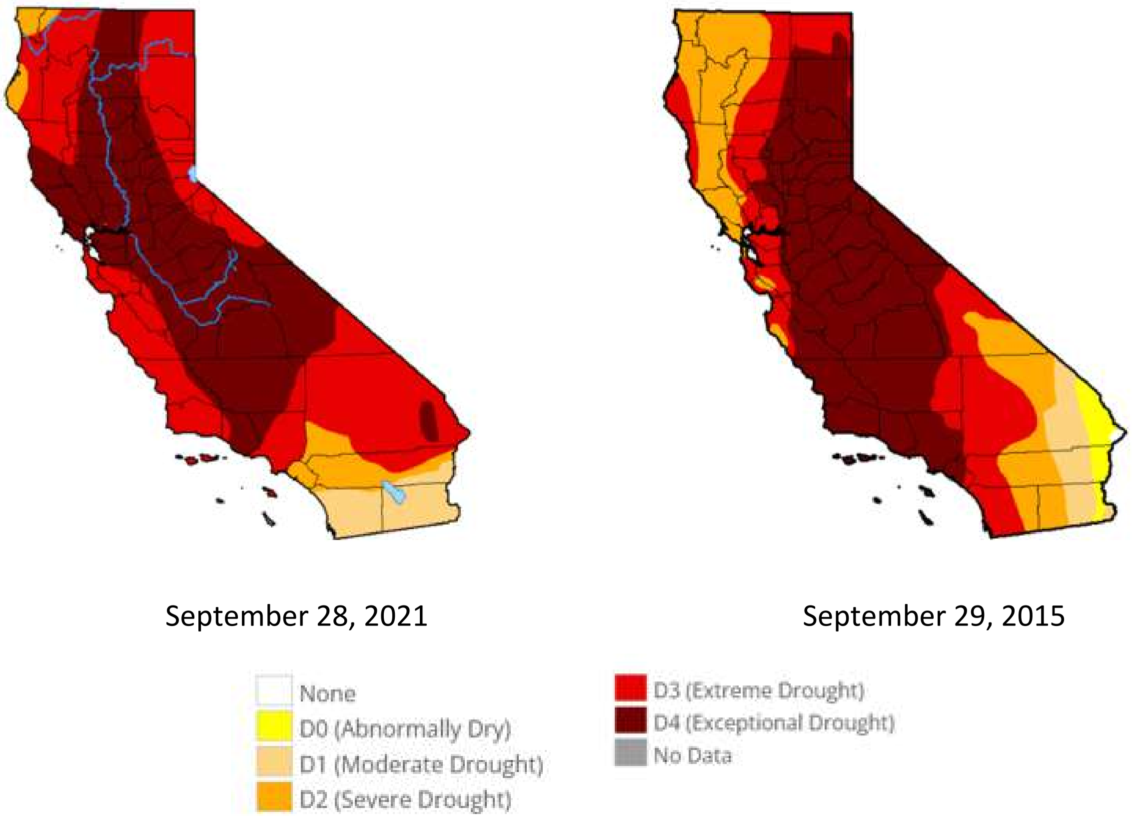
Figure 1 shows PDSI values since 1895: positive values (blue bars) indicate "wet" years; negative values (red bars) are "dry" years. Values at or below -3 represent severe drought. Values below -6 represent very extreme drought. From 2012 to 2016, California experienced the most severe drought since instrumental records began in 1895 (AghaKouchak et al., 2014; Diffenbaugh et al., 2015; DWR, 2021a; Harootunian, 2018; Griffin and Anchukaitis, 2014; Robeson, 2015; Swain et al., 2014; Williams et al., 2015). It was possibly the most severe for a millennium or more (Griffin and Anchukaitis, 2014; Robeson, 2015). The 2012-2016 drought in California ended with unusually high precipitation in 2017. Drought conditions began developing again in early 2020 and remained through the 2021 water year (October 2020 to September 2021); drought conditions have continued into the 2022 water year. This coincided with a period of anomalously warm temperatures and low precipitation. California's other major droughts occurred from 1929-1934, 1976-1977, and 1987-1992 (DWR, 2015).

Figure 2 shows the percentage of land area in California impacted by different levels of drought severity since 2000 according to the USDM. The index uses five "dryness" categories, from least intense ("D0, abnormally dry" but not considered drought) to most intense ("D4, exceptional drought"). Geographically, the 2012-2016 drought affected the entire state, with more than two-thirds of California experiencing extreme or exceptional drought conditions during that time. During the 2021 water year, at least 90 percent of the state was under severe drought for 22 weeks, during which at least 85 percent was under extreme drought (for 17 consecutive weeks), and at least 45 percent under exceptional drought (for 10 weeks).

The maps in Figure 3 compare the intensity of the drought at the end of the 2021 and the 2015 water years (NDMC, 2021a). In September 2021, the entire state was in drought, with 88 percent experiencing extreme to exceptional drought. In September

2015, 97 percent of the state was experiencing drought, with 71 percent in the "extreme" to "exceptional drought" categories.

Figure 3. Drought intensity in California: Comparison of conditions at the end of the Water Year, 2021 vs. 2015



September 28, 2021

September 29, 2015

Source: NDMC, 2021a

Why is this indicator important?

Droughts have major environmental, social, and economic repercussions, affecting water availability for human use, such as urban uses (including drinking water supply and industrial uses), agriculture, hydroelectricity generation, and ecosystems (DWR, 2015). The unprecedented drought of 2012-2016 led to significant and widespread impacts across the state, underscoring the need to prepare for drought's broad and devastating effects. These impacts include widespread tree mortality, greater wildfire activity, threatened fish populations, and harmful algal blooms in freshwater bodies. In addition, drought challenges water management systems by exacerbating drinking water shortages, further reducing water deliveries to farmers, and increasing groundwater pumping (CNRA, 2021). The impacts of drought on natural systems, managed water systems, and human health are discussed below.

Natural systems

Forests and aquatic ecosystems are especially vulnerable to the impacts of drought. The record warmth and low stream flows during the 2012-2016 drought put threatened, endangered, and culturally and economically important salmon and steelhead populations, already in decline due to other stressors, at risk (CNRA, 2021; Hanak et al., 2020). Widespread tree mortality, conversion of forests to shrubland and grassland, and changes in habitat range are some ways in which drought has impacted vegetation in California (see the *Changes in forest and woodlands* and *Forest tree mortality* indicators). Dead or dying vegetation increases the risk of wildfires: for example, the unusually high tree mortality seen during the 2012-2016 drought, which was caused by water stress, created a massive fuel load (see *Wildfires* indicator).

Figure 4. Southwestern willow flycatcher

Photo: USGS.
Source: Pala Tribe, 2022

The drying of riparian habitats threatens species dependent on these habitats, including birds such as the southwestern willow flycatcher (*Empidonax trailii extimus;* Figure 4). These songbirds were once abundant in nearly all shrubby riparian areas throughout California but have sharply declined statewide over the past several decades. In the Sierras, for instance, the number and density of willow flycatcher territories declined between 1997 and 2019 at a local watershed (Loffland et al., 2022). In addition, the Pala Band of Mission Indians in Southern California reports that these songbirds have not been seen on their land since 2013, citing drought stress and riparian habitat loss as likely factors of this local extirpation (Pala, 2019), with the latter a primary factor for the decline of this species statewide. Dams, water diversion for agriculture, and groundwater pumping all have altered streamflow, affecting riparian vegetation. Aside from drought, other factors that have impacted riparian habitats include livestock grazing, off-road vehicle use, increased fires, and urban development (NPS, 2016).

Many of the impacts of drought on California's ecosystems disproportionately affect people who depend on these diverse natural resources. People most reliant on annual rainfall usually feel the impacts of drought first. A single dry year can impair activities like dryland farming or livestock grazing that depend on unmanaged water supplies (DWR, 2015). Drought impacts on local habitats place additional burdens on rural populations that depend on them for food, firewood, or their livelihood (Roos, 2018; SWRCB, 2021a). Furthermore, the loss of culturally significant animals and plants can have profound impacts on Tribes who rely on them for traditional foods, medicine, and cultural practices.

Drought impacts on plant and animal species important to California Tribes include:

- Reduced deer and Bighorn sheep on Tribal lands, hunted for food (Big Pine Paiute and Pala, 2022)
- Loss of Clear Lake hitch, a ceremonial food source (Big Valley Pomo, 2022)
- Declines in shrubs and reeds like tules, used in traditional ceremonies, for weaving and boat building, and as food (Big Valley Pomo, 2022)
- Declining numbers of trees like sugar pines (provide pitch for medicine, and roots for basketry) and coast live oak (source of acorns for food) (Karuk and Pala, 2022)

Managed water systems

Domestic water supply

Although drinking water shortages affected many local and regional water suppliers during the 2012-2016 drought, many large urban water districts with diversified water sources and stored supplies did not suffer major disruptions (Lund et al., 2018). Communities that were highly dependent on supply from a single source and had no connections with other water utilities experienced severe shortages. These included more than 100 small water systems and more than 2,000 domestic wells in some small, poor, rural communities, particularly in the Central Valley and the Sierra Nevada foothills (PPIC, 2016). These small communities – often communities of color – remain vulnerable (PPIC, 2021a).

In addition to water supply, droughts also compromise drinking water quality (Bell et al., 2018). Saltwater intrusion, for instance, can happen because of drought, sea-level rise, and changing water demands (US EPA, 2021). As discussed further below (see “Human health impacts”), pathogens in drinking water are another concern. Compounding this issue, low-income communities and people of color are disproportionately impacted by water quality even during normal (non-drought) years. An analysis of drinking water quality, accessibility, and affordability in California found that water quality is worse in low-income communities and that small drinking water systems face greater affordability challenges compared to larger systems (OEHHA, 2021a). In the San Joaquin Valley, for example, tens of thousands of people living in low-income unincorporated communities often lack access to safe drinking water. Most of the Central Valley’s residents who live in low-income unincorporated communities are Hispanic (London et al., 2018).

The rising cost of water services during droughts places an even greater burden on low-income households (Famiglietti, 2014; Feinstein et al., 2017; PPIC, 2021b). Issues of water affordability were exacerbated by the COVID-19 economic recession, when low-income families, women, African Americans, and Latinos were especially impacted by unemployment and underemployment (Bohn et al., 2020). A survey by the California Water Boards (December 2020) found that approximately 1.6 million households in California had water debt at an average amount of $500 per household. A state moratorium on water service shutoffs helped to ensure that homes and small businesses unable to pay their bills continued to have access to water (SWRCB, 2021b).

California's water utilities face fiscal challenges during major droughts and recessions when revenues decline (PPIC, 2021b). Exacerbating this issue, wildfires worsened by droughts can damage water utilities, as seen when the 2018 Camp Fire destroyed the water distribution system at Paradise in northern California (Chow et al., 2021).

Hydroelectric power generation
Drought also impacts the generation of hydroelectricity, a major source of power in California that depends on snowmelt runoff and rainfall. Reductions in hydroelectricity generation during the 2012-2016 drought increased state electricity costs and raised California's carbon footprint until a shift towards different renewable energy sources helped to offset the increased emissions (Gleick, 2016; Hardin et al., 2017; Herrera-Estrada et al., 2018; Szinai et al., 2020; Zohrabian and Sanders, 2018).

Agricultural water supply
As the 2012-2016 drought reduced water deliveries for agricultural use, farmers compensated by fallowing cropland (leaving cropland idle). More than 500,000 acres, or 6 percent of irrigated acreage, were fallowed in 2015. Additional economic impacts on California's agricultural sector from the 2012-2016 drought included abandoned orchards and vineyards and lost jobs; the livelihoods of many people dependent on seasonal farm jobs and agricultural goods and services disappeared (DWR, 2015; Howitt et al., 2014 and 2015; Lund et al., 2018; PPIC, 2016; Roos, 2018).

Along with fallowed land, farmers compensate for water shortages from droughts by pumping groundwater (Lund et al., 2018). Most groundwater in California gets used for agriculture, and to a lesser degree for urban and domestic supply (some communities rely solely on groundwater) and managed wetlands. From 1998 through 2018, groundwater levels decreased in approximately 65 percent of wells statewide (DWR, 2021b).

Overpumping of groundwater in the San Joaquin Valley has depleted the region's groundwater supply. Farmers first started pumping groundwater in the early 1900s. By 1970, about half of San Joaquin Valley experienced land subsidence (i.e., the land surface sinks). Some areas had dropped by as much as 28 feet. Reduced surface water availability during 1976-77, 1986-92, 2007-09, and 2012-2015 caused even more groundwater pumping. Worsening droughts will make it hard to achieve sustainable levels of groundwater by the early 2040s as required by the Sustainable Groundwater

Management Act passed in 2014. People in the San Joaquin Valley may need to permanently fallow 500,000 acres of land (Hanak et al., 2019).

Overpumping of groundwater also results in aquifer compaction, reducing its water-holding capacity, and land subsidence. Some of the most severe recorded land subsidence in history occurred in the western San Joaquin Valley near Mendota, where the land surface has subsided about 30 feet (NASA, 2016; Sneed et al., 2018). The photograph in Figure 5 shows the approximate height of the land surface in 1925 compared to much lower levels in 1955 and 1977 because of excessive groundwater pumping in the San Joaquin Valley. Surface water deliveries from the California Aqueduct replaced reliance on groundwater for irrigation, slowing subsidence showed over a large part of the affected area (Galloway et al., 1999) Land subsidence impacts infrastructure — including water conveyance systems, roads, railways, bridges — aquifer storage capacity, and land topography (USGS, 2017a and 2017b). Moreover, many rivers and wetlands that rely on groundwater for some or most of their flow suffer from groundwater overdraft that worsens during droughts (Hanak et al., 2020; Klausmeyer et al., 2018). Additional impacts of groundwater overuse, exacerbated by droughts, include dying crops, habitat loss, and species extinction (The Nature Conservancy, 2020).

Figure 5. Land subsidence in the San Joaquin Valley

Photo: USGS, 2017c

Land surface in the San Joaquin Valley subsided ~9 m from 1925 to 1977 due to aquifer-system compaction. Signs on the telephone pole indicate the former elevations of the land surface in 1925 and 1955 (Faletti RC, 2022).

Human health

Droughts adversely impact human health in a myriad of ways other than through impacts on drinking water (Bell et al., 2018). For instance, reduced water quantity during periods of drought decreases water flow and promotes the production of pathogens that favor warm, stagnant environments (Paz, 2015; see the *Vector-borne diseases* indicator). Consumption or contact with water containing pathogens, such as *Vibrio* species, may result in ear, eye, wound infections, diarrheal illness, and death (Trtanj et al., 2016). Reduced hand and food washing in response to the drought increased the risk of communicable diseases, such as enteric disease and influenza, and exposure to pesticide residues (CDC, 2016a and 2016b, 2017).

Drought also increases air pollution from wildfires and dust storms (DWR, 2015). Under dry conditions, winds tend to transport inhalable soil particles, leading to air quality concerns. In the Owens Valley, for example, where the soil is alkaline (Big Pine Paiute, 2022), and there has been a rise in the level of PM10 (Bishop Paiute, 2022) the Big Pine Paiute Tribe has reported eye, throat, and lung irritation during dust storms. The Tribe is concerned over the impacts of wind-blown dust on Paiute Tribal elders with lung issues and the growing number of cases of children with asthma and other breathing issues. Drought also stresses peoples' mental and emotional well-being (Barreau et al., 2017; CDC, 2016a and 2016b, 2017; Vins et al., 2015).

A visible surface water quality impact during the 2012-2016 drought came in the form of more frequent harmful algal blooms. These blooms appeared in freshwater bodies throughout the state, from the Klamath River in the north to Lake Elsinore and the Salton Sea in the south (CNRA, 2021). Certain bloom-forming organisms such as cyanobacteria, produce toxins that adversely impact people and their pets. In humans, exposure to these toxins can lead to a wide array of symptoms including skin rashes, blisters, vomiting, and abdominal pain (CWQMC, 2021; OEHHA, 2021b). In pets, exposure can be lethal (CNRA, 2021).

Exposures to the toxins can occur through consuming contaminated water and foods and by direct contact with water. Communities that rely on recreational water use to generate revenue from tourism and those who use freshwater bodies as drinking water sources are disproportionately affected. During periods of bloom, certain Tribes are unable to carry out cultural traditions or practices that involve immersion in, or other contacts with, water bodies. The Karuk's World Renewal Ceremonies in which the medicine man traditionally bathes and drinks Klamath River water overlaps annually with the highest levels of toxin in river water (Karuk, 2022). At Clear Lake, members of the Big Valley Band of Pomo Indians are prevented from spiritual activities, water immersion for ceremonies, using plants for ceremonies and basketry, and the collection and consumption of fish and other aquatic organisms when toxin levels are high (Big Valley, 2022). In addition, the Tribe has reported that clogged drinking water intakes in Clear Lake due to sludge induced by blooms, and that detection of toxins in raw water have led to additional operational and water treatment costs.

What factors influence this indicator?

Droughts are a naturally occurring feature of California's climate (DWR, 2021c). They are naturally influenced by modes of global climate variability such as the El Niño-Southern Oscillation, regional atmospheric pressure anomalies, and the frequency of landfalling "drought-busting" atmospheric rivers (Dettinger, 2013; Griffin and Achukaitis, 2014). Singular wet years composed of frequent landfalling atmospheric rivers can terminate persistent droughts (e.g., Dettinger, 2013; Hatchett et al. 2016). Historically, dry winters in California have been associated with a ridge of high atmospheric pressure off the west coast, and wet winters have been associated with a trough off the west coast and an El Niño event (Seager et al., 2015).

Droughts of the 21st century are hotter, longer lasting, and spatially larger than previous droughts (Crausbay et al., 2017). A growing body of evidence suggests that anthropogenic warming has increased the likelihood of extreme droughts in the state (AghaKouchak et al., 2014; Williams et al., 2015; Diffenbaugh et al., 2015; Shukla et al., 2015; Swain et al., 2014; Griffin and Achukaitis, 2014; Luo et al., 2017; Hatchett et al. 2016; Harootunian, 2018) and worldwide (Chiang et al., 2021). Atmospheric circulation patterns like those observed during California's most extreme dry and hot years have increased during recent decades (Swain et al., 2016). Climate change may be increasing the likelihood of the type of rare atmospheric events associated with the 2012-2016 drought (Swain et al., 2017; Cvijanovic et al., 2017). Notably, this was part of a larger drought across the southwestern United States that has been described as a "megadrought." Using a tree-ring reconstruction to extend summer soil moisture records back to 800 CE, investigators determined 2000-2021 to be the driest 22-year period in the region over this period. About 19 percent and 42 percent of the dryness in 2021 and in 2000-2021, respectively, were attributable to anthropogenic climate change (Williams et al., 2022). Climate change will continue to make dry and warm years happen more often (Diffenbaugh et al., 2015) and drought conditions will worsen (Underwood et al., 2018; Ullrich et al., 2018). Other ways climate change directly contributes to drought conditions include more variable but less frequent precipitation (Gershunov et al., 2019) and widespread snowpack decline (Siirla-Woodburn et al., 2021; see the *Snow-water content* indicator).

As temperatures warm, the atmosphere takes up more water from land through evapotranspiration (McEvoy et al. 2020; Pottinger, 2020). "Evaporative demand," often referred to as the "thirst" of the atmosphere, reflects maximum evapotranspiration assuming unlimited moisture supply and ambient atmospheric conditions. Almost all the western U.S. has seen a rise in the atmosphere's thirstiness since the 1980s when temperatures began to noticeably warm (Pottinger, 2020). During the 2021 summer and water year, the evaporative demand over much of California was higher than it had been over the last 40 years (NIDIS, 2021). A thirstier atmosphere also means California's big storms will get even bigger because more water will go into the atmosphere (see the *Precipitation* indicator for a discussion on atmospheric rivers, which also affect heavy precipitation). Altogether, projections of climate change suggest that California will experience a perennial drought for most of the year, interrupted periodically by large storms that produce heavy to extreme precipitation (Pottinger, 2020).

Regional variations such as geography and local climate patterns also determine the extent and severity of droughts. The 2012-2016 drought was more severe in southern California, which has displayed greater drying trends over the past century than in northern California (Dong et al., 2019).

Technical considerations

Data characteristics

PDSI identifies droughts by incorporating data on temperature, precipitation, and the soil's water-holding capacity. The metric takes into consideration moisture received as precipitation and moisture stored in the soil, while also accounting for potential loss of water due to temperature. It originally functioned to identify drought affecting agriculture but has since been used to identify drought associated with other types of impacts (WMO and GWP, 2016). PDSI is used to assess long-term drought patterns (NOAA, 2017).

The U.S. Drought Monitor provides a big-picture look at drought conditions in the United States. As previously mentioned, along with PDSI, metrics used in the U.S. Drought Monitor include soil moisture data, streamflow conditions, the standardized precipitation index, and blends of various drought indicators.

Strengths and limitations of the data

The PDSI and USDM as used in this report are not intended to gather information about water availability or delivery in California.

PDSI is considered a robust index of drought, universally used, and has been employed since the 1960s. However, PDSI assumes all precipitation comes as rain (Williams et al., 2015) and does not account for frozen precipitation or frozen soils very well (WMO and GWP, 2016). PDSI also does not provide information on human water demand, streamflow and reservoir storage, or groundwater accessibility (Williams et al., 2015). It represents drought conditions in natural (unmanaged) systems only.

The USDM is based on many types of data, including observations from local experts across the country, as well as information about reservoir storage. It can be used to identify likely areas of drought impacts but should not be used to infer specifics about local conditions.

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Impacts on Physical Systems

Physical systems include the ocean, lakes, rivers, glaciers, and snowpack that are part of the water cycle. Globally, warming temperatures have altered the water cycle, resulting in the decrease in Northern Hemisphere spring snow cover, a global retreat of glaciers, warming oceans, sea level rise, and reduced oxygen levels in ocean waters (IPCC, 2021).

In California, every aspect of the water cycle has been changing. With less precipitation falling as snow, less water is stored in the Sierra Nevada snowpack. Runoff from melting snow has historically accounted for approximately one-third of the state’s yearly water supply. A greater fraction of this runoff has been flowing earlier in the spring, diminishing the amount of water available from snowpack during the warmer summer months. These changes have tremendous implications for California’s water, for freshwater habitats, and for forest ecosystems—including increasing the risk of wildfires. Reduced stream flows and warmer air temperatures lead to warmer water temperatures. The Salmon River, Lake Tahoe and other rivers, streams and lakes in the state are warming.

Among the most visible indicators of climate change, California glaciers continue to shrink. Water from melting mountain glaciers and ice sheets is the main source of global sea level rise today (IPCC, 2019; Slater et al., 2020). Heat-driven expansion of ocean waters has also been a major contributor (IPCC, 2019). Consistent with global observations, sea levels are rising along most of California’s coast, threatening coastal infrastructure and communities – where flooding hazards pose disproportionate impacts on low-income households – and ecosystems (CCC, 2015; LAO, 2020).

The oceans have absorbed over 90 percent of the increased heat energy on the Earth over the past 50 years (Jewett and Romanou, 2017; NOAA, 2021; Rhein et al., 2013). Along California, coastal waters have warmed over the past century, particularly off Southern California. An unprecedented marine heatwave off the California coast from 2014 to 2016 led to a wide range of effects on marine life and significant economic loss. Along with warmer ocean temperatures, the associated reduction in dissolved oxygen levels and ocean acidification present serious threats to global marine ecosystems.

INDICATORS: IMPACTS ON PHYSICAL SYSTEMS

Snow-water content *(updated)*
Snowmelt runoff *(updated)*
Glacier change *(updated)*
Lake water temperature (*updated*)
Salmon River water temperature *(new)*
Coastal ocean temperature *(updated)*
Sea level rise *(updated)*
Dissolved oxygen in coastal waters *(updated)*

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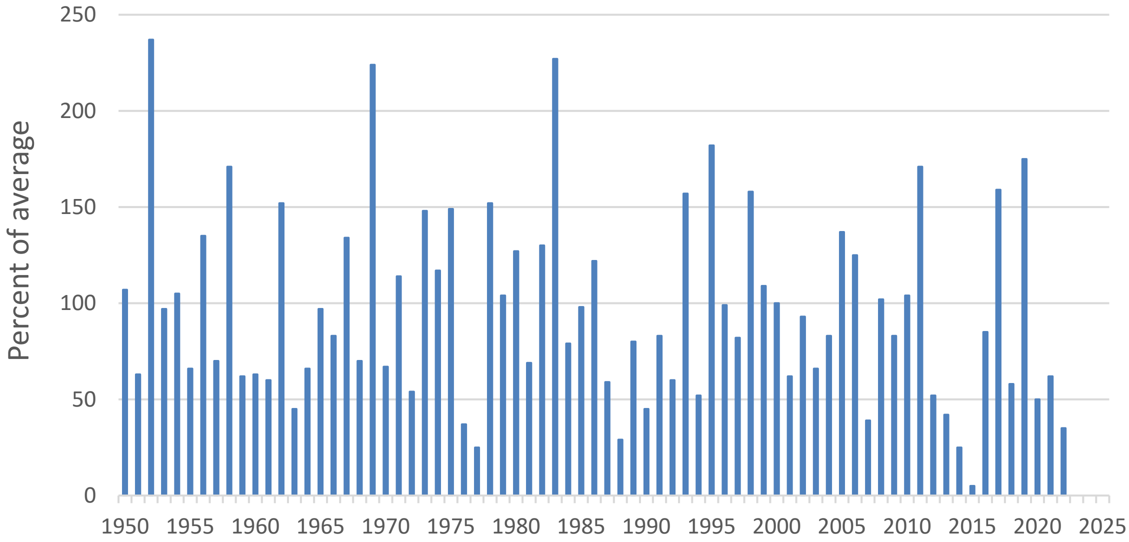
SNOW-WATER CONTENT

The amount of water stored in the state's snowpack varies greatly from year to year, reflecting the variability in the amount and form of precipitation over California's mountain areas. Average statewide snow-water content—a measure of the amount of liquid water contained in the snowpack—is about 28 inches. It has ranged from a high of about 240 percent of average in 1952 to a record low of 5 percent in 2015. In 2022, snow-water content was 35 percent of average.

Figure 1. Statewide April 1 snow-water content based on snow courses*
(Percent of average)



Source: DWR, 2022a

*Snow courses are permanent locations where snow-water content is measured by weighing cores of snow pulled from the entire depth of the snowpack at a given location. The measurements represent snowpack conditions at a given elevation in a given area.

What does the indicator show?

Since 1950, statewide snow-water content has been highly variable, ranging from more than 200 percent of average in 1952, 1969 and 1983, to 5 percent in 2015 during the multi-year drought (2012 to 2016) (Figure 1). The past decade included years that were among the lowest (2013, 2014, 2015 and 2022) and the highest (2011, 2017, 2019) on record. In 2022, snow-water content was 35 percent of average. The historical average snow-water content on April 1, based on the water years 1991-2020, is about 28 inches.

Snow-water content – also referred to as snow water equivalent – is the amount of water contained in snowpack. It represents the depth of water that would cover the ground if the snow cover was in a liquid state (NWS, 2018). It is traditionally measured by weighing the mass of a core of snow — from snow surface to soil — collected by an observer (snow gauger) in the field. The weight of snow is a measure of how much liquid water would be obtained by melting the snow over a given area. Manual measurements are taken near the first of the month starting about January 1 and ending in May. The most important one is taken around April 1, near the time when the snowpack has historically been deepest on a monthly scale. The statewide values are based on measurements taken at about 260 snow course stations from the Trinity Alps and Mount Shasta in northern California, and throughout the Sierra Nevada down to the Kern River basin in the south (see map in *Technical Considerations*).

Why is this indicator important?

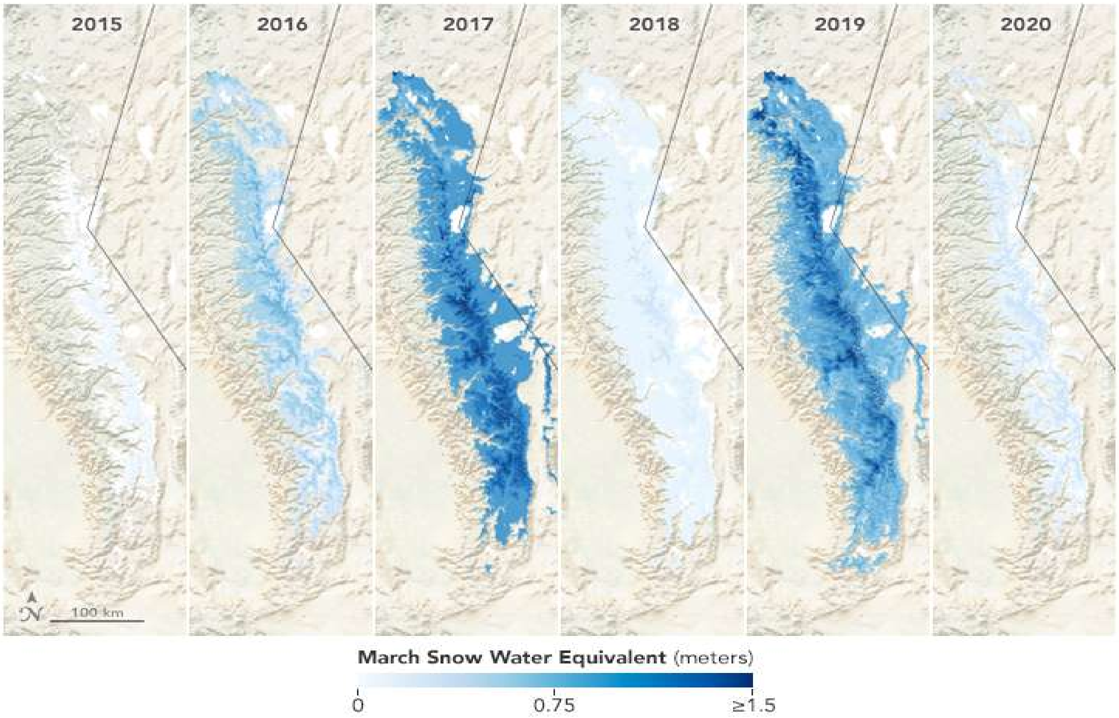
This indicator tracks how much water is locked up in the state's snowpack, which accumulates from October through March in the Sierra Nevada and southern Cascade Mountains. Although some of this water will be lost to direct evaporation and transpiration, most will be available to percolate into soils or run off into streams and rivers as temperatures rise. Sierra Nevada snowpack provides the primary source of streamflow in the Central Valley. The snowpack supplies water to meet human needs such as domestic and agricultural uses and hydroelectric production. It also supports ecosystems, for example by providing suitable aquatic habitat and moisture for forest vegetation. Snowpack is also vital for winter recreation and tourism (Hatchett and Eisen, 2018).

Historically, California's snowpacks contained the most water (about 15 million acre-feet) between mid-March and mid-April of each year, and the Sierra Nevada snowpack added about 35 percent to the reservoir capacity available in the state. While the date of maximum snow-water content may vary from year to year and place to place, measurements taken on April 1 have been used to estimate how much water stored in the state's snowpacks will be released as snowmelt later in the year.

Monitoring snowpack is key to managing both the state's water supplies and flood risks. California's water managers have developed a strategy of maintaining empty space in major reservoirs during winter, so that flows can be captured or at least reduced during large storms to prevent floods. By about April 1, flood risks generally decline considerably as large winter storms stop impacting California. At this time, reservoir managers change strategies and instead capture and store as much streamflow as possible in reservoirs for the summer when water demands are highest. This strategy works primarily because, during winter, the state's snowpacks are holding copious amounts of the winter's precipitation in the mountain watersheds, only releasing most of it as runoff after about April 1. In big snowpack years like 2017 and 2019, some of the early portion of the snowmelt is released in March and April prior to the normal peak snowmelt. The gradual release of snowmelt during the spring precludes the need for overly high-volume reservoir releases later in the runoff season. Forecasts of runoff volume and timing based on snow-water content data are a critical tool to guide reservoir operations. (Forecasts are published by the Department of Water Resources in Bulletin 120)

The series of maps in Figure 2 showing early March snowpack clearly illustrate the variability over the last six years in the Sierra Nevada: record low snowpack in 2015, an average year in 2016, two of the highest snowpack years in 2017 and 2019, and two years at about 60 and 50 percent of average – 2018 and 2020, respectively.

Figure 2. Snow-water equivalents across the Sierra Nevada in early March, 2015 to 2020



Source: NASA 2020

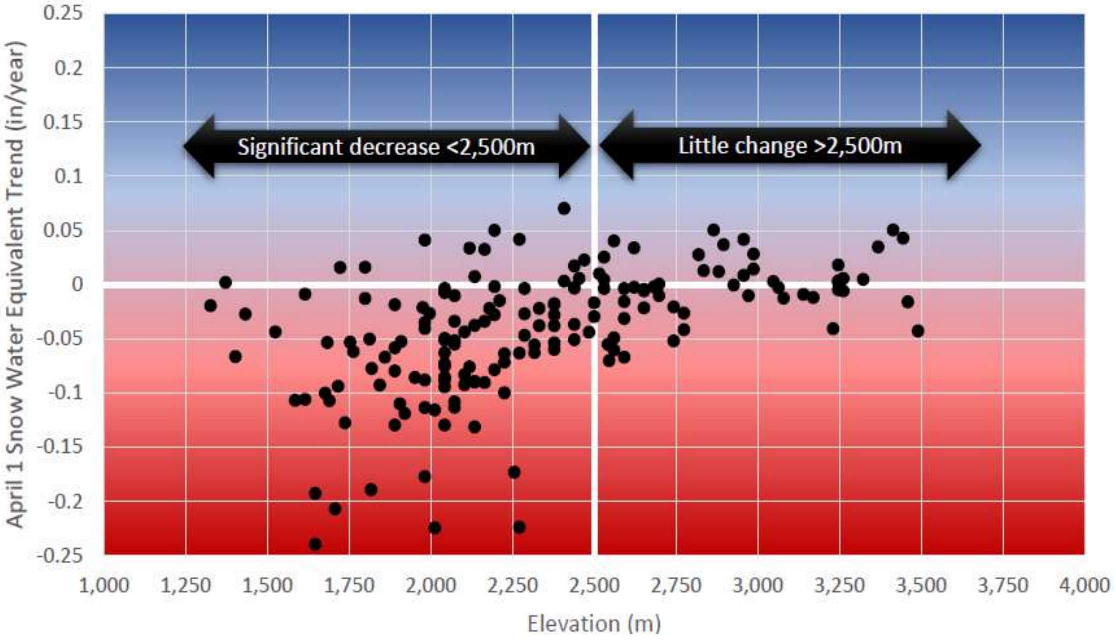
Maps developed by the University of Colorado's Center for Water, Earth Science, and Technology. Data are derived from ground-based data, computer models, and satellite imagery. They incorporate a data set from the [Jet Propulsion Laboratory](#) called the MODIS Snow Covered Area and Grain-size (MODSCAG), which uses data from NASA's Terra satellite to determine properties of the snow—things like the area covered, grain size, and albedo—that are useful for deriving accurate estimates of snow-water equivalent.

Adaptive strategies employing advanced observations, forecasts, and system management perspective are needed to maintain the functionality of the existing water management infrastructure in the face of climate change. Current management practices for water supply and flood management in California will need to be revised for a changing climate (Siirila-Woodburn et al., 2021). This is in part because such practices were designed for historical climatic conditions, which will continue to change as the climate warms. Adapting to a warming climate will bring numerous challenges to both supply and demand sides (Sterle et al., 2019), however planning for a future characterized by less water availability is prudent based on the state of climate science.

What factors influence this indicator?

Factors that affect snow-water content include winter and spring precipitation, air temperature, and elevation. Colder air temperatures at higher elevations generally mean higher snow accumulations compared to lower elevations. The influence of elevation is evident in an analysis of snowpack trends in the Sacramento River, San Joaquin River, and Tulare Lake Basins (see Figure 3; Riddlebarger et al., 2021).

Figure 3. 60-year trends in April 1 snow water equivalent at Sierra Nevada and Cascade Mountain snow courses, by elevation



Source: Riddlebarger et al., 2021

The 60-year trend at each snow course is represented by each dot. Over this period, snowpack has declined at 78 percent (129 of 166) of the snow courses: snow courses at elevations below 2,500 meters showed negative trends at an overall average of --0.07 inch/year; at higher elevations, the trends clustered between -0.05 and +0.05 inch/year.

The snow courses that make up the northern Sierra group in Figure 2 are at lower elevations (average 6,900 feet) compared to the southern group (average 8,900 feet). In the past 70 years, the proportion of precipitation as snow has decreased at the rate of 4 percent per decade over lower and middle elevation regions of the northern Sierra Nevada, while the highest elevations of the southern Sierra Nevada, where temperatures remain at or below 0°C during winter and spring, showed no declines (Lynn et al., 2020). In an analysis of data on April snow-water content and temperature from 1985 to 2016, the northern Sierra Nevada was found to be more vulnerable to warming than the southern region (Huning and AghaKouchak, 2018). Over the past decade, the average snow level (the altitude where precipitation changes from snowfall to rain) along the western slope of the northern Sierra Nevada has risen over 1,200 feet (Hatchett et al., 2017).

A study of trends in the Sierra Nevada snowpack found warm daily maximum temperatures in March and April to be associated with a shift toward earlier timing of peak snow mass by 0.6 day per decade since 1930; this earlier trend is associated with snow melting earlier, which also results in trends toward lower snow-water equivalent (Kapnick and Hall, 2010). Under climate change, warming is likely to lead to less snowpack if precipitation does not increase too markedly (Knowles and Cayan, 2004). If precipitation increases, snow-water content could increase in those areas above the retreating snowlines that are still cold enough to receive snowfall; if precipitation decreases, snow-water content may be expected to decline even faster than due to warming alone.

The term “snow drought” refers to anomalously low snow-water content (Cooper et al. 2016). Snow drought occurs under conditions that reflect either a lack of winter precipitation (“dry” snow drought) or near-normal winter precipitation when temperatures prevent accumulation of snowpack (“warm” snow drought) (Harpold et al., 2017). During water years 1951 to 2017 in the northern Sierra Nevada, snow droughts have originated and evolved in various ways, including from extreme early season precipitation, frequent rain-on-snow events, low precipitation years, lower fractions of precipitation falling as snow, and midwinter peak runoff events (Hatchett and McEvoy, 2018). Consecutive snow drought years, which currently occur in the western United States at about 7 percent of the time, are projected to become more frequent in the mid-21st century, occurring at about 42 percent of the time under a high greenhouse gas emissions scenario (Marshall et al., 2019).

The record low snowpack in 2015 was accompanied by the warmest winter temperatures as well as the fifth lowest precipitation volume since 1950 (see *Air Temperature* and *Precipitation* indicators). In addition to enhancing the likelihood of rain instead of snow, warm temperatures increase the frequency of melt events, leading to a reduction of snow-water content. Across western North America, early snowmelt has increased at over one-third of the long-term snow stations studied; at these locations, snowmelt occurred before peak snow accumulation (Musselman et al., 2021). The same study found decreased snow-water content at about 11 percent of snow stations. Snowmelt trends were found to be highly sensitive to temperature, while trends in snow water equivalent were more sensitive to variability in precipitation.

Across the western United States, a broad pattern of declining snowpack has been reported (e.g., Siirila-Woodburn et al. 2021; Musselman et al., 2021; Mote et al., 2018; Mote, 2003; Barnett et al., 2008). Declining trends have been observed across all months, states, and climates, but are largest in spring, in the Pacific states, and in locations with mild winter climate (Mote et al., 2018). By removing the influence of natural variability, investigators showed a robust anthropogenic decline in western U.S. snowpack since the 1980s, particularly during the early months of the accumulation season (October–November) (Siler et al., 2019).

To a lesser extent, snow-water content may be influenced by the amount of solar radiation that falls on the snowpack in each season, which, in turn, depends on cloudiness and timing of the beginning of the snowmelt season (Lundquist and Flint, 2006). Cloudiness decreases solar radiation on the snowfields, and would tend to result in less wintertime snowmelt and thus more snow-water content left by April 1 (the opposite would occur if cloudiness declines in the future).

A potential confounding factor in the variation and trends in snowpack is the effect of dust and air pollutants (including black carbon, a component of soot) on both the initial formation of mountain snowpack and on snowmelt timing. Field measurements and modeling have shown that the presence of dust in the atmosphere, including dust from Asia and the Sahara carried to California by high-altitude winds, may increase snowfall over the Sierra Nevada by serving as ice nuclei, which in turn could contribute to increased snowpack (Ault et al., 2011; Cremean et al., 2013). Recent studies in the Colorado River Basin have helped to quantify important influences on snowmelt timing and, ultimately, amounts that are due to springtime snow albedo (reflectivity) changes associated with dust (mostly from within the region) falling onto snow surfaces across the Western US (e.g., Painter et al., 2010). Black carbon, which in burned forests is deposited onto the snow surface, has been measured in the Sierra Nevada snowpack at concentrations sufficient to increase surface temperatures and increase snowmelt (Hadley et al., 2010). These factors likely play roles in past and future variations of April 1 snowpack amounts, but the long-term past and future trends in these additional factors in California remain largely unknown at present.

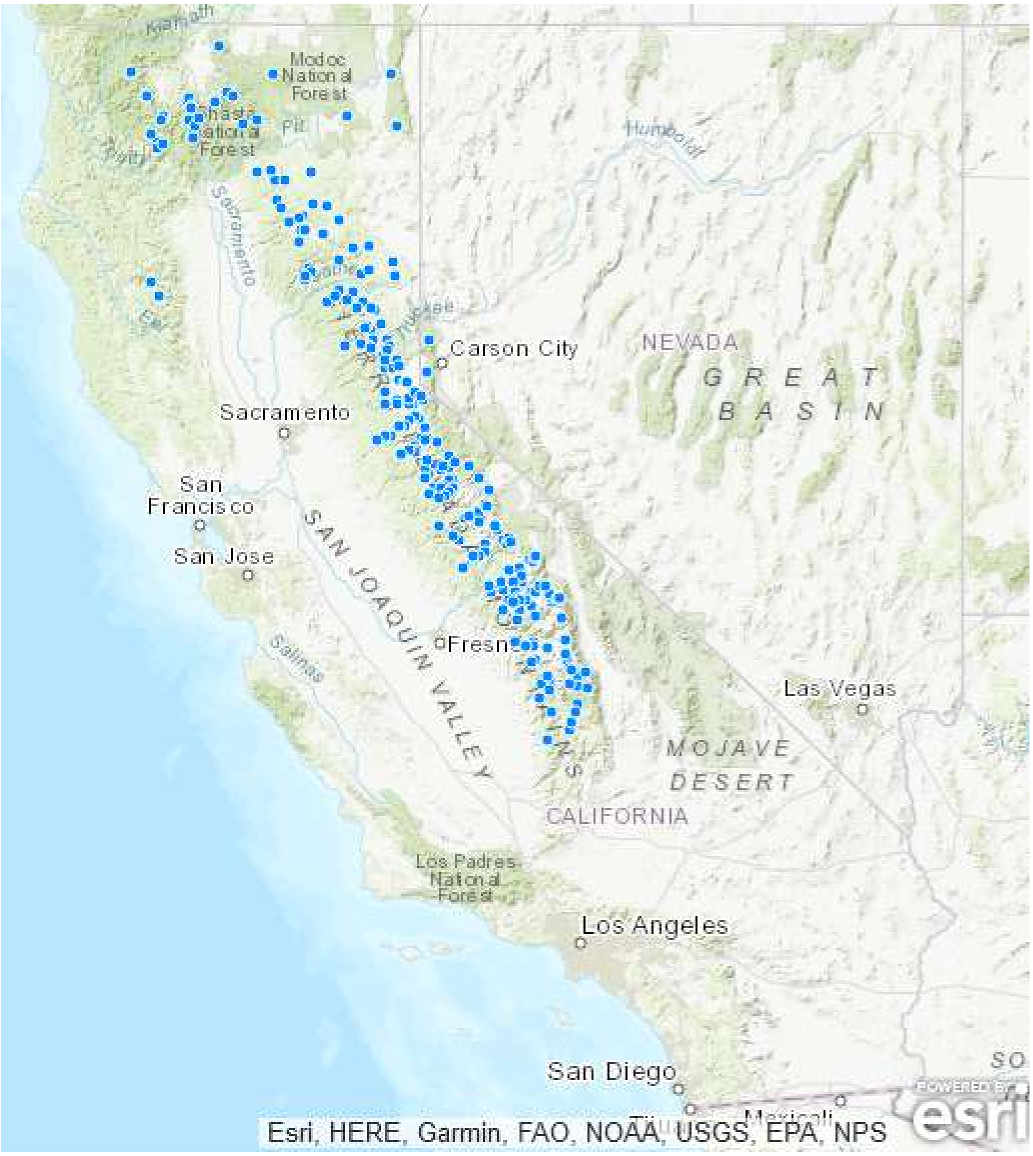
Technical Considerations

Data characteristics

Statewide snow-water content is based on observations from permanent snow courses. At these locations, snow-water content is measured by weighing cores of snow pulled from the whole depth of the snowpack at a given location. Since the 1930s, within a few days of the beginning of each winter and spring month, measurements have been taken along snow course locations that represent snowpack conditions at a given elevation in a given area.

Measurements are taken by skiing or flying to remote locations and extracting 10 or more cores of snow along ¼ mile-long pre-marked “snow course” lines on the ground. The depth of snow and the weight of snow in the cores are measured. The weights are converted to a depth of liquid water that would be released by melting that weight of snow, and the results from all the measurements at the snow course are averaged to arrive at estimates of the snow-water content at that site (Osterhuber, 2014). More than 50 state, federal and private entities pool their efforts in collecting snow data from over 250 snow courses in California (see Figure 4 for locations).

Figure 4. Location of snow courses



Source: DWR, 2022b

The map shows permanent snow courses where snow-water content is measured during regular snow surveys (more details in text).

Data from monthly snow surveys are supplemented by daily information from an automatic snow sensor network (often called snow pillows), developed and deployed over the last 30 years. They serve as a valuable check on the representativeness and accuracy of the snow-course measurements. The snow sensors measure the accumulation and melting cycles in the snowpack, providing data on the effect of individual storms or hot spells. In addition to tracking changes during the snow accumulation season, snow sensor data help greatly in forecasting water volumes involved in the late-season filling of reservoirs. There are approximately 130 snow sensor sites from the Trinity Alps to the Kern River, with 36 sites included from the Trinity area south to the Feather and Truckee basins, 57 sites from the Yuba and Tahoe basins to the Merced and Walker basins, and 36 sites from the San Joaquin and Mono basins south to the Kern basin.

Snow-water content data for snow courses and snow sensors can be downloaded from the Department of Water Resources' California Data Exchange Center.

Strengths and limitations of the data

The measurements are relatively simple, and the methods have not changed since monitoring started. Averaging of the 10 or more measurements at each course yields relatively accurate and representative results for each survey.

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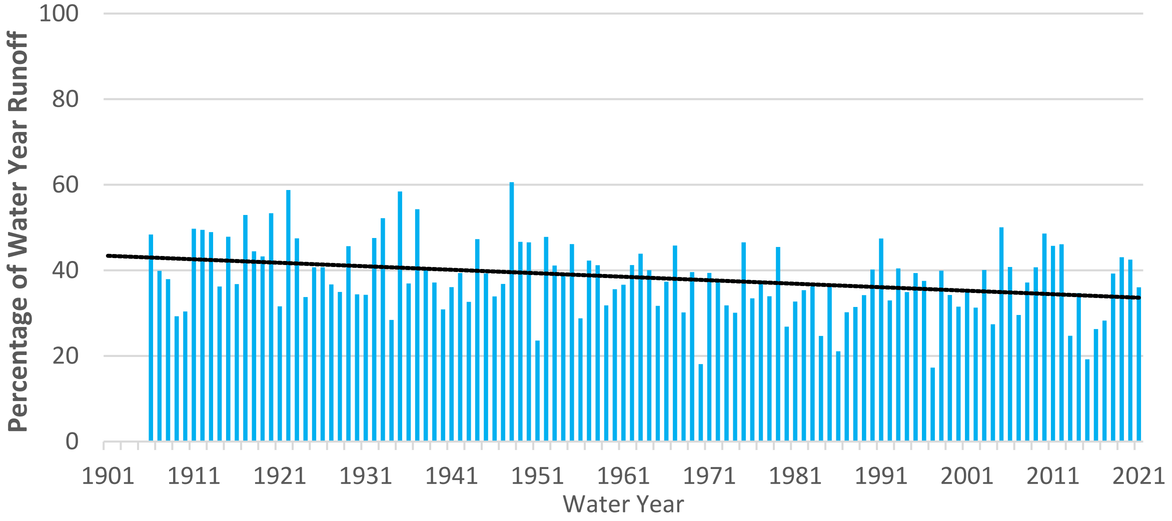
SNOWMELT RUNOFF

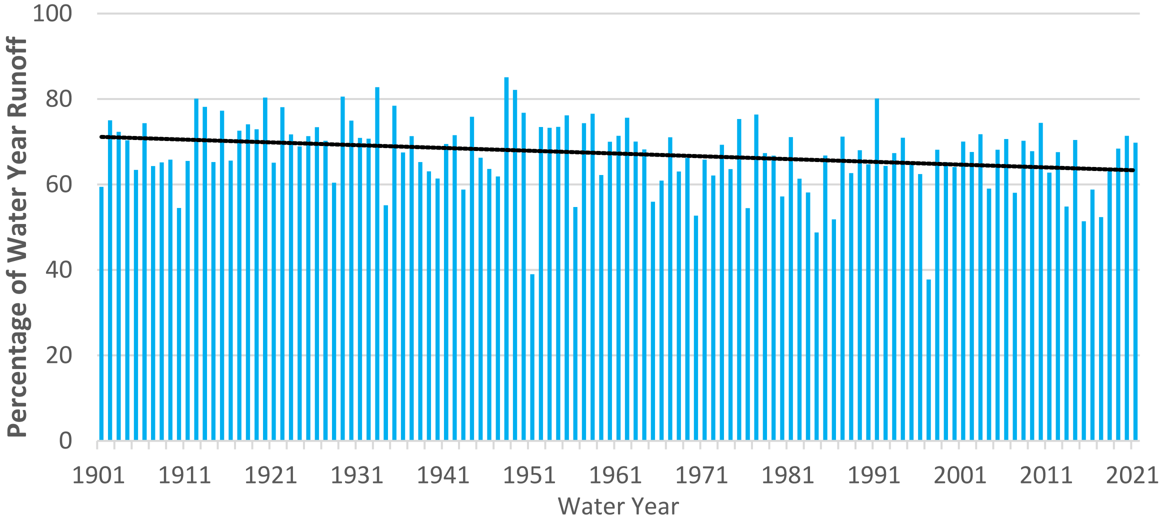
The fraction of snowmelt runoff from the Sierra Nevada into the Sacramento River and the San Joaquin River hydrologic regions between April and July relative to total year-round water runoff, while highly variable, has declined over the past century.

Figure 1. Sacramento River spring runoff
(April-July runoff as a percentage of total water year runoff)



Source: DWR, 2022

Figure 2. San Joaquin River spring runoff
(April-July runoff as a percentage of total water year runoff



Source: DWR 2022

What does the indicator show?

The fraction of annual unimpaired snowmelt runoff that flows into the Sacramento River and the San Joaquin River between April and July ("spring") has decreased by about eight and seven percent per century, respectively, while showing large year-to-year variability. Figures 1 and 2 show this spring fraction as a percentage of total runoff for the entire water year, the period from October through the following September. In the Sacramento River, three of the last ten years ranked among the ten lowest in the percentage of total water year runoff occurring in the spring: 2015, 2013 and 2016 were third, seventh and eighth lowest, respectively. In the San Joaquin River, two of the last ten years had among the lowest in percentage of total runoff in the spring (2015 and 2017 were ranked fourth and sixth lowest, respectively); notably, 2015 recorded the lowest, and 2017 the fifth highest, spring runoff volumes. The 2015 water year also saw the lowest snowpack on record. There is no significant trend in total water year runoff into either river, just a change in the timing: i.e., an increasingly larger proportion of runoff occurring earlier in the spring.

Average values for the percentage of runoff in the spring are higher for the “snow-dominated” San Joaquin River, compared to the “rain-dominated” Sacramento River – about two-thirds and one-third of the total water year runoff, respectively (DWR 2021). This difference is explained further in *What factors influence this indicator?*

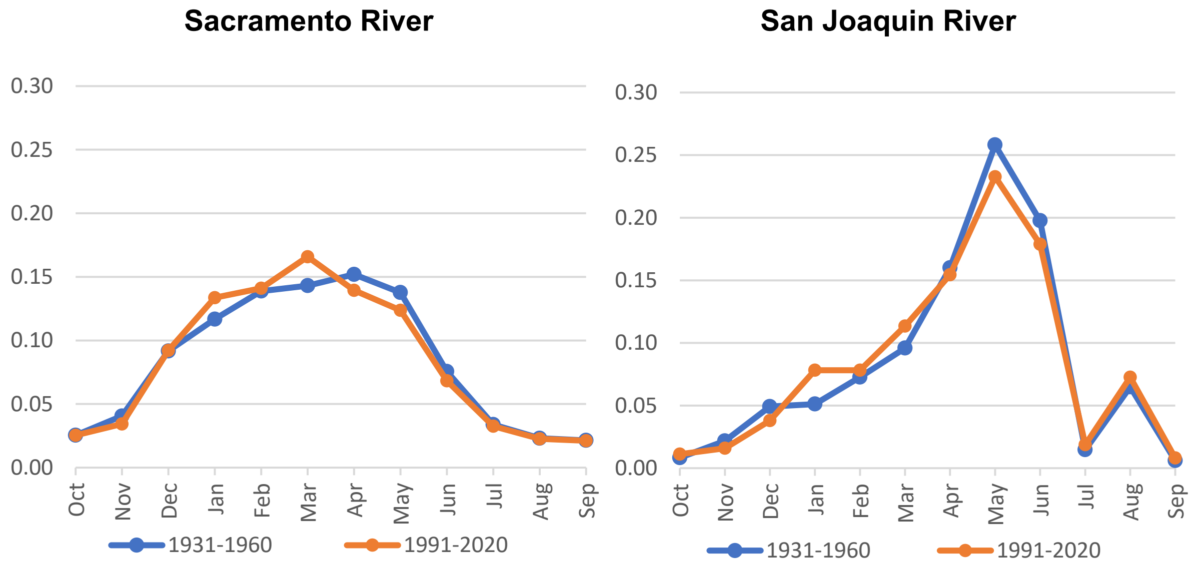
Why is this indicator important?

The Sacramento River and the San Joaquin River, the two largest river systems in California, serve as the major sources of water for the state. Snowmelt runoff into streams and rivers supplies water to meet human needs and to support ecosystems. In the Sierra Nevada and southern Cascade Mountains, snow accumulates from October through March (see *Snow-water content* indicator), preserving much of California’s water supply in cold storage. As temperatures warm in the spring and there is more daylight and solar radiation, the snowpack melts, releasing runoff, typically from April through July.

Spring runoff averages around 14.1 million acre feet (18 billion cubic meters) water, which is about 35 percent of the usable annual supply for agriculture and urban needs (Roos and Anderson, 2006; DWR, 2021). Spring runoff data, along with related snowpack information, are used for water supply and flood forecasting. (Forecasts of seasonal runoff are published weekly by the Department of Water Resources in Bulletin 120.

Much of the state’s flood protection and water supply infrastructure was designed to capture high volumes during winter storms to prevent flooding. In the spring, as much streamflow as possible is captured and stored in reservoirs to be delivered for multiple uses during the drier summer and fall months. This infrastructure was designed and optimized for historical conditions. Changing patterns of spring runoff, such as in the timing of peak monthly runoff, can strain the current water management system, requiring adjustments in water storage and flood strategies. In the last 30 years, peak runoff has shifted earlier by a month on the Sacramento River (March instead of April), compared to earlier years in the record (1931-1960); no such shift occurred in the San Joaquin River (see Figure 3).

Figure 3. Monthly average runoff: historical (1931-1960) vs. current (1991-2020)



Source: DWR, 2022

A comparison between historical and current 30-year averages of the fraction of total water year runoff that occurs each month shows peak runoff occurring earlier in recent years in the Sacramento River, while the San Joaquin River is largely unchanged.

The earlier onset of spring runoff generally results in less available water in warmer months for domestic and agricultural uses, hydroelectric power production, recreation and other uses. This results in lower soil moisture, which could stress vegetation, lead to tree deaths (see *Forest tree mortality* indicator), and increase wildfire risk (see *Wildfires* indicator). Changes in the amount and the timing of snowmelt runoff can alter streamflow and impair cold water habitats, particularly for salmonid fishes (Roos, 2000; Halofsky, 2021). Runoff during rain-on-snow events – when rain falls on existing snowpack – has been associated with mass erosion of slopes, damage to riparian zones, and downstream flooding (Li et al., 2019). Past warming has been shown to increase early season runoff in the Sierras by about 30 percent, thus increasing runoff-driven flood risk (Huang et al., 2018).

What factors influence this indicator?

Lower water volumes of spring snowmelt runoff compared to the rest of the water year indicate warmer winter temperatures or early onset of warm springtime temperatures. With warmer winter temperatures, a greater proportion of precipitation occurs as rain, and snow falls and accumulates at higher elevations than in the past. Higher elevations of the snow line mean reduced snowpack and runoff in the spring.

Increased winter snowmelt was found to be highly sensitive to temperature in 34 percent of snow monitoring stations across western North America (Musselman et al., 2021). In the Sierra Nevada, the peak snow mass and snowmelt shifted earlier over the past 30 years, as daily maximum temperatures increased in March and April (Kapnick and Hall, 2010). Years of “snow drought” – defined as anomalously low snow-water content (Cooper et al., 2016) –between 1951 and 2017 originated and evolved in various ways in the northern Sierra Nevada (Hatchett and McEvoy, 2018), including from extreme early season precipitation, frequent rain-on-snow events, lower fractions of precipitation falling as snow, and midwinter peak runoff events. These conditions are generally associated with earlier snowmelt runoff.

The characteristics of a watershed affect changes in runoff. Because they are located at lower elevations, the Sacramento River watersheds are more vulnerable to reduced snowpack than the San Joaquin River watersheds. A study of projected changes in runoff in the 21st century found that the rain-dominated Sacramento watersheds will experience earlier and increased amounts of peak runoff; in contrast, in the snow-dominated San Joaquin watersheds, runoff peak timing and amounts are projected to remain relatively unchanged (He et al., 2019; He et al., 2020).

Technical Considerations

Data characteristics

Runoff for the Sacramento River system is the sum of the estimated unimpaired runoff of the Sacramento River and its major tributaries, the Feather, Yuba, and American Rivers. “Unimpaired” runoff refers to the amounts of water produced in a stream unaltered by upstream diversions, storage, or by export or import of water to or from other basins. The California Cooperative Snow Surveys Program of the California Department of Water Resources (DWR) collects the data. Runoff forecasts are made systematically, based on historical relationships between the volume of April through July runoff and the measured snow water content, precipitation, and runoff in the preceding months (Roos, 1992).

Related snowpack information is used to predict how much spring runoff to expect for water supply purposes. Each spring, about 50 agencies, including the United States Departments of Agriculture and Interior, pool their efforts in collecting snow data at about 260 snow courses throughout California. A snow course is a transect along which snow depth and water equivalent observations are made, usually at ten points. The snow courses are located throughout the state from the Kern River in the south to Surprise Valley in the north. Courses range in elevation from 4,350 feet in the Mokelumne River Basin to 11,450 feet in the San Joaquin River Basin.

Since the relationships of runoff to precipitation, snow, and other hydrologic variables are natural, it is preferable to work with unimpaired runoff. To get unimpaired runoff, measured flow amounts have to be adjusted to remove the effect of infrastructure or water management operations such as reservoirs, diversions, or imports (Roos, 1992). The water supply forecasting procedures are based on multiple linear regression equations, which relate snow, precipitation, and previous runoff terms to April-July unimpaired runoff.

Major rivers in the forecasting program include the Trinity, Pit, McCloud, Sacramento, Feather, Yuba, American, Cosumnes, Mokelumne, Stanislaus, Tuolumne, Merced, San Joaquin, Kings, Kaweah, Tule, Kern, Truckee, East and West Carson, East and West Walker, and Owens.

Strengths and limitations of the data

River runoff data have been collected for over a century for many monitoring sites. Stream flow data exist for most of the major Sierra Nevada watersheds because of California's dependence on their spring runoff for water resources and the need for flood forecasting. The April to July unimpaired flow information represents spring rainfall, snowmelt, as adjusted for upstream reservoir storage calculated depletions, and diversions into or out from the river basin. Raw data are collected through water flow monitoring procedures and used along with the other variables in a model to calculate the unimpaired runoff of each watershed.

Over the years, instrumentation has changed and generally improved; some monitoring sites have been moved short distances to different locations. The physical shape of the streambed can affect accuracy of flow measurements at monitoring sites, but most foothill sites are quite stable.

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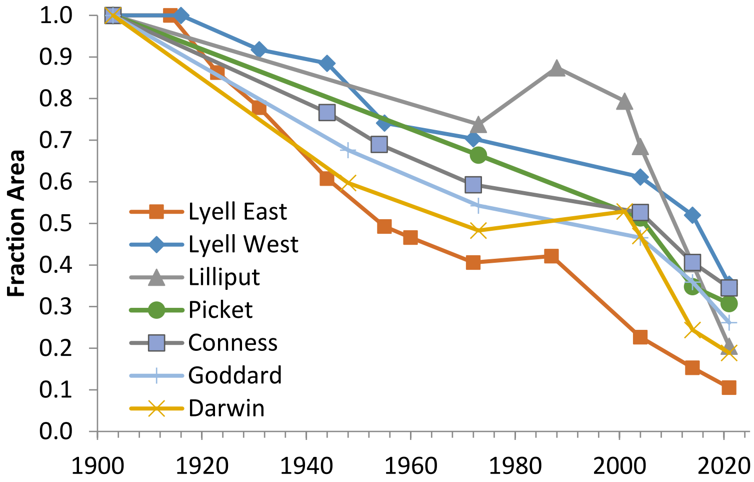
GLACIER CHANGE

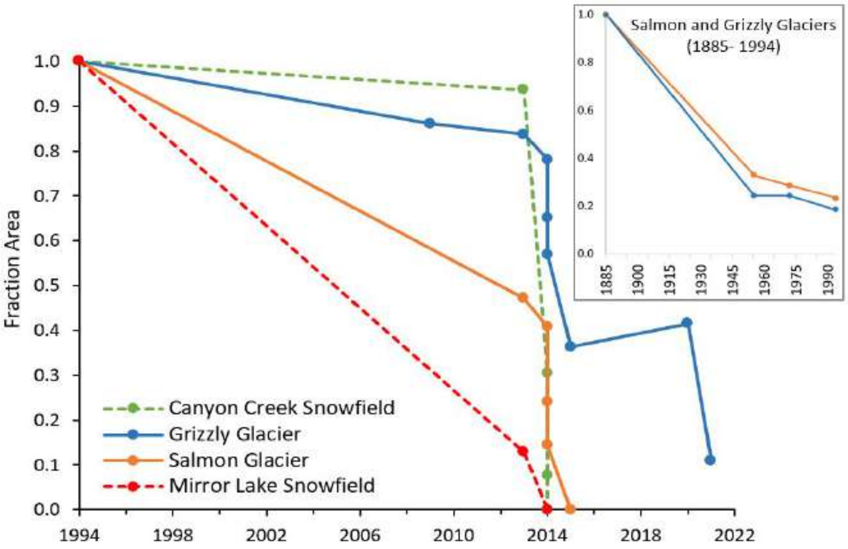
California's glaciers have melted dramatically over the past century. From the beginning of the twentieth century to 2021, some of largest glaciers in the Sierra Nevada have lost an average of about 75 percent of their area. Of the two glaciers in the Trinity Alps, one has recently disappeared and the other has lost more than 98 percent of its area.

Figure 1. Change in area, selected Sierra Nevada glaciers (as fraction 1903 area)



Source: Basagic and Fountain, 2011
(updated 2021 H. Basagic, unpublished data)

Figure 2. Change in area, Trinity Alps glaciers and snowfields (as fraction of 1994 area)



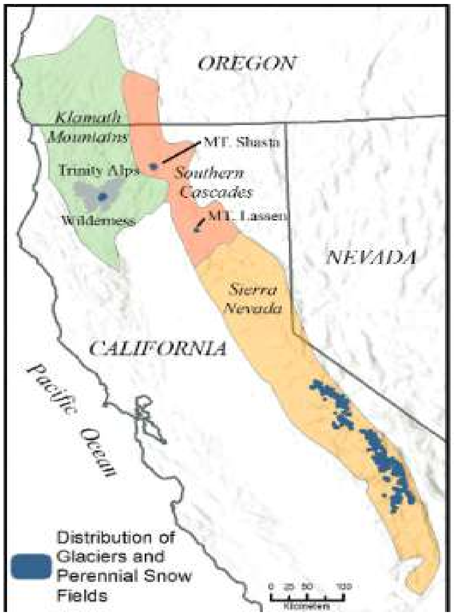
Source: Garwood et al., 2020
(updated 2021, J. Garwood, unpublished data)

Note: inset shows change in glacier areas relative to about 1885.

What does the indicator show?

Dramatic reductions in the area of selected glaciers and snowfields have occurred in California (see Figure 3 for locations). A “glacier,” by definition, is a mass of perennial snow or ice that moves (Cogely et al., 2011). Figure 1 shows large declines in the area of seven Sierra Nevada glaciers relative to 1903. Figure 2 shows substantial losses in the size of glaciers and snowfields in the Trinity Alps since 1994. Historical and contemporary photographs allow for a visual comparison of the changes (see Appendix A).

Figure 3. Glaciers and perennial snow regions in California



Source: Garwood et al., 2020

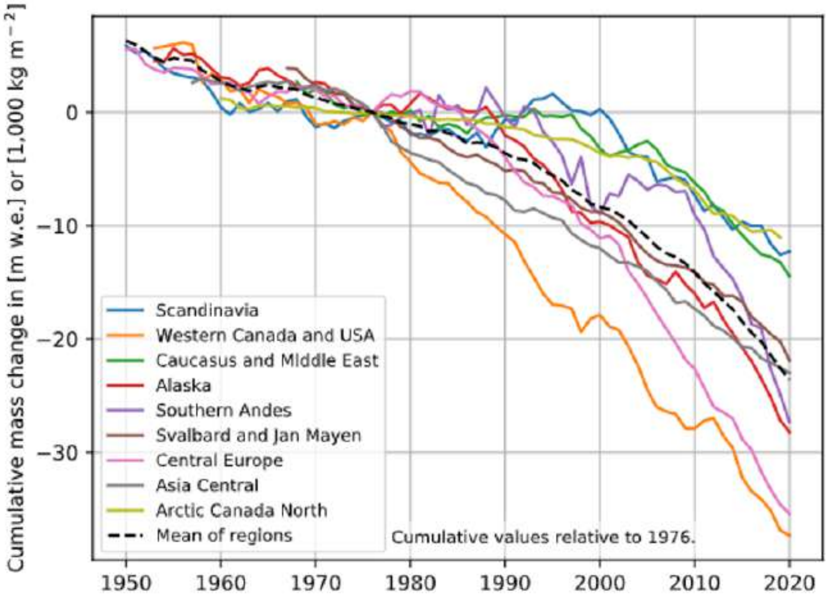
As shown in Figure 1, by 2021, the Sierra Nevada glaciers lost 65 to 89 percent (an average of about 75 percent) of their 1903 area, after having lost about half of their area since the 1970s (Basagic and Fountain, 2011, updated to 2021). These findings are consistent with those from a separate study of 769 glaciers and perennial snowfields that were identified within the Sierra Nevada in the 1970s and 1980s based on the US Geological Survey’s 1:24,000-scale, topographic maps (Fountain et al., 2017). The largest 39 glaciers, free of rock debris mantling the surface, covered an area of 2.74 ± 0.12 square kilometers (km^2) in the 1970s and 1980s. By 2014, overall, they lost about 50 percent of their area.

The main graph in Figure 2 shows the percentage glacier area remaining relative to 1994 for two glaciers and two perennial snowfields in the Trinity Alps between 1994 and 2015 (Garwood et al., 2020) and subsequent measurements of Grizzly Glacier recorded through 2021 (Garwood, unpublished data). The inset shows changes in the area of Grizzly and Salmon Glaciers relative to their estimated areas around 1885; data prior to 1994 are not available for the Canyon Creek and Mirror Lake Snowfields. Both glaciers had lost 70 to 75 percent of their area between 1885 and 1955; by 1994, only about 20 percent of their 1885 area remained. Between 1994 and 2013, Salmon Glacier experienced far greater loss than Grizzly Glacier: 53 and 16 percent, respectively, of their areas in 1994. The extended drought, which occurred from 2012 to 2016, resulted in the catastrophic loss of both glaciers. In 2015, Salmon Glacier disappeared entirely and the lower half of Grizzly Glacier broke apart into large ice blocks, leaving only the upper portion of the glacier intact (see historical and contemporary photographs in Appendix A).

Measurements of Grizzly Glacier taken between the fall of 2020 and the fall of 2021 revealed more catastrophic decline with a 76 percent further reduction in area. Given this substantial reduction, it is uncertain whether what remains in the fall of 2021 is still considered a glacier, or whether it is now a perennial icefield. Appendix B shows the outlines of the glaciers for selected years between approximately 1885 to 2015 for Salmon Glacier and 1885 to 2021 for Grizzly Glacier; estimated areas from 1955 to 2021 are presented in an accompanying table.

Two prominent snowfields that were still present in 1994 completely melted during the extended drought. Mirror Lake Snowfield diminished precipitously and disappeared by 2014; Canyon Creek Snowfield melted gradually between 1994 and 2013, shrank in area by almost 70 percent from late 2013 to mid 2014, and disappeared in late 2014. Both snowfields have yet to persist more than a year through 2021 due to low winter precipitation and high summer temperatures (Garwood et al., 2020, updated to 2021).

Figure 4. Regional cumulative mass change of global reference glaciers*



Source: WGMS, 2021

*“**Cumulative mass change**” is reported in meters of water equivalent (m w.e.) or 1,000 kilogram per square meter (kg m^{-2}). Cumulative values are relative to 1976 and calculated using a single value (averaged) for each mountain range. **Regional values** are calculated as arithmetic averages. **Global values** are calculated using one single value (averaged) for each region with glaciers to avoid a bias to well-observed regions.*

Over the 20th century, with few exceptions, alpine glaciers have been receding throughout the world in response to a warming climate. Figure 4 presents trends since 1950, although global measurements date back to 1917 or earlier. The graph is based on standardized observations of a set of glaciers collected by the World Glacier Monitoring Service (WGMS, 2021) in more than 40 countries worldwide. Regional mass changes are shown relative to 1976 global mean values (dotted line). Glacier mass change is reported as “cumulative mass change in meters of water equivalent (m w.e.)”; this unit is the equivalent of a mass loss of 1,000 kilograms per square meter of ice cover or an annual glacier-wide ice thickness loss of about 1.1 meter per year. As shown in the graph, glaciers in the Western United States and Canada (two in Alaska and seven in the Cascade and Pacific Coast Ranges of Washington State and Canada) are experiencing greater glacier loss than other regions of the world.

Why is this indicator important?

Glaciers are important indicators of climate change. Because glaciers are sensitive to fluctuations in temperature, they provide visual evidence of warming. Glacier loss can lead to cascading effects on hydrology, alter aquatic habitats, contribute to sea level rise, and impact recreation and tourism (USGS, 2021a).

Glaciers are important to alpine hydrology by acting as frozen reservoirs of snow. They begin to melt most rapidly in late summer after the bright, reflective seasonal snow disappears, revealing the darker ice beneath. This often causes peak glacial runoff to occur in late summer when less water is available and demand is high. Glacier shrinkage reduces this effect, resulting in earlier peak runoff and drier summer conditions. These changes are likely to have ecological consequences for flora and fauna in the area that depend on available water resources. For example, many aquatic species in alpine and subalpine environments require cold water temperatures to survive. Some aquatic insects – fundamental components of the food web – are especially sensitive to stream temperature and require glacial meltwater for survival. Finally, glacier shrinkage worldwide is an important contribution to global sea level rise (IPCC, 2019).

The Trinity Alps is a glaciated subrange of the Klamath Mountains in northwest California (see Figure 3 map). This region has experienced much greater fractional losses of glacier area than the Sierra Nevada and other glaciated regions of the western US. Around 1885, at least six glaciers existed in the Trinity Alps (Garwood et al., 2020). Grizzly and Salmon glaciers are the only two that persisted into the 21st century. In addition, all snowfields throughout the Trinity Alps and greater Klamath Mountains of southern Oregon and northern California had fully disappeared by 2014.

The Trinity Alps and entire Klamath Range ecoregion are globally recognized for their rich biodiversity (DellaSala et al., 1999; Olson et al., 2012). Glacial ice and persistent snow influence local species composition and their distributions by extending perennial wetlands into high elevations that normally lack surface waters. The freshwater habitats of the region support exceptionally high levels of endemic species. Most mollusk populations have declined dramatically throughout the region, and over 10 fish taxa have a special status designation due to habitat degradation and changes in hydrology and water quality. A beetle species (*Nebria praedicta*) endemic to the Grizzly Glacier basin depends on perennial snow and ice to maintain the cool microclimate needed to survive (Kavanaugh and Schoville, 2009). The coastal tailed frog (*Ascaphus truei*), a California Species of Special Concern (see Figure 5), is adapted to cold-water streams.

Its highest known population across its range was discovered in 2009 directly below the Canyon Creek snowfield, which disappeared in 2014 (Garwood et al., 2020).

Figure 5. Coastal Tailed Frog

Photo credit: Thompson *et al.*, 2016

The Coastal tailed frog (Ascaphus truei) ranges from British Columbia to northern California, from near sea level in Humboldt County up to elevations of 2150 meters in the Trinity Alps (CDFW, 2016).

Three watersheds in this region contribute glacial and/or snowmelt cold-water streamflow directly to fish-bearing streams containing small populations of spring Chinook salmon (*Oncorhynchus tshawytscha*) and summer steelhead (*Oncorhynchus mykiss*). The Klamath-Trinity River spring Chinook salmon were listed as threatened by the State of California in June 2021 (CDFW, 2021) and are currently being considered for listing as endangered under the Federal Endangered Species Act (Federal Register 2018, 2019). These species migrate from the Pacific Ocean to these streams and stage in deep cold-water pools throughout the summer months before spawning in the fall. The dramatic local declines of glacial ice and annual snowpack in the Klamath Range foretell how climate change threatens the unique distributions and resiliency of fish adapted to local glacier and snow dependent environments (Garwood et al, 2020).

What factors influence this indicator?

A glacier is a product of regional climate, responding to the combination of winter snow and spring/summer temperatures. Typically, glaciers exist in areas with significant accumulations of snow, temperatures during the year that do not result in the complete loss of the winter snow accumulation, and average annual temperatures near freezing, (USGS, 2021b). Winter snowfall nourishes the glaciers; winter temperature determines whether precipitation falls as rain or snow, thus affecting snow accumulation and glacier mass gain. The greater the winter snowfall, the healthier the glacier. Spring and summer air temperature affects the rate of snow and ice melt.

In the early 20th century, glaciers retreated (decreased in size) rapidly throughout the western US in response to the end of the Little Ice Age and warming air temperatures (Basagic and Fountain, 2011). In recent years, increasing winter and spring temperatures across North America have led to less snowpack in spring and early summer (Mote *et al.*, 2018). Based on their assessment of studies of glaciers in various parts of the world, the Intergovernmental Panel on Climate Change concluded that human-induced warming likely contributed substantially to widespread glacier retreat during the 20th century (IPCC, 2021).

Alpine glaciers gain or lose mass primarily through climatic processes controlling energy and mass exchange with the atmosphere, then respond by either growing (advancing) or shrinking (retreating). The area changes observed in the Sierra Nevada study glaciers were triggered by a changing climate and modified by the dynamics of ice flow. Hence, glacier change is a somewhat modified indicator of climate change, with local variations in topography and climate either enhancing or reducing the magnitude of change so that each glacier's response is somewhat unique. Because glaciers persist across decades and centuries, they can serve as indicators of long-term climatic change.

Sierra Nevada

The glacier retreat in the Sierra Nevada occurred during extended periods of above average spring and summer temperatures; winter snowfall appears to be a less important factor (Basagic and Fountain, 2011). Following a cool and wet period in the early part of the 20th century, during which glacier area was constant, the Sierra Nevada glaciers began to retreat rapidly with warmer and drier conditions in the 1920s. The glaciers ceased retreating, while some glaciers increased in size (or "advanced") during the wet and cool period between the 1960s and early 1980s with below average temperatures. By the late 1980s, with increasing spring and summer temperatures, glacier retreat resumed, accelerating by 2001. Hence, the timing of the changes in glacier size appears to coincide with changes in air temperatures. In fact, glacier area changes at East Lyell and West Lyell glaciers were found to be significantly correlated with spring and summer air temperatures. In the past century, average annual temperatures in the Sierra Climate Region have warmed by almost 2 degrees Fahrenheit (°F), with summer and fall having warmed the most (2.6 and 2.5°F, respectively) (WRCC, 2021).

As can be seen from Figure 1, the seven glaciers studied have all decreased in area. However, the magnitude and rates of change are variable, suggesting that factors other than regional climate influenced these changes. One of these factors is glacier geometry. A thin glacier on a flat slope will lose more area compared to a thick glacier in a bowl-shaped depression, even if the rate of melting is the same. In addition, local topographic features, such as headwall cliffs, influence glacier response through shading solar radiation, and enhancing snow accumulation on the glacier through avalanching from the cliffs.

Trinity Alps

Grizzly and Salmon Glaciers and Canyon Creek and Mirror Lake Snowfields in the Trinity Alps occur at 2,460 meters, an elevation far lower than other glaciated areas in California. The high latitude region has a particularly wet climate during the winter months due to its proximity to the Pacific Ocean (Garwood et al., 2020). Although a marginal climate for glaciers, these glaciers have persisted into the 21st century due to topographic features where tall headwalls increase shading and enhance localized snow accumulation through avalanching and wind transport.

Although large data gaps exist, clearly the largest amount of ice loss in the Trinity Alps occurred during the first half of the 20th century with a combined area loss of 72 percent for Grizzly and Salmon glaciers (inset, Figure 2) (Garwood et al., 2020; also see Appendix B). Since then, the glaciers receded at a much slower but steady rate and persisted even while winter precipitation in the Trinity Alps was below the long-term average (using 1895 to 2015 as baseline) in 9 of the 20 years from 1996 to 2015, and summer temperatures exceeded the long-term average in 18 years of the same period. Scientists attribute the recent glacial retreat in the Trinity Alps (see Appendix, Figures A-2 and A-3) largely to unprecedented and consistently high summer temperatures coincident with record-low winter precipitation in the region during the 2012 to 2016 drought (Garwood et al., 2020) and thereafter in 2020 and 2021 (Garwood, unpublished data).

California's recent drought differed from earlier periods of persistent low precipitation by coinciding with a period of consistently record-high summer temperatures (see *Drought* indicator). During the severe drought, snowpack was at an all-time low – no other year since 1950 reported an April 1st snowpack of less than 34 percent in the Klamath Mountains (Garwood et al., 2020). As shown in Figure 2, it was this time period where Salmon Glacier melted completely and Grizzly Glacier partially broke apart and declined greatly in size.

Technical considerations

Data characteristics

Sierra Nevada

To quantify the change in glacier extent, seven glaciers in the Sierra Nevada were selected based on the availability of past data and location: Conness, East Lyell, West Lyell, Darwin, Goddard, Lilliput, and Picket glaciers. Glacier extents were reconstructed using historical photographs and field measurements. Aerial photographs were scanned and imported into a geographic information system (GIS). Only late summer photographs, largely snow free, were used in the interpretation of the ice boundary. The historic glacier extents were interpreted from aerial photographs by tracing the ice boundary. Early 1900 extents were based on ground-based images and evidence from moraines. To obtain recent glacier areas, the extent of each glacier was recorded using a global positioning system (GPS) in 2004. The GPS data were processed (2 to 3 meter accuracy), and imported into the GIS database. Glacier area was calculated within the GIS database. The 2014 outlines were derived from aerial photographs acquired by the US Department of Agriculture National Agricultural Imagery Program, 1-meter ground resolution. The 2021 imagery were acquired from DigitalGlobe WorldView © 2021 Maxar, 0.5-meter ground resolution. For both years, the imagery was loaded into ArcGIS and the glacier outlines digitized at a scale of about 1:500.

Trinity Alps

Long-term changes in glaciers and perennial snowfields were quantified using clearly defined moraines (loose sediment and rock debris deposited by glacier ice); vertical aerial orthophotos (photographs geometrically corrected such that the scale is uniform); high-resolution satellite images; and GPS mapping (Garwood et al., 2020; Garwood, unpublished data). The 1885 outlines were generated by mapping the ridgelines of prominent Holocene moraines coupled with mapping the near vertical bedrock headwalls at the upper extent of the glaciers. Eleven aerial and satellite images were acquired from 1955 to 2021. All aerial photographs had spatial resolutions of 1 meter; satellite imagery resolutions ranged from 0.33 to 0.5 meter. In addition, glacier perimeters were mapped using a GPS with an accuracy ± 2.6 meters. Ground-based photograph monitoring stations were established at each of the two glaciers to document qualitative changes in glacier geometry and morphology during field visits between the years of 2009 and 2018.

To examine the response of glaciers and perennial snowfields in the Trinity Alps to variations in climate, changes in glacier area were compared to winter precipitation and summer air temperature from the PRISM re-analysis data (Daly et al. 2008, PRISM Climate Group 2018), employing a similar analysis as Sitts et al. (2010), using data for the 4 km × 4 km PRISM grid cell centered on Thompson Peak for the period of January 1895 to September 2015.

Strengths and limitations of the data

The observation of tangible changes over time demonstrates the effects of climate change in an intuitive manner. This indicator relies on data on glacier change based on photographic records, which are limited by the availability and quality of historical photographs. The use of both aerial photographs and satellite images provides high quality visual data for measuring changes in glacier area. Detailed information about uncertainties associated with mapping the area of glaciers can be found in the methods section of Garwood et al. (2020). A limitation in relying on satellite and photographic images is that change in glacial volume cannot be assessed.

Increasing the number of studied glaciers and the number of intervals between observations would provide a more robust data set for analyzing statistical relationships between glacier change and climatological and topographic parameters. Additionally, volume measurements would provide valuable information and quantify changes that area measurements alone may fail to reveal.

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APPENDIX A. Historical and Contemporary Glacier Photographs

Historical glacier responses preserved in photographs are important records of past climates in high alpine areas where few other climate records exist. Repeat photographs – paired historical and contemporary images – for selected glaciers are presented below. Additional photographs of the Sierra Nevada, Trinity Alps and other western glaciers can be viewed at the "Glaciers of the American West" web site (PSU, 2017).

Figure A-1. Historical and contemporary late summer photographs of two Sierra Nevada glaciers

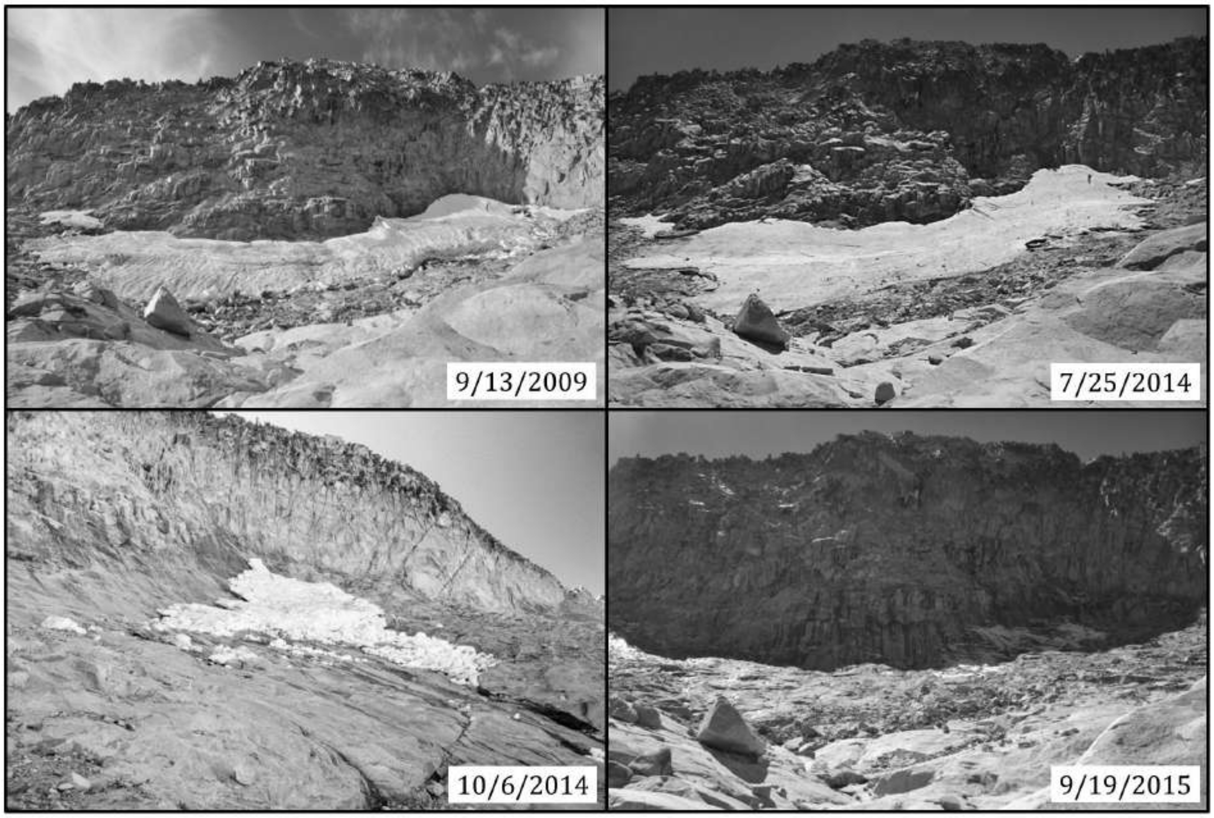
Dana Glacier

Credit: U.S. Geological Service, photo station ric046: I.C. Russell, 1883 (left); R. Hallnan (right)

Conness Glacier

Credit: National Park Service, photo station Conness 5555 (left); H. Basagic (right)

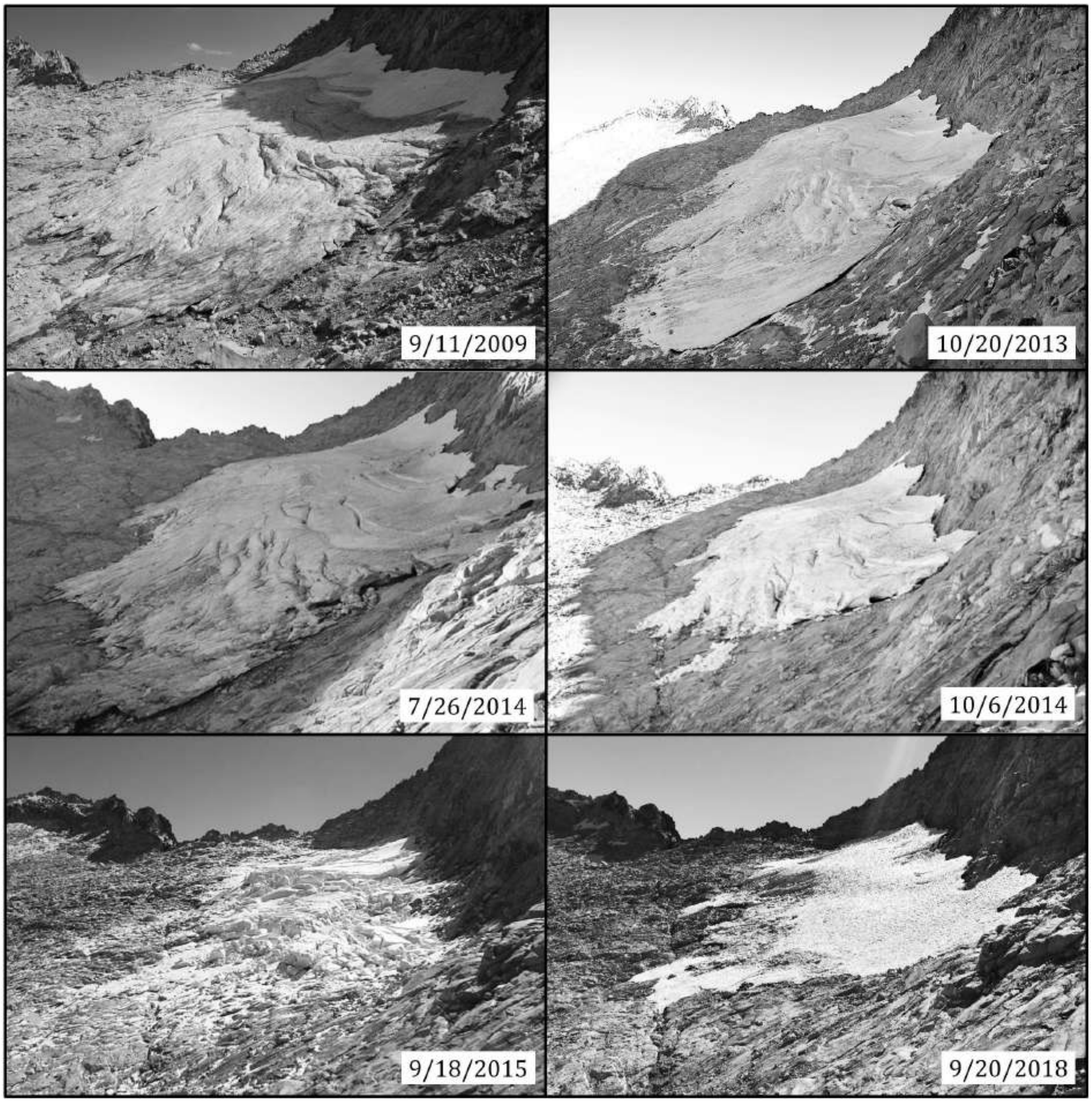
Figure A-2. Salmon Glacier, repeat photographs



Credit: Photos taken by J. Garwood (September 2009 and 2015), R. Bourque (July 2014) and J. Barnes (October 2014)

Repeat photographs of Salmon Glacier were taken between September 2009 and September 2015. The October 2014 image was taken northeast of the feature facing southwest whereas the others were taken north of the feature facing due south. The glacier broke apart in 2014 and completely melted away by the fall of 2015. The patchy snow observed in shadows of the 2015 image accumulated during a small storm that occurred two days prior to the image date (Garwood et al.*, 2020).*

Figure A-3. Grizzly Glacier, repeat photographs



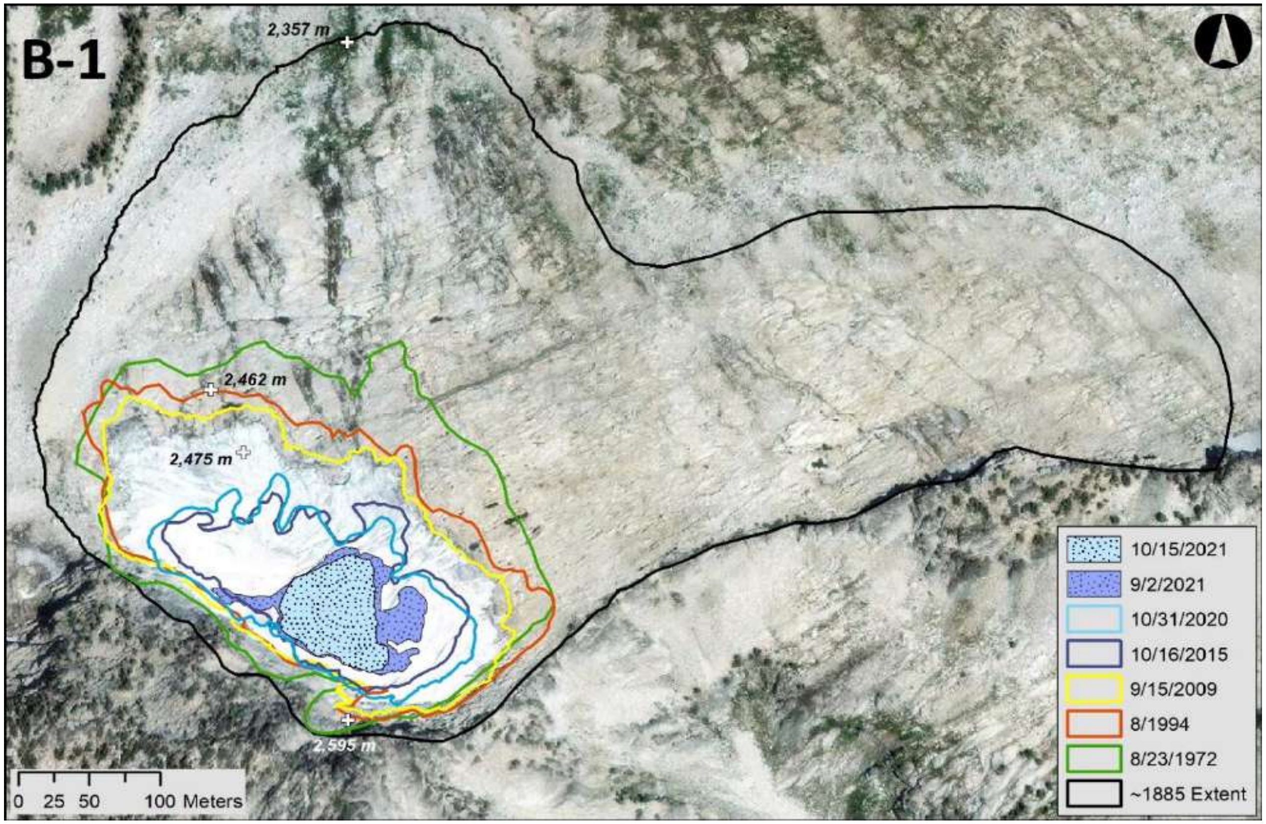
Credit: All photographs taken by J. Garwood
with exception of October 2013 by K. Lindke and October 2014 by J. Barnes

Repeat photographs of Grizzly Glacier were taken between September 2009 and September 2018. The lower half of the glacier broke apart in the fall of 2015. A thin layer of fresh snow visible in the September 2015 image accumulated during a brief storm that occurred two days prior to the image date. This snow cover visually exaggerates the actual glacier size beyond the visible pile of scattered ice debris visible in the photo; a result of extreme calving in the lower half of the feature during the summer of 2015 (Garwood et al., 2020).

APPENDIX B. Glacier area loss for in the Trinity Alps, California

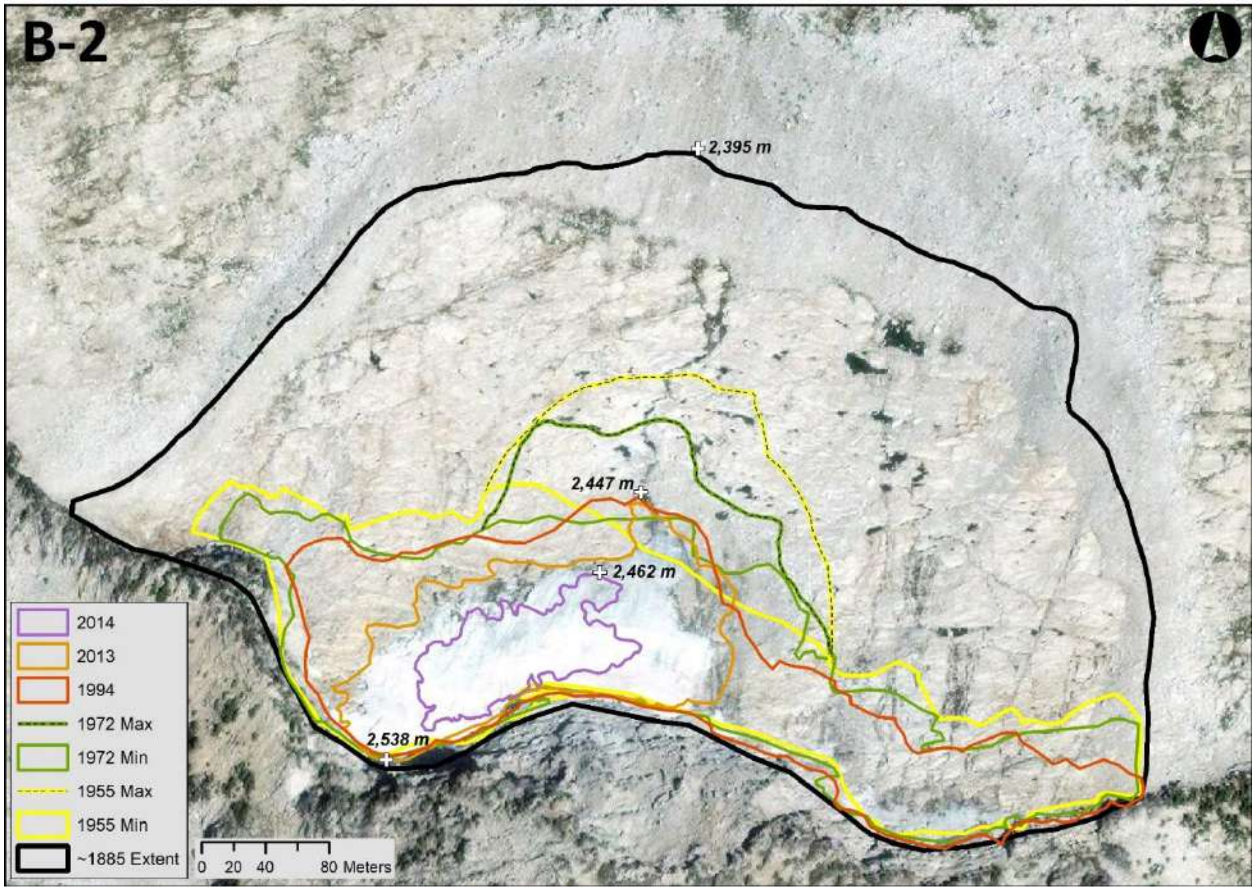
Digitized outlines of Grizzly Glacier (B-1) and Salmon Glacier (B-2) from approximately 1885 to 2021. Salmon Glacier disappeared completely by the fall of 2015 while Grizzly Glacier maintained a similar area between 2015 and 2020 before losing 76 percent of its 2020 area during the summer and early fall of 2021. The 1885 outlines were generated by mapping the ridgelines of prominent Holocene moraines coupled with mapping the near vertical bedrock headwalls at the upper extent of the glaciers. The 1885 outlines represent the most recent Little Ice Age glacial advance. Due to extensive residual snow cover on Salmon Glacier in 1955 and 1972, outlines include a minimum estimated area (solid colors) and additional maximum estimated area dotted lines. Satellite base image date is from 26 July 2014. Approximate surface elevations are noted at four locations at each glacier.

Figure B-1. Grizzly Glacier, digitized outlines



Source: Garwood et al., 2020 (updated 2021; J. Garwood, unpublished data)

Figure B-2. Salmon Glacier, digitized outlines



Source: Garwood et al., 2020

Table 1. Estimated areas* in hectares of glaciers in the Trinity Alps, from ca. 1885 to 2021

Year	Grizzly Glacier	Salmon Glacier
ca. 1885	24.44	19.40
1955	6.01*	6.45
1972 (Aug)	6.00*	5.58
1994 (Aug)	4.60	4.54
2009 (Sept)	3.96	not measured
2013 (Oct)	3.85	2.14
2014 (July)	3.59	1.85
2014 (Sept)	2.99	1.09
2014 (Oct)	2.62	0.65
2015 (Oct)	1.67	extinct
2020 (Oct)	1.91	extinct
2021 (Oct)	0.45	extinct

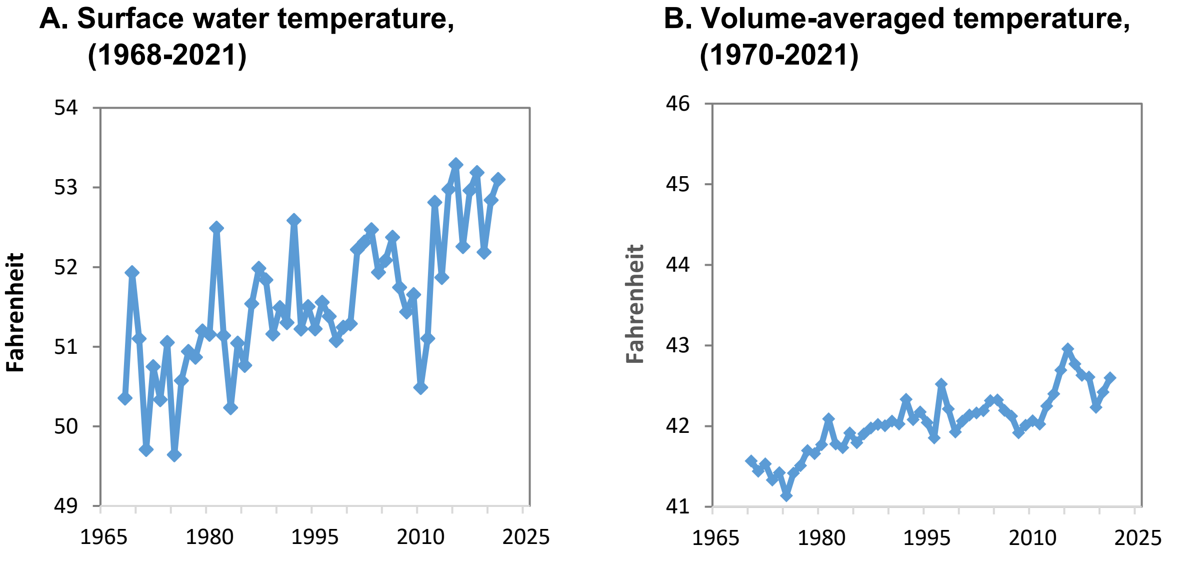
Source: Garwood et al., 2020 (updated 2021; J. Garwood, unpublished data)

* Average areas shown are estimated due to residual snow cover partially obscuring lower glacier margin;
1 hectare = 10,000 square meters or 2.5 acres

LAKE WATER TEMPERATURE

Lake Tahoe waters are warming in response to changing climate conditions in the Sierra Nevada.

Figure 1. Annual average water temperatures at Lake Tahoe



Source: UC Davis, 2022

What does the indicator show?

Annual average surface water temperatures at Lake Tahoe, which varied greatly from year to year, have increased by 1.97 degrees Fahrenheit (°F) since 1968, at a rate of 0.39°F per decade (Figure 1A). The highest average surface temperatures were recorded in seven of the last 10 years, with 2015 reporting the warmest on record (53.29°F).

Figure 1B shows annual average lake water temperatures across multiple depths (”volume-averaged”). Volume-averaged temperatures have warmed overall in the past fifty years by approximately 1.1°F, at a rate of 0.22°F per decade: a smaller increase compared to surface water temperatures (Figure 1A). After peaking in 2015, volume-averaged temperatures trended down until 2019, but showed an uptick in 2020 and 2021.

While Lake Tahoe is unique, the physical, chemical and biological forces and processes that shape it reflect those acting in most natural ecosystems. Thus, Lake Tahoe can serve as an indicator for other systems both in California and worldwide (UC Davis, 2022).

Warming has also been reported in other lakes in the western United States. Temperature data derived from satellite observations show increasing summertime surface water temperatures in a 16-year study of four lakes in Northern California (including Lake Tahoe) and two in Nevada (Schneider et al., 2009). From 1992 to 2008, these six lakes showed a significant warming trend for summer (July through September) nighttime surface temperatures, ranging from 0.05 degrees Celsius (°C) per year at Clear Lake to 0.15°C per year at Lake Almanor and Mono Lake. The lakes exhibited a fairly similar rate of change, with the mean warming rate of 0.11°C per year (± 0.03°C per year).

Why is this indicator important?

Climate change is among the greatest threats to lakes (O'Reilly et al., 2015). Lakes are sensitive to climate, respond rapidly to change, and integrate changes in the land areas that drain into them (catchment). Thus, they also serve as good sentinels for climate change. Lakes in mountain regions may be particularly sensitive to ongoing changes in climate in part because high-elevation ecosystems are warming at among the fastest rates found globally. Aquatic habitats most vulnerable to climate effects, especially rising temperatures, are alpine lakes like Lake Tahoe that sit at high altitude.

Even small changes in water temperature are known to affect physical and biological processes and the functioning of ecosystems in mountain lakes (Sadro et al., 2019). In the Sierra, interrelated factors such as the amount of snowpack, the timing and magnitude of snowmelt, and water temperature have important implications for growth of benthic algae and phytoplankton, primary productivity and food web dynamics. Elevated water temperatures can increase metabolic rates of organisms, from plankton to fish (UC Davis, 2022).

Rising lake water temperatures reduce water quality by increasing thermal stability (stratification) and altering lake mixing patterns (O'Reilly et al., 2015). During the summer, Lake Tahoe water forms horizontal layers with less mixing due to differing water temperatures. In the late fall and winter, surface waters cool and sink to the bottom, and upwelling brings nutrients to the surface. The magnitude of cooling during winter helps to determine how deep the lake mixes vertically. This mixing plays a critical role in providing nutrients to the food web and distributing oxygen throughout the lake. Without this circulation, oxygen-rich surface water does not make it to the lake bottom, depriving fish and other aquatic life of oxygen.

When winter temperatures are warm, mixing tends to occur at more shallow depths, resulting in warmer lake temperatures. In 2020 and 2021, relatively shallow mixing likely contributed to warmer surface temperatures, while in 2019, top to bottom mixing of lake waters led to cooler water temperatures (UC Davis, 2022). Resistance to lake mixing increases markedly even at temperature increases of only a few degrees (Sahoo et al., 2015). Since 1968, the amount of time Lake Tahoe has been in its stratified, 'summer'-state has increased by a month (UC Davis, 2022). Scientists are predicting that in a warming climate, mixing in Lake Tahoe will become less frequent — a change that will disrupt fundamental processes that support a healthy ecosystem. For example, suppressed mixing may create new thermal niches that introduced species can take advantage of, potentially disadvantaging native species that have evolved under clear, cold water conditions.

The lack of seasonal lake mixing can cause shifts in Lake Tahoe's algal species and their distribution (UC Davis, 2022). When mixing is suppressed, larger algae sink and leave the smallest algae suspended at the surface where they scatter light and decrease the lake's clarity. As clarity decreases, greater warming of the surface water takes place, increasing stratification and the likelihood of more small algal species. This vicious cycle presents an additional climate-induced challenge. Reduced mixing may also prolong periods of reduced lake clarity that occur following years of heavy stream runoff, by causing fine particles to be retained in the upper layer of the lake (Coats et al., 2006).

Water clarity measurements have been taken continuously at Lake Tahoe since 1968 using an instrument called a Secchi disk (UC Davis, 2022). This allows for a better understanding of how factors such as temperature, precipitation, and nutrient and sediment inputs into the lake are changing physical, chemical, and biological processes that affect the lake's clarity. While the average clarity of the lake has been relatively stable over the past 20 years, there is a long-term trend of reduced summer clarity. Because water clarity impacts the amount of light penetration, it has important implications for the diversity and productivity of aquatic life that a system can support. In addition, clear waters are valued for aesthetic and recreational purposes.

Photo credit: UC Davis/Getty

Lake Tahoe is a crystal-clear high altitude mountain lake, considered one of the jewels of the Sierra. It is known around the world for its water clarity and cobalt blue color. The lake is 22 miles long, has a surface area of 190 square miles, and a total volume of 130 million acre feet. Its maximum depth of 1,644 feet makes it the third deepest lake in North America, and the eleventh deepest lake in the world. The UC Davis Tahoe Environmental Research Center documents changes in physical and biological parameters to inform management strategies for the lake and its surrounding area (UC Davis, 2021b).

A recent study describes a widespread decline in dissolved oxygen levels among 393 temperate lakes across the US from 1941 to 2017 (Jane et al, 2021). The decline in surface waters was primarily associated with reduced oxygen solubility under warmer water temperatures. By contrast, the decline in dissolved oxygen in deep waters was associated with stronger thermal stratification and loss of water clarity. The authors concluded that despite a wide range of lake and catchment characteristics, the overall trend of lake deoxygenation is clear. Reduced dissolved oxygen in deep water lake habitats may lead to future losses of cold-water and oxygen-sensitive species, the formation of harmful algal blooms, and potentially increased storage and subsequent outgassing of methane.

A decline in the water clarity and ecosystem health of the lake could jeopardize future tourism. The scenic beauty of Lake Tahoe offers cultural and recreational opportunities, such as hiking, skiing, camping and boating. The annual visitor population of about 15 million (California Tahoe Conservancy, 2021) makes it a region of national economic significance, with estimated annual revenues of 4.7 billion dollars (Mooney and Zavaleta, 2016).

What factors influence this indicator?

Lake temperature responses to climate change can vary and in part from the multiple ways in which climate interacts with lake 'heat budgets' (Sadro et al., 2019; Sharma et al., 2017; Woolway et al., 2020). Climate affects lake temperature by increasing heat gains or reducing heat losses. Key drivers controlling lake water temperature are solar radiation, air temperature (influenced by greenhouse gas concentrations), ice cover, cloud cover, humidity, and wind. In addition, suppressed lake mixing (discussed above) can enhance warming of surface waters. Landscape characteristics such as latitude, elevation, and catchment features or land cover can modulate climate effects on individual lakes (Schmid et al., 2014). The climate signal might be further modified by a lake's morphometric attributes, such as lake size and shape, or through differences in the source and magnitude of water inputs (Rose et al. 2016).

A study of lakes around the world found summer air temperature to be the single most consistent predictor of lake summer surface water temperature (LSSWT) (O'Reilly et al., 2015) largely because so many of the factors that control lake temperature are correlated with air temperature. The study reported that LSSWT is warming significantly, with a mean trend of 0.34°C per decade across 235 globally distributed lakes between 1985 and 2009. This warming water surface rate is consistent with the annual average increase in air temperatures and ocean surface temperatures over a similar time period (1979–2012).

Lake Tahoe warming trends reflect overall air temperature trends in the region (UC Davis, 2022). Since 1912, the average daily *maximum* temperature has risen by 2.25°F (1.2°C) and the average daily *minimum* temperature has increased by 4.5°F (2.5°C). Although year-to-year variability is high, the number of days when air temperatures averaged below-freezing has declined by almost 30 days since 1911. Snow has declined as a fraction of total precipitation, from an average of 52 percent in 1910 to 33 percent in 2020. A warming climate is affecting other physical changes at Lake Tahoe -- including a shift in snowmelt timing to earlier dates—that may have significant impacts on lake ecology and water quality. For more information about meteorological trends in the Lake Tahoe area, refer to: *Tahoe: State of the Lake 2022* (UC Davis, 2022).

In California lakes that experience ice cover, the amount of snowpack, timing of snowmelt runoff, and ice formation and ice-off (date of ice thawing and breakup) influence lake water temperatures (Melack et al., 2020; Sadro et al., 2019; Smits et al., 2020). For example, Emerald Lake is a high elevation lake in the southern Sierra Nevada that is covered with ice six to nine months of the year. Despite a strong warming trend in regional air temperature over the past three decades, researchers found warming water temperatures occurred only during drought years, when snowpack was reduced (Sadro et al., 2019). Snowpack and lake temperature are strongly correlated in mountain systems likely due to tight coupling between snowpack and ice cover in lakes (Smits et al., 2020). Years with low snowpack at Emerald Lake were accompanied by a reduction in the duration of ice-cover, which acts to buffer lake water from exposure to solar radiation and warming. As snowpack declines in the Sierra Nevada and other mountain ranges (see *Snow-water content* indicator), lake temperature will become increasingly sensitive to warming with reduced ice cover.

Technical Considerations

Data characteristics

The University of California, Davis and its research collaborators collect the measurements used for monitoring Lake Tahoe. They have recorded water temperature measurements at two locations in Lake Tahoe since 1968:

(1) at the Index Station (about 0.6 kilometers off the California side west shore) at depth increments of 2 to 15 meters starting at the surface to a depth of about 100 meters, on an approximately weekly basis (and since 1996 at 20-centimeter increments to a depth of 125 meters biweekly);

(2) at the Midlake Station, the exact location of which has varied slightly over time, at nominal depths of 0, 50, 100, 200, 300 and 400 meters, on an at least monthly basis through 1996, and since then monthly at 20-centimeter intervals to a depth of 450 meters.

Strengths and limitations of the data

A variety of thermometers and digital thermographs have been used at the Index Station over the years. Although the sensitivity, accuracy, and calibrations of these instruments have varied over time, these data are adequate for characterizing the thermal structure of the epilimnion and thermocline. Temperatures at the Midlake Station were originally measured at 13 depths with mercury-reversing thermometers, as follows: a protected thermometer, unaffected by pressure, records the temperature at reversal depth; readings from this thermometer are corrected for glass expansion and, along with a second, unprotected thermometer affected by pressure in deep water, provide measure of the actual depth of the temperature reading (Coats et al., 2006). These instruments were accurate to 0.01°C. More recently temperature is measured using a high precision thermistor that is part of a suite of instruments on a Seabird SBE-25plus profiler. Accuracy of the thermistor is 0.001°C. The Seabird measures at a rate of 8 times per second as it falls through the water at a velocity of 60 centimeters/sec.

Lake surface temperature data derived from thermal infrared satellite imagery (ATSR and MODIS), when validated against corresponding *in situ* data for Lake Tahoe, were found to agree very well over the entire range of temperatures. This, along with an additional assessment of inter-sensor bias between all ATSR sensors, indicates that accurate and stable time series of lake surface temperature can be retrieved from ATSR and MODIS satellite data.

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References:

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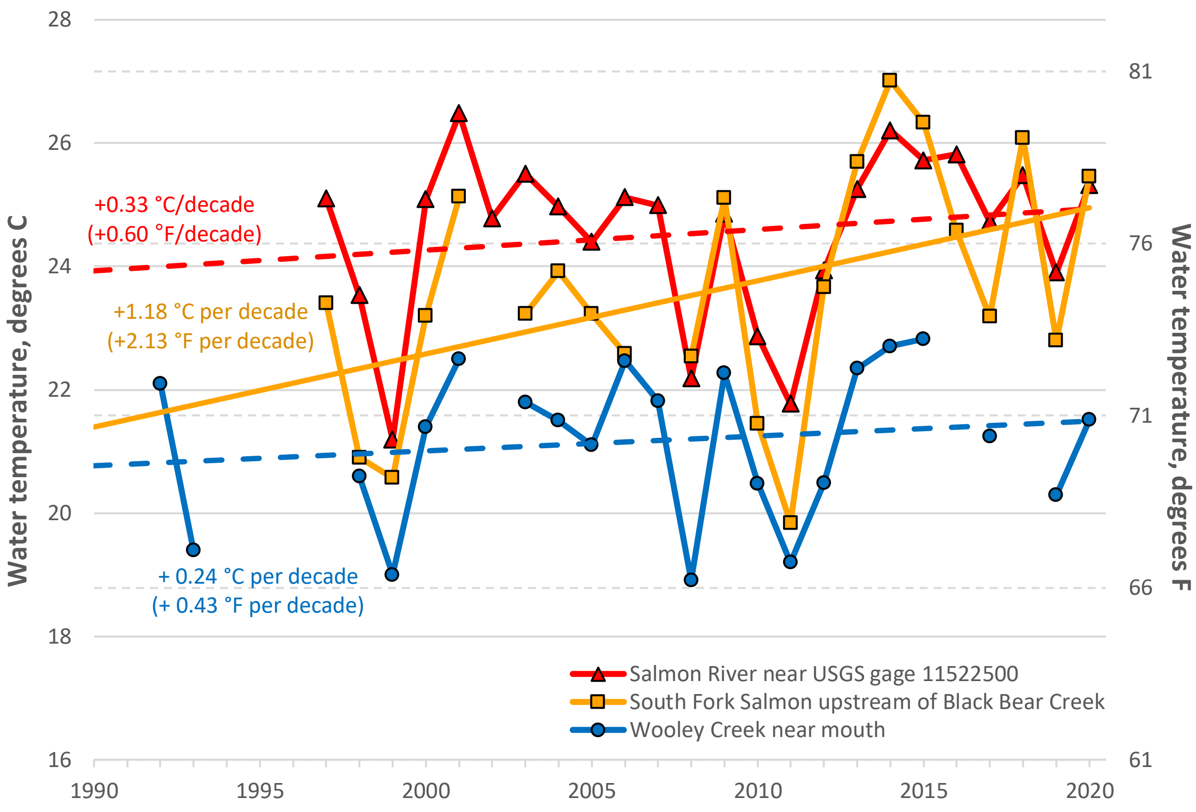
SALMON RIVER WATER TEMPERATURE

Water temperatures in the Salmon River and its tributaries have been warming, coincident with warming air temperatures and decreasing snowpack. The Salmon River watershed's relatively modest human influences make it an excellent location for tracking the effect of climate change.

Figure 1. Salmon River Water Temperatures* (1992-2020)



Source: Karuk Tribe, SRCC, and USFS 2021

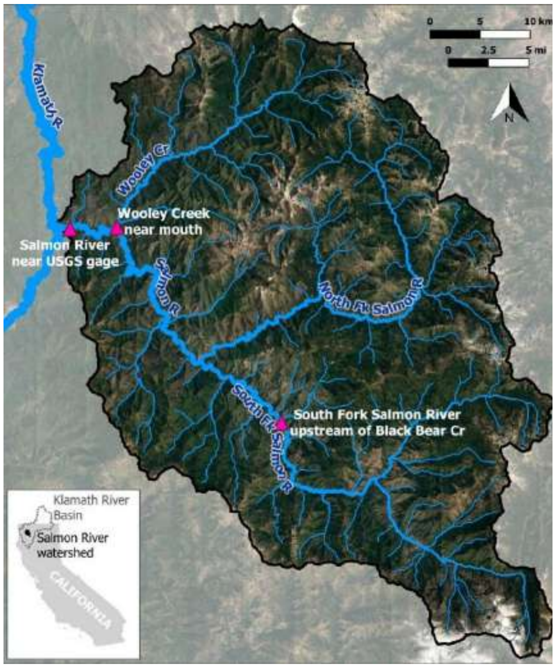
The value for each year is the **annual maximum temperature -- i.e., the highest instantaneous maximum temperature--during the summer. Solid line denotes statistically significant trend (p<0.05).*

What does the indicator show?

From 1992 to 2020, water temperatures, measured as annual maximum temperature (AMT) at three sites in the Salmon River watershed (Figure 1) have been variable but trending higher. The Salmon River watershed is a 750-square mile sparsely populated area in Siskiyou County surrounded by subranges of the Klamath Mountains. Temperatures at the South Fork Salmon River site upstream from Black Bear Creek are increasing the fastest, with a rate of 2.13 degrees Fahrenheit (°F) per decade. Water temperatures at the Wooley Creek and Salmon River at US Geological Survey (USGS) gage stations are increasing more slowly, with rates of 0.60°F and 0.43°F per decade, respectively.

The three monitoring sites (shown in Figure 2) are a subset of many sites throughout the Salmon River and its tributaries where water temperatures are monitored. A previous analysis combined 27 long-term sites in the watershed to assess collective trends for the month of August during the period 1995-2017, finding that daily maximum temperatures warmed by 0.70°F per decade and daily mean temperatures warmed at a rate of 0.38°F per decade (Asarian et al. 2019). Years showing higher water temperatures generally coincided with low stream and river flows and high air temperatures; years reporting the lowest stream temperatures coincided with high flows and cool air temperatures (Asarian et al., 2019).

Figure 2. Location of three temperature monitoring sites in the Salmon River watershed



Source: Riverbend Sciences

Why is this indicator important?

Water temperature is a fundamental regulator of river ecosystems. It influences species' metabolism, growth rates, reproduction and distributions (David et al., 2018). The Salmon River watershed provides cold water habitat for anadromous fish, notably steelhead and Coho and Chinook salmon. Identified as a Key Watershed by the US Forest Service, it serves as refugia for at-risk salmon and steelhead stocks in the Pacific Northwest (Elder et al., 2002). This river system still retains wild runs of salmonid species that have disappeared from much of their historic range within California (SRRC, 2020).

Although the Salmon River (pictured in Figure 3) is still affected by the legacy of historic mining that began in the mid-19th century during the California Gold Rush, and some of the watershed's forests have been logged, today's relatively modest human influences make it an excellent location for tracking the effect of climate change on water temperatures (Asarian et al., 2019). The river has no dams and much less water is diverted for human uses in the Salmon River watershed than in other areas of California due to the area's low population density.

Warming summer water temperatures threaten the production and health of culturally and economically important fish in the Salmon River watershed (Asarian et al., 2019). Higher temperatures can increase metabolic demands, susceptibility to disease and pose a threat to fish populations, especially to spring-run Chinook salmon. Fish live in these habitats through the entire summer, and under current conditions peak summer temperatures in portions of the river and its tributaries are likely at or exceeding thermal suitability for this species. The year 2020 marks the second lowest number of returning spring Chinook since surveys began in 1990 and the sixth consecutive year that numbers have been below average (SRRC, 2020). The survival of the dwindling population of spring Chinook salmon, as well as Coho salmon, hangs in the balance. These fish are critical to the food security, cultural survival and well-being of the Karuk Tribe and other indigenous peoples in the Klamath Basin (Karuk Tribe, 2016).

The Karuk Tribe's Ancestral Territory occupies 60 percent of the Salmon River watershed, a sub-basin of the larger Klamath River Basin (Elder et al., 2002). The Karuk consider the Salmon River sub-basin as one of the most culturally significant watersheds within the Klamath National Forest. There is a strong commitment for cooperative stewardship of the watershed among local residents, the Salmon River Restoration Council (SRRC), the Karuk Tribe, the US Forest Service (USFS), and the California Department of Fish and Wildlife (CDFW) (Elder et al., 2002).

In 1994, the North Coast California Regional Water Quality Control Board and the US Environmental Protection Agency determined that beneficial uses in the Salmon River, including cold water salmonid fisheries, are impaired due to elevated water temperatures (NCRWQCB, 2005). Regulations intended to address those impairments were adopted in 2005. Coho salmon in the basin are state and federally listed as threatened (NCRWQCB, 2005). Spring Chinook salmon were listed as endangered by the State of California in June 2021 (Karuk Tribe, 2021) and are currently being considered for listing by the federal government (NMFS, 2021).

Figure 3. Salmon River

Photo Credit: USDA Forest Service

The Salmon River flows from the high peaks of the Salmon Mountains, a sub-range of the Klamath Mountains, in far Northern California. It is the second largest tributary to the Klamath River and joins the Klamath at Somes Bar, California, about 106 km (66 miles) upstream from the Pacific Ocean.

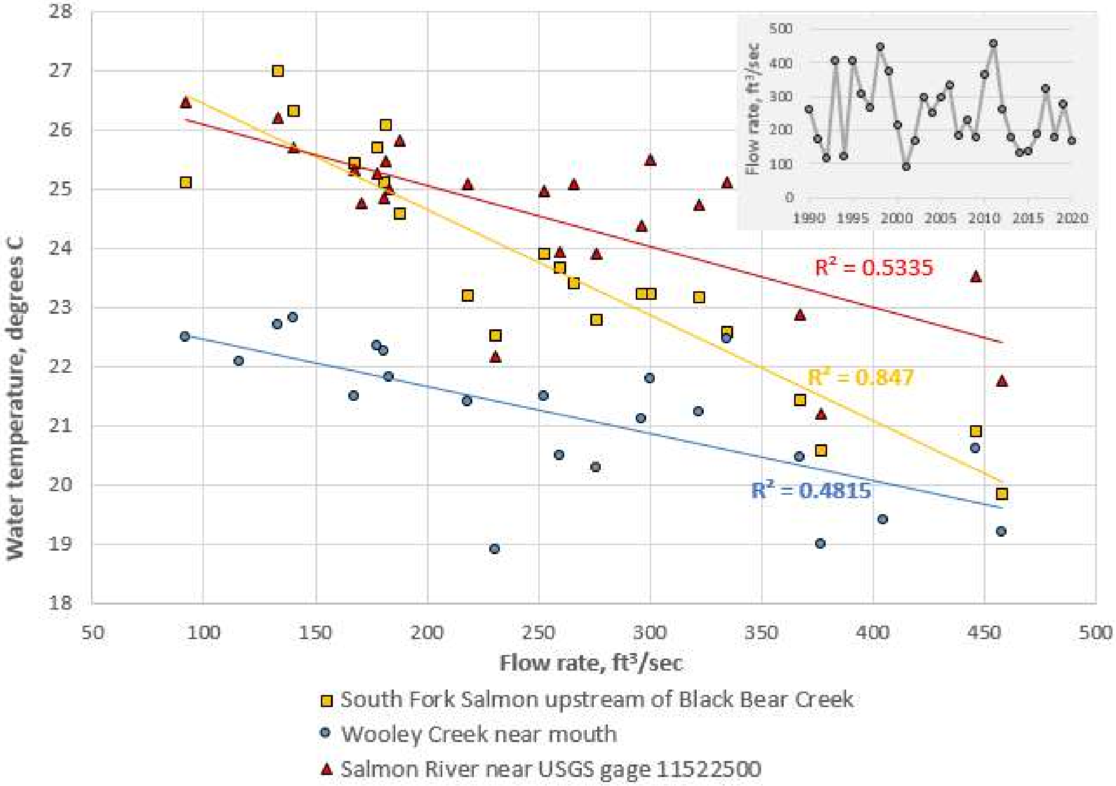
What factors influence this indicator?

Summer stream temperatures in the Salmon River and its tributaries are trending warmer due to warming air temperatures, decreased snowpack, earlier snowmelt and spring runoff, and decreases in water flow (Asarian et al., 2019). Years of low snowpack and snow water runoff tend to yield decreases in stream and river flow in watersheds

(Asarian, 2020). Since the 1940s, April 1 snowpack has been decreasing in the Salmon River watershed (CDEC, 2021; Van Kirk and Naman, 2008). Since summer river flow is strongly influenced by snowpack, temperatures at the South Fork Salmon River site are particularly sensitive to climate change and have warmed relatively rapidly since monitoring began in 1997. Water temperature has been increasing at the highest rate at this location (Figure 1).

Streamflow is an important determinant of water temperature. River and stream temperatures are cooler when flows are high and warmer during years with diminished flows. Figure 4 shows the relationship between stream flow rates during the month of August at the Salmon River monitoring station and maximum temperatures at the three stations shown in Figure 1. Low August flow rates coincided with warmer stream temperatures in 2001, 2014, and 2015. Conversely, higher flow rates in 1999, 2010, and 2011 corresponded with much cooler stream temperatures during those years.

Figure 4. River water temperatures and August stream flow (1992-2020)



Source: Karuk Tribe, SRCC, and USFS 2021 (water temperatures); USGS 2021 (streamflow)

Annual maximum water temperatures at the three monitoring sites are plotted against average August streamflow measured at the Salmon River monitoring station (at Somes Bar, USGS Gage 11522500). (R^2 values indicate the strength of the correlation; a value of 1 indicates a perfect correlation between the variables.) The inset graph presents annual average August streamflow over the past 30 years.

A symptom of warmer temperatures and less snow is the complete melting of the Salmon Glacier in the Trinity Alps at the headwaters of the Salmon River's South Fork in 2015 following a multi-year drought and many decades of ice loss (Garwood et al., 2020; also see *Glacier change* indicator). The nearby Grizzly Glacier which drains to the Trinity River has declined by 97 percent since 1885. When these glaciers were larger in previous decades, they fed cold water to streams during the summer.

A number of other physical factors influence water temperatures in streams and rivers, including solar radiation, heat radiated from objects (e.g., clouds and vegetation), evaporation, convection of heat from air to water, conduction of heat between the water and stream bed, and mixing of water from different sources (Dugdale et al., 2017). During the summer, water temperatures in streams and rivers with wider channels that are more exposed to solar radiation tend to be warmer than water upstream in small well-shaded streams. Water temperatures fluctuate over time in response to atmospheric conditions (air temperatures, clouds, and smoke), hydrologic conditions (snowmelt, rain, stream flow, and groundwater), and growth or loss of vegetation. Factors affecting spatial patterns in water temperature include elevation (cooler air temperatures at higher elevations), topography (mountainous terrain reduces solar exposure), and near-stream vegetation (cooler temperatures where trees provide shade). Wooley Creek flows through steep, mountainous terrain, which partially protects it from solar radiation and keeps its waters relatively cool for its size. As shown in Figure 1, temperatures are increasing at a slower rate at Wooley Creek due to these characteristic features.

Shade provided by near-stream vegetation has the effect of cooling water temperatures. Fire plays an integral role in regulating vegetation in the Salmon River watershed. Prior to fire suppression that became effective in the early/mid-20th century, fires burned more frequently and typically in smaller patches compared to what is occurring today (Skinner et al., 2018). Approximately a century of fire suppression has dramatically altered forest structure and fuel continuity. As a result, when fires now occur and escape containment, the probability of high fire severity is increased, which can reduce stream shade and increase water temperature (Karuk Tribe, 2016).

Researchers have been studying the effects of wildfire smoke and its potential to cool water temperatures. David et al. (2018) analyzed ground-based measurements of air and water temperatures from 12 stations throughout the lower Klamath River Basin in correlation with atmospheric smoke data derived from satellite imagery during six years with widespread wildfires. The analysis indicated that wildfire smoke had a cooling effect on both air and water temperatures at all study locations. This smoke-induced cooling has the potential to benefit cold-water adapted species, particularly because wildfires are more likely to occur during the warmest and driest years and seasons. A follow-up analysis of a larger number of stations showed the cooling effects of smoke were greater in August than in other months and were stronger in larger waterbodies than smaller waterbodies (Asarian et al., 2020). Wildfire smoke has limited increases in August water temperatures, but has not affected annual maximum water temperatures because in most years fires do not start until after the year's hottest water temperatures have already occurred. The Karuk Tribe has used fire to manage the mid-Klamath landscape since time immemorial, and has proposed using prescribed fire smoke as an emergency measure to cool potentially lethal stream temperatures in fish habitat areas (Karuk Tribe, 2019).

Researchers conducted an analysis of both climate and non-climate factors and their comparative influence on August stream temperatures using statistical models (Asarian et al., 2019). The climate parameters evaluated were streamflow, air temperature, snowpack, and smoke; the non-climate parameters included landscape features such as riparian vegetation and river channel morphology. The results of the analysis indicated that the warming stream temperatures observed across the Salmon River watershed are largely attributed to climate conditions. The greatest amount of warming occurred at sites whose temperatures are highly sensitive to river flow, including the South Fork of the Salmon River.

Technical considerations

Data characteristics

The Salmon River Restoration Council (SRRC); the Karuk Tribe; and US Forest Service (USFS) [Klamath National Forest (KNF) and Six Rivers National Forest (SRNF)] have been monitoring water temperatures in the Salmon River Watershed since 1990 using automated probes that record measurements every 15–60 minutes. Probes are placed in well-mixed flowing water and are intended to represent overall conditions (i.e., "stream temperature"), not isolated pockets of cold or warm water. At most sites, probes are deployed in late spring or early summer, remain through the summer, and are retrieved in the fall for data download (KNF, 2011). A few sites are monitored year-round.

Sampling and equipment and monitoring techniques have changed since monitoring began in 1992. Prior to 2010, the KNF, SRNF, and SRRC used a combination of Pro v2 u22-001, Optic StowAway, and other ONSET temperature logger models (Onset Computer Corporation, 1999). Ryan TempMentors data loggers were used only by KNF in 1992–1993 at Wooley Creek (TFWTWG, 1990). At the Salmon River gage, the Karuk Tribe used a Hydrolab 4a for 2005–2006 and a YSI 6600 V2 datasonde for 2007 to present (Karuk Tribe 2006, 2007, 2018). Since 2010, KNF, SRNF, and SRRC have used ONSET Pro v2 data logger u22-001 for all temperature monitoring (KNF, 2011).

Although many sites are monitored, a subset of three sites that have long, relatively complete records were selected for this indicator:

1) Salmon River at USGS gage 11522500, approximately 1 mile upstream from its confluence with the Klamath River. In addition to the seasonal temperature probes placed by the USFS at this site, the Karuk Tribe also operates a

permanent monitoring station here that provides year-round multi-parameter water quality data available online in real-time at: https://waterquality.karuk.us/Data/Location/Summary/Location/11522500

2) Wooley Creek, approximately 0.3 miles upstream from its confluence with the Salmon River. Wooley Creek is one the Salmon River's largest tributaries and its watershed is entirely protected within the Marble Mountain Wilderness, so human impacts are slight.

3) South Fork Salmon River upstream of Black Bear Creek. Long-term data analyses (Asarian et al., 2020) show that water temperatures at this site are highly sensitive to river flow, with temperatures being cool in high-flow years and warm in low-flow drought years.

Strengths and limitations of the data

There are many ways to summarize stream temperature data, and previous Salmon River analyses (Asarian et al., 2019, 2020) evaluated trends for multiple metrics of summer stream temperature. For this indicator, annual maximum temperature is the highest instantaneous maximum temperature recorded during the summer. This metric was chosen because it is simple to calculate, easy to understand, and biologically meaningful. This metric was calculated only for sites and years when there were enough data to be representative (i.e., complete measurements available during the hottest period of the summer) (Asarian et al., 2020). Equipment and techniques for monitoring these sites have improved over time.

Figure 1 shows data gaps for certain years at the Wooley Creek and South Fork monitoring sites. Reasons for data gaps include logistical constraints preventing site access (e.g., fires or staffing shortages), probes malfunctioning, loss of probes due to vandalism, or low water levels exposing probes to air.

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OEHHA respects the right of tribal nations to govern the collection, ownership, and application of their data. The Karuk Tribe has given OEHHA permission to use the water temperature data and related information presented in this indicator.

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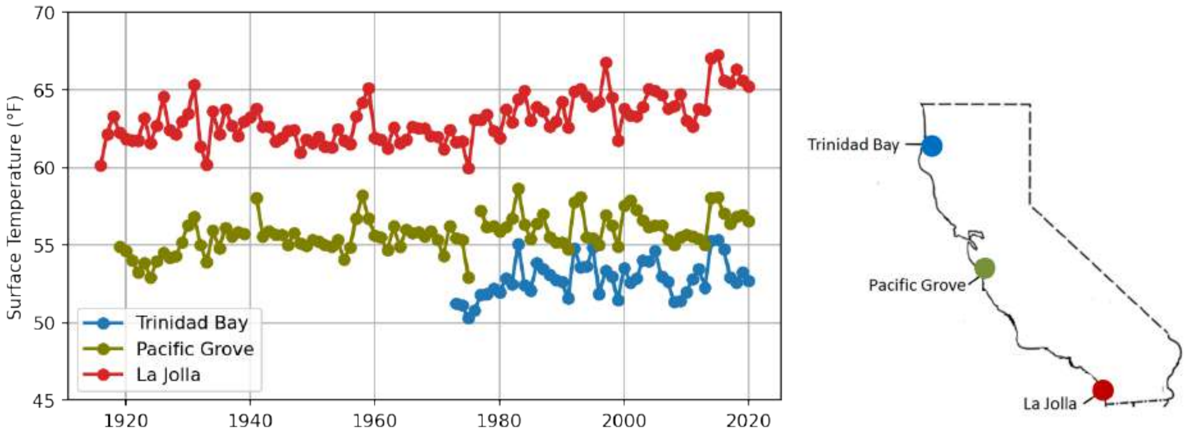
COASTAL OCEAN TEMPERATURE

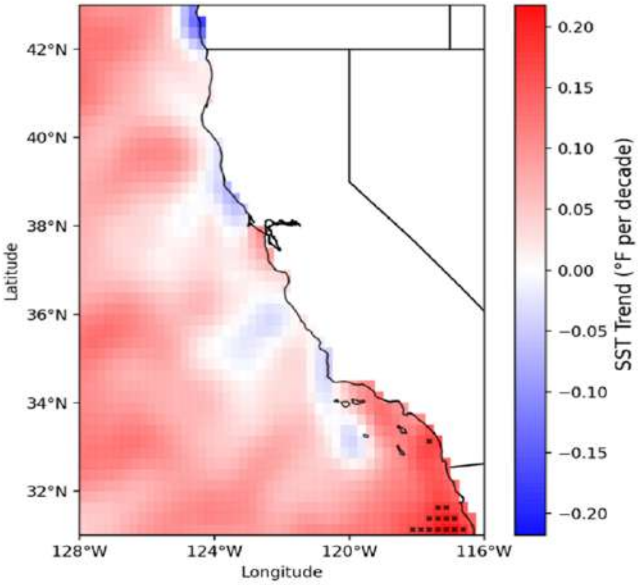
Measurements at California's shore stations show that nearshore coastal waters have warmed over the past century, particularly in Southern California. Similarly, satellite-based records over the past four decades show warming ocean waters off Southern California. An unprecedented marine heatwave affected the West Coast of the United States from 2014 to 2016.

Figure 1. Annual average sea surface temperatures (SST) at selected shore stations (1916-2020)



Source: SIO. 2021

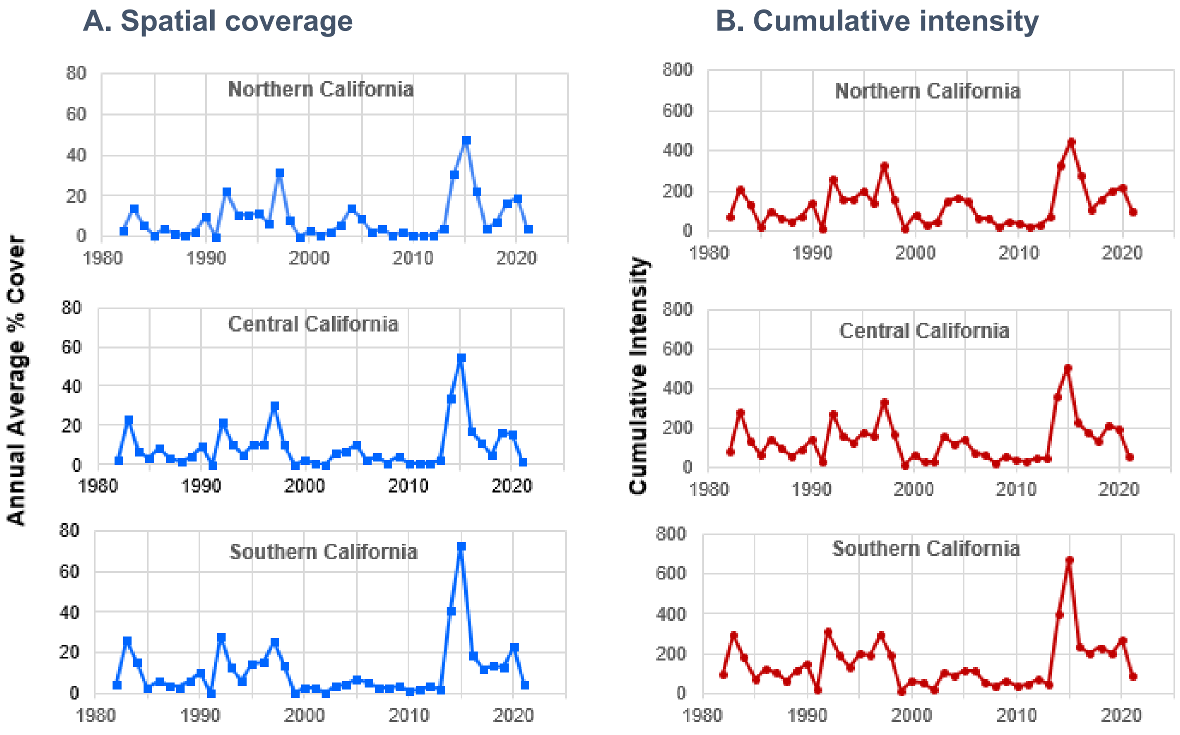
Figure 2. Satellite-based sea surface temperature (SST) trends along the California Coast (1982-2021)



Source: NOAA, 2021a

The map shows SST trends off the California coast, in °F per decade, for the 40-year period (1982 to 2021). Black dots (one off San Diego County; the rest off Mexico) denote locations with statistically significant trends (p<0.05).

Figure 3. Marine heat waves off California (1982-2021)



Source: Data provided by Leising, 2022;
also available at NOAA, 2022

*A **marine heat wave** occurs over a region when the difference between the sea surface temperature (SST) and the long-term mean (1971-2000) is above the 90th percentile of all values for a given location on a given day of the year. **[A]**: **Spatial coverage** is the annual average percentage of the region in heat wave status; **[B]**: **Cumulative intensity** is the annual sum of daily average SST measurements above the long-term mean. See Figure 4 for a map of the regions.*

What does the indicator show?

California coastal ocean temperatures have warmed over the past century. Although sea surface temperature (SST) fluctuates naturally each year, warming SST trends of are clearly detected. The longest time series for SSTs are based on measurements at shore stations along the California coast. Figure 1 presents data for three of these stations. SST has increased at the rate of 0.2 degree Fahrenheit (°F) per decade at Pacific Grove between 1919 and 2020, and at a faster rate of 0.3°F per decade at La Jolla between 1916 and 2020. At Trinidad Bay, SSTs increased at the rate of 0.3°F per decade over a shorter time period (1973-2016). All three stations show statistically significant trends ($p<0.05$). SSTs have also increased at other shore stations along the coast (Table 1). Stations farthest south, La Jolla and San Clemente, are experiencing the most warming.

Table 1. Trends in sea surface temperature (°F per decade) at shore stations (p-values less than 0.05 indicate statistical significance.)

Station	Years	Decadal Trend	*p*-value
Trinidad	1973 - 2020	0.34	0.007
Farallon Island	1925 - 2020	0.09	0.061
Pacific Grove	1919 - 2020	0.18	< 0.001
Granite Canyon	1971 - 2020	0.33	0.001
Santa Barbara	1955 - 2020	0.23	0.009
Point Dume *	1956 - 2020	0.21	0.067
Newport Beach	1924 - 2020	0.08	0.194
San Clemente	1965 - 2020	0.39	< 0.001
La Jolla	1916 - 2020	0.27	< 0.001

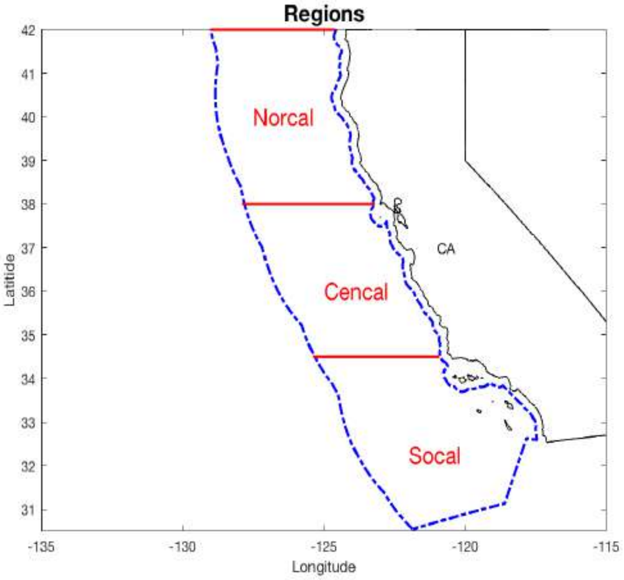
**Uncertain values for Point Dume between 1995 and 2006 were not included in the analysis.*

Globally, average SSTs have increased by 0.88°C (~1.58°F) since the beginning of the 20th century (IPCC, 2021). The global surface temperature — over both land and oceans — has warmed at a rate of about 0.14°F per decade since 1880; the rate of warming from 1981 to 2020 was over twice that rate, at 0.32°F per decade, reflecting sharper increases in sea surface temperatures over the recent period (NOAA, 2021). The Southern California coastal trend over the last four decades is consistent with that sharp global increase.

Four decades of satellite-based data from the National Oceanic and Atmospheric Administration Optimal Interpolation SST reanalysis (NOAA OISST) allow the tracking of SST trends along the entire coast of California and offshore; this would not have been possible with shore station data alone (Huang et al., 2021; Reynolds et al., 2002). As shown in Figure 2, for the period 1982-2021, the waters over the state's continental shelf (within approximately 30 nautical miles offshore) have both warmed and cooled, although the trends are generally not statistically significant ($p>0.05$). However, offshore waters are largely warming. Both near-shore and offshore, Southern California is exhibiting a distinct warming trend compared to the rest of the state, with warming being more prominent near shore.

In recent years, prolonged periods of extremely high ocean temperatures, known as marine heatwaves (MHW), have occurred across the globe, focusing attention on their devastating effects on the marine ecosystem. Two metrics for tracking the size and intensity of MHWs are presented in Figure 3 for Northern, Central and Southern California; see Figure 4 for a map of the regions. A MHW is an extreme climate event in which anomalously warm sea surface temperatures are observed in a region (Oliver et al., 2021). Specifically, a MHW over a region occurs when the difference between the SST and the long-term or "climatological" mean for the period 1971-2000 (the difference is also known as the "anomaly") for a given time and place is above the 90th percentile of the values for a baseline period (Hobday et al., 2016). See discussion in *Technical Considerations* for more information about the metrics. As shown in Figure 3, the largest and most intense MHW recorded in the three regions of California – known as "the Blob" – occurred in 2014 to 2016. While MHWs have occurred in the past, the magnitude and duration of the warming during this event was unprecedented for the west coast of North America (Di Lorenzo and Mantua, 2016; Gentemann et al., 2017). Other notable MHWs occurred in 1983, 1992, 1997 (all associated with El Niños), and more recently in 2019 and 2020 (which, unlike MWHs associated with El Niños, originated in the south, rather than from the Central North Pacific) (Leising et al., 2015).

Figure 4. Marine heatwave monitoring off the California coast



Source: NOAA, 2022

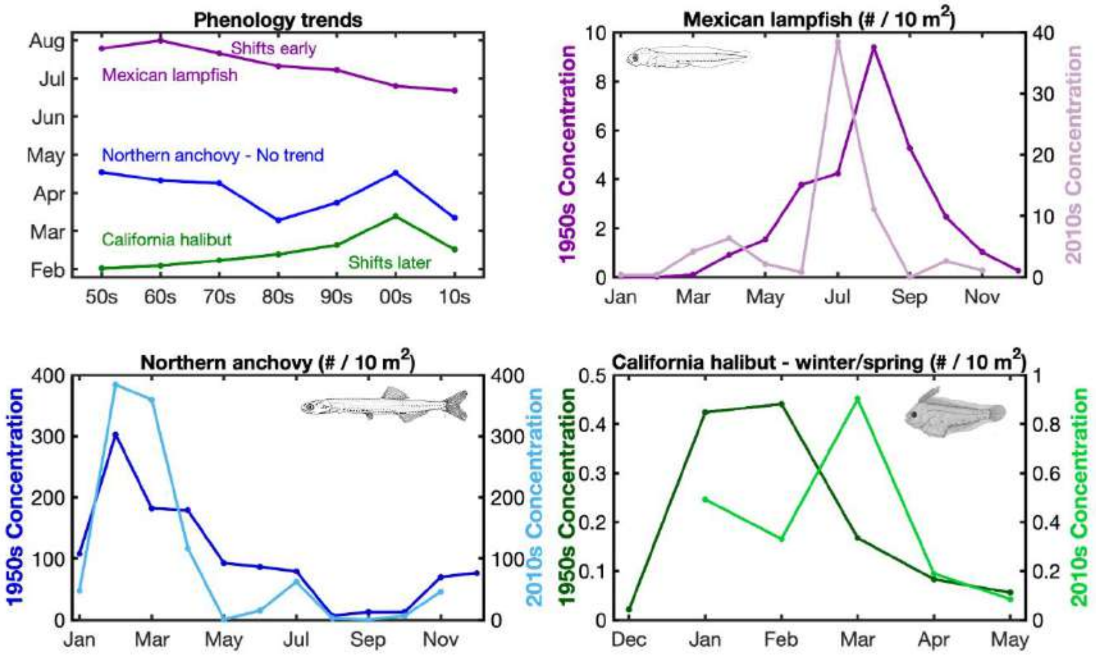
Marine heat waves are monitored along the California Current, including in three regions off the California coast designated as Northern, Central and Southern California regions.

In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) reports that MHWs have become more frequent over the 20th century, approximately doubling from 1982 to 2016; they have also become more intense and longer in duration since the 1980s (IPCC, 2021). Over the last two decades, MHWs have occurred in all of the world's ocean basins.

Why is this indicator important?

Temperature is one of the best-measured signals of climate change. As atmospheric concentrations of greenhouse gases increase, excess heat is absorbed and stored by the oceans and atmosphere. The ocean's large mass and high heat capacity allow it to store large amounts of heat. It is estimated that over 90 percent of the observed heat energy increase on the Earth over the past 50 years has occurred in the ocean (Jewett and Romanou, 2017; NOAA, 2021b; Rhein et al., 2013). In addition to absorbing excess heat, the ocean also absorbs about 30 percent of carbon emissions. As a result, the ocean acts as a buffer against global warming (IPCC, 2019).

Figure 5. Decadal changes in peak fish larvae abundance



Source: Asch, 2015; updated 2021 using data from California Cooperative Oceanic Fisheries Investigations pers comm.

Graph, top left, shows shifts in the timing of peak larvae abundance (number of fish per 10 m^2) for the northern anchovy, California halibut and Mexican lampfish in Southern California waters. Separate graphs compare peak larvae abundance in the 1950s with the 2010s for three fish species. Peak timing shifts earlier in the year for Mexican lampfish and later for California halibut; northern anchovy showed no trend.

Changes in SST along the coast of California have been shown to alter the distribution, abundance, and recruitment of many marine organisms, including commercially important species. Fluctuations in the distribution and abundance of many California coastal marine populations have been related to temperature variability (e.g., Goericke et al., 2007; IPCC, 2019; Sagarin et al., 1999). The direct effects of temperature on the physiological performance of marine organisms and the timing of their key developmental stages (such as from egg to larva) are the likely mechanisms underlying these patterns. Several fish species have shifted their spawning phenology between the 1950's to the 2010's due to increased ocean temperature (Asch, 2015). Commercial species such as California Halibut shifted to reproduce earlier while prey fish Mexican Lampfish and Northern Anchovy shifted to later reproduction or had no change in spawning phenology, respectively (Figure 5). Water temperature can also influence species indirectly, by altering interactions between species and their competitors, predators, parasites, facilitators, and prey.

The California Current, which extends from British Columbia, Canada to Baja California, Mexico, is one of four major "Eastern Boundary Upwelling Systems" – biologically productive marine regions that cover less than one percent of the ocean area, but provide about 20 percent of the world's ocean fish catch (Mann, 2000). In these systems, coastal upwelling creates a band of cool waters along the coast, supplying the food chain with nutrients, and providing habitat that supports high biological productivity. During the Blob, anomalously warm offshore waters in the California Current Ecosystem restricted the cool upwelling habitat to a narrow band along the coast, resulting in reduced upwelling habitat, or "habitat compression" (Santora et al., 2020). This compression was associated with changes in the composition and distribution of marine species, including whale prey. Alterations in prey abundance and distribution, in combination with a delayed Dungeness crab season and other factors, contributed to record increases in whale entanglements in fishing gear during this MHW. To support efforts to understand and mitigate the causes of whale entanglements, a recently developed "habitat compression index" (HCI) tracks patterns in the surface area of cool water over time. A low HCI value indicates that cool habitat is compressed onshore. The HCI is used to assess the likelihood of ecosystem shifts and shoreward distribution patterns of whales and other top predators. The HCI and other indicators of conditions associated with whale entanglements are presented in an online "Whale Entanglement Data Dashboard."

The extremely high temperatures during MHWs have had dramatic effects on the marine ecosystem. MHWs in the 1980's and 1990's, associated with El Niño events, led to negative consequences for the marine ecosystem through local processes (such as changes in physical and chemical properties, and food web changes) and advection, or poleward and/or onshore transport of organisms (Ohman et al., 2017). The 2014-2016 MHW was associated with mass strandings of some marine mammals and sea birds (Cavole et al., 2016; Piatt et al., 2020). High temperatures initiated toxic algal blooms that affected the commercial and recreational crab fishing season and poisoned marine mammals (Gentemann et al., 2017). The closure of the Dungeness crab fishery alone led to a loss of an estimated $48 million in revenue for crab fishermen statewide (Brown, 2016).

The MHW also contributed to the rapid and extensive loss of kelp forests in Northern and Southern California (Gleason et al. 2021, Cavanaugh et al., 2019). In Northern California this led to the closure of the recreational red abalone fishery and the commercial red sea urchin fishery (Gleason et al. 2021). Both kelp and abalone are culturally significant species to Native American Tribes, such as the Chumash and the Scotts Valley Band of Pomo Indians (Santa Ynez Band of Chumash Indians, 2022; Amah Mutsun Tribal Band, 2022; Big Valley Band of Pomo Indians and Middletown Rancheria of Pomo Indians, 2021). Since kelp provide a wide range of ecosystem services as primary producers and as essential habitat for marine organisms, among other things, the loss of kelp forests has larger scale consequences (Bell et al., 2020; Gleason et al, 2020; Teagle et al., 2017). For example, without kelp forests to act as buffers, the coast has become more vulnerable to coastal erosion from high energy storms and swell events; along with sea level rise, coastal erosion is threatening cultural sites along the shoreline in the Amah Mutsun's ancestral territory (Amah Mutsun Tribal Band, 2022).

The 2014-2016 MHW was accompanied by northward shifts in the geographic distributions of a variety of marine animals including fish, sea turtles, pelagic red crabs, southern copepods and many other marine invertebrates (Leising et al., 2015; Cavole et al., 2016; Sanford et al., 2019). During the 2014-2016 and 2019-2020 MHWs, the increased abundance of lipid-poor southern copepods and the decreased abundance of lipid-rich, higher nutritional value northern copepod impacted the entire food web (Cavole et al., 2016, Weber et al., 2021).

Temporary shifts in other species distributions have also occurred during past warm-water anomalies, including major El Niño-Southern Oscillation (ENSO) events (Pearcy and Schoener, 1987), however, these recent North Pacific-originating MHWs differ from El Niños in that they tend to bring a somewhat different assemblage of organisms into the California Current (Leising et al., 2015; Cavole et al., 2016). While the impacts of coastal temperature change are increasingly being documented, offshore temperature variability is complex and may influence a suite of other biological processes, including migration patterns.

Changes in temperature can affect the chemical and physical properties of the ocean. Since warmer water is less dense than colder water, changes in SST can alter currents and transport patterns. Warming SSTs can cause more stable layers of seawater to form near the surface, thus increasing "stratification"; when this happens, upwelling and vertical mixing that transports nutrients, oxygen, carbon, plankton and other material across ocean layers is reduced (Roemmich and McGowan, 1995; Jacox and Edwards, 2011). Temperature also affects the solubility of gases in ocean waters. For example, warmer waters hold less oxygen, while also accelerating the rate of oxygen consumption by marine organisms (e.g., Somero et al., 2015; Breitburg et al, 2018).

Surface ocean water temperature affects weather, specifically the occurrence of coastal fog and the strength of winds, as well as the thickness of the marine atmospheric boundary layer. The latter is a primary factor controlling the inland intrusion of cool coastal air and therefore inland weather patterns. Warmer waters play a role in extreme weather events by increasing the energy and moisture of the atmosphere. Warmer ocean temperatures also contribute to global sea level rise because warming water not only expands but also accelerates the melting of land-based ice sheets (IPCC, 2021).

Global oceans are projected to continue to warm in the 21st century. MHWs are expected to further increase in frequency, duration, spatial extent, and intensity, although changes will not be globally uniform (IPCC, 2021). Given the severe impacts of MHW on the marine ecosystem and the coastal communities and economies it supports, oceanographers have developed the California Current MHW Tracker as a tool for forecasting future MHWs (NOAA, 2022).

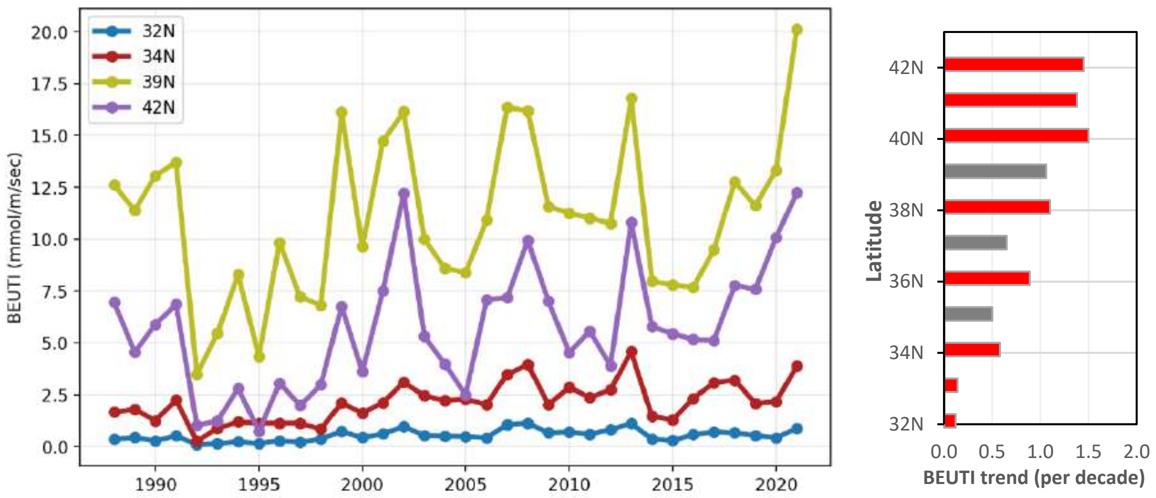
What factors influence this indicator?

Global SSTs have increased due to a net heat flux from the atmosphere stemming from the greenhouse effect. Deeper regions of the oceans have also warmed, to depths of 3000 meters during the past several decades (first documented by Levitus et al., 2001; also Levitus et al., 2012). A combination of oceanic and atmospheric processes, including ocean currents, winds, and climate modes like El Niño can lead to the periods of extremely high ocean temperature, and their classification as MHWs depends on the magnitude of 'normal' warming events in a given location (Hobday et al., 2016).

Near-surface ocean water temperatures along the California coast are influenced by seasonal upwelling, already discussed above. Historically, upwelling was measured using only estimates of the amount of water transported. A new index called the Biologically Effective Upwelling Transport Index, or BEUTI (pronounced "beauty") incorporates estimates of the amount of nutrients (nitrate) in vertically transported waters, thus providing information relevant to biological responses (Jacox et al., 2018).

As shown in Figure 6A, annual mean values for BEUTI (in millimoles of nitrate per meter per second) are highest – indicating more effective upwelling – along Northern California, especially at 39°N (due to the enhancing effect of the promontories at Point Arena and Cape Mendocino on the winds). Considerably less effective upwelling occurs along the Southern California coast at 32°N (south of San Diego) and 34°N (off Los Angeles). This difference is due to a combination of strong upwelling-favorable winds in Northern California and cooler waters flowing from the north Pacific within the California Current; the small temperature difference between surface and deeper waters means weaker stratification, which facilitates upwelling. In contrast, Southern California experiences weak upwelling-favorable winds and greater stratification, as warmer waters from the equatorial Pacific dominate (Bograd et al., 2019). Figure 6B shows that over the past 33 years, upwelling trends have generally increased along a latitudinal gradient, with larger increases in Northern California.

Figure 6. Biologically Effective Upwelling Transport Index (BEUTI) along the California Coast



A. **Annual mean values at selected latitudes**

B. **Decadal trends, 1988-2021**

Source: NOAA, 2021

[A] Annual mean values of BEUTI at selected latitudes along the California Coast: 32°N, south of San Diego; 34°N, Los Angeles; 39°N near Point Arena, and 42°N near the California-Oregon border. [B] Linear trends in the magnitude of BEUTI per decade at different latitudes along the California Coast; red bars indicate statistically significant trends ($p<0.05$)

Trends in coastal temperatures are complex owing to the simultaneous interaction of surface warming and the cooling effect of upwelling. In general, it is expected that surface temperatures will increase offshore and in sheltered coastal waters, where upwelling does not occur or is weak, as observed in the warming trends of La Jolla. In contrast, cooler or non-changing SSTs are expected during the upwelling season in open shelf waters (Seabra et al., 2019), especially off Central and Northern California (García-Reyes and Largier, 2010; Largier et al., 2010). The lack of statistically significant warming trends in the Central and Northern California coast in the last four decades may be an indication of the cooling effect of upwelling in coastal waters. In certain upwelling regions, including the California Current, studies suggest that upwelling favorable winds may intensify with climate change (Bakun, 1990; García-Reyes et al., 2015; García-Reyes and Largier, 2010; Rykaczewski et al., 2015; Sydeman et al., 2014). In the last three decades, the influx of nutrients to the coastal area has increased (Figure 5), likely as a result of the concurrent increase in upwelling favorable winds.

Natural fluctuations in temperature, wind, and circulation patterns that occur in coastal waters can introduce significant interannual and interdecadal fluctuations in the long-term trend. The El Niño (or La Niña) events, positive (negative) phases of the El Niño-Southern Oscillation (ENSO), are responsible for anomalously warm (or cool) ocean temperatures along the California coast. El Niño is the warm or positive phase, with major El Niño events occurring every 5-10 years (UCAR, 1994). La Niña is the cool or negative phase. Additionally, the West Coast is affected by multi-decadal variability in temperature, characterized by patterns such as the Pacific Decadal Oscillation, or PDO (Mantua et al., 1997), and the North Pacific Gyre Oscillation, or NPGO (Di Lorenzo et al., 2008). MHW occurrence involves two interwoven processes: a long-term increase in temperatures driven by anthropogenic climate change and large amplitude fluctuations that are enhanced because of that increase (Fumo et al., 2020). Recent work projects that future SSTs will continue to increase; globally, SSTs for the years 2070 to 2099 are projected in many regions to be warmer than the warmest year in the period from 1976 to 2005 (Alexander et al., 2018).

Technical considerations

Data characteristics

Coastal California is home to the longest continuous record of SST on the US West Coast and the Pacific Rim. Long-term time series from three sites — Trinidad Bay in Humboldt County, Pacific Grove in Monterey County, and La Jolla in San Diego — are presented in this report; these sites were chosen based upon their long operational duration (~40 to 100 years), public data availability, and regional/geographic coverage. Data for the three sites and other California coastal sites have been collected by the Shore Stations Program (SIO, 2021). The time series at Scripps Pier, La Jolla Shores, which extends back to 1916, is the longest running SST data set in the state.

Trinidad Bay temperature measurements are taken daily by staff from the Humboldt State University Marine Laboratory, located on the rocky headland between the ocean and Trinidad Bay. Bay temperature is measured from the fishing pier on the southeast side of the headland. Pacific Grove measurements are taken daily by staff from Stanford University's Hopkins Marine Station from a beach on the north side of Point Cabrillo. This location is representative of coastal conditions on the south side of Monterey Bay. La Jolla temperature measurements are taken daily at Scripps Pier by representatives from Scripps Birch Aquarium. The proximity of the pier to the deep waters at the head of La Jolla submarine canyon results in data representative of oceanic conditions.

The NOAA OISST reanalysis data (v2, Huang et al., 2021) merges satellite and in situ measurements from different platforms into a single gridded SST product, allowing a spatial resolution of roughly 13nm along California (here averaged longitudinally to ~30nmi), and daily temporal resolution, starting in September 1981.The dataset is interpolated to fill gaps on the grid and create a spatially complete map of sea surface temperature. Satellite and ship observations are referenced to buoys to compensate for platform differences and sensor biases (NOAA, 2021a). Data are provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA.

MHW cover and cumulative intensity are products reported in the California Current Marine Heatwave Tracker, an experimental tool for tracking marine heatwaves from

British Columbia to Baja, along the path of the California Current. The tool was designed to investigate the 2014-2016 MHW (NOAA, 2022). Indices are developed to help forecast or predict future MHWs expected to impact the coast. A MHW is based on the definition in Hobday, et al. (2016); however, no time constraint was used since values were summed over relatively large regions. The analysis presented here is based on a long-term baseline mean for the period 1971 to 2000, and the threshold was set at the 90th percentile of all values for the period 1982-2021. Further information about the tracker, including access to the data, is available at the Integrated Ecosystem Assessment webpage.

Five regions along the California Current are monitored, including three in California as shown in Figure 5. For each region, the “spatial coverage,” is calculated as the annual mean of the daily percentage of the area in “heatwave status”. This describes the size of the MHW each year. “Intensity” describes how hot the ocean waters are compared to a historical baseline. This index does not depend on whether it is in “heatwave status.” The “cumulative intensity” presented in Figure 3B is the sum of daily intensity values in a year for a given region, specifically the sum of average daily SST measurements above the baseline temperature. These temperature measurements are standardized for the location and time of day to ensure that the data is comparable over time. The cumulative intensity is the sum of the daily intensity values.

Strengths and limitations of the data

A growing network of ocean monitoring along California is an important resource for separating natural and anthropogenic influences on increasing temperatures. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) and National Oceanic and Atmospheric Administration (NOAA) National Data Buoy programs represent the largest coordinated efforts to collect SST data across broad spatial scales. In addition, the Central and Northern California Ocean Observing System and the Southern California Coastal Observing System provide coordinated long-term monitoring of environmental conditions to support ocean management decisions as part of an eleven-region US Integrated Ocean Observing System (IOOS, 2018).

The NOAA satellite-based product provides a shorter SST record than those of the shore stations, however its record has no spatial gaps and a larger cover offshore, allowing a better understanding of the different trends observed in this indicator along the California coast and over the continental shelf (NOAA, 2021a). It is important to note that the data points closest to shore cover waters over the continental shelf, and do not represent temperatures near shore (beaches and intertidal) values due to its coarser resolution. For nearshore values, the coastal values are more representative, although sparse in space.

Temperature and BEUTI were averaged annually before trends were calculated. This reduces the number of data points and therefore statistical significance.

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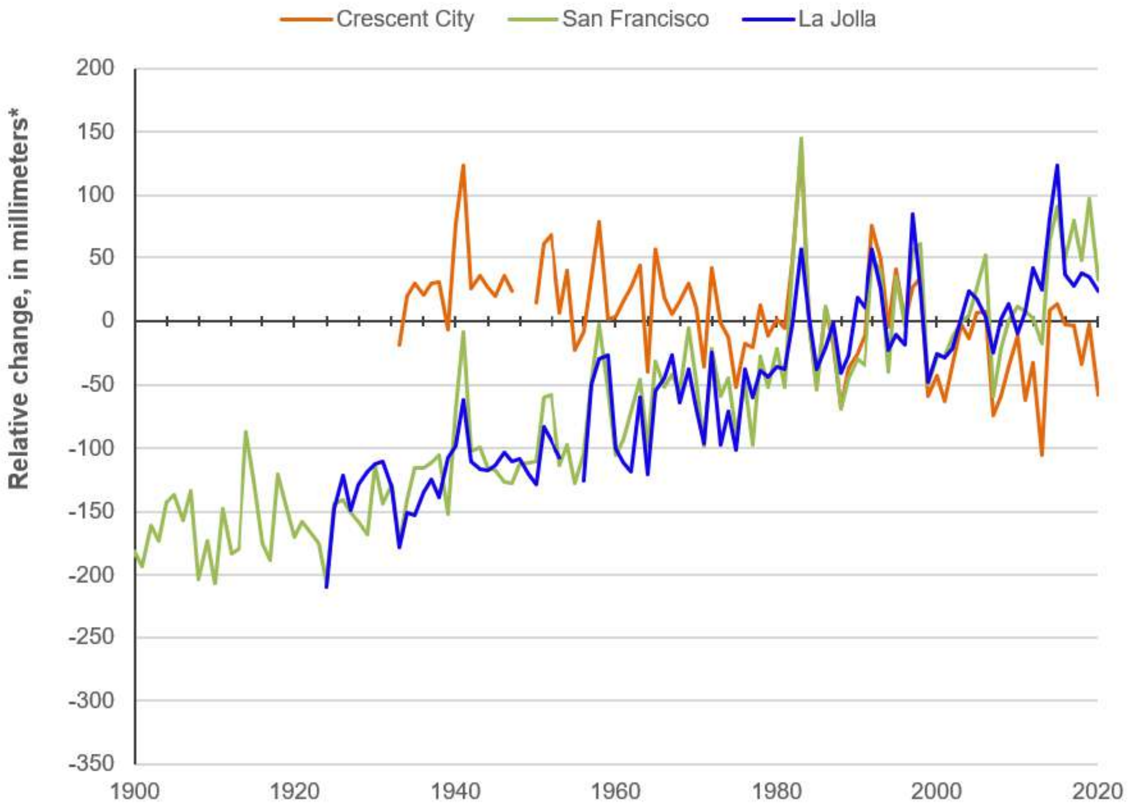
SEA LEVEL RISE

Sea levels along the California coast have risen over the past century, except along the far north coast where an uplift of the land surface has occurred due to the movement of the Earth's plates, resulting in a small relative fall in sea level.

Figure 1. Annual mean sea level trends



Source: NOAA, 2021a

**Relative to tidal datum (reference point set by NOAA)*

What does the indicator show?

As shown in Figure 1, mean sea levels have increased over the past century by about 200 millimeters (mm) (8 inches (″)) in San Francisco and in La Jolla. This is consistent across the California coastline except for Crescent City where the sea level has declined by about 80 mm (3″) due to regional land uplift driven by the movement of the Earth's plates. Sea level values are the average height of the ocean relative to the tidal datum, a standard elevation established by the National Oceanic and Atmospheric Administration (NOAA) as a reference point (see *Technical Considerations* for details).

Mean sea levels show year-to-year (interannual) variability. They peak during El Niño years (when the waters of the eastern Pacific Ocean became warmer, temporarily raising coastal water levels from 10 to 40 centimeters (cm), or about 4 to 16″). Levels at all three locations rose in 2014 and 2015, due to unusually warm sea surface temperatures in the Pacific Ocean during that period (Hu et al., 2017), further exacerbated by the large El Niño that peaked in late 2015 (Flick et al., 2016).

Trends at 17 tide stations in California (see map, Figure 2) are presented in Table 1, listed in order from north to south (NOAA, 2021).

Figure 2. Trends at California tide stations

Source: NOAA, 2021a

Interactive map is online at [NOAA's Tides and Currents webpage]

Table 1. Sea Level Trends (stations listed from north to south)

Location	Period of record	Trend, mm/year (inches/year)
Crescent City	1933-2020	-0.79 (-0.03)
North Spit	1977-2020	+4.91 (+0.2)
Arena Cove	1978-2020	+0.89 (+0.04)
Port Chicago*	1976-2020	+2.03 (+0.08)
Point Reyes	1975-2020	+2.15 (+0.08)
Alameda*	1939-2020	+0.87 (+0.03)
San Francisco	1897-2020	+1.97 (+0.08)
Redwood City*	1974-2020	+2.54 (+0.1)
Monterey	1973-2020	+1.63 (+0.06)
Port San Luis	1945-2020	+0.96 (+0.04)
Santa Barbara	1973-2020	+1.08 (+0.04)
Rincon Island**	1962-1990	+3.22 (+0.1)
Santa Monica	1933-2020	+1.54 (+0.06)
Los Angeles	1923-2020	+1.03 (+0.04)
Newport Beach***	1955-1993	+2.22 (+0.09)
La Jolla	1924-2015	+2.13 (+0.08)
San Diego	1906-2020	+2.2 (+0.09)

** Gauge not along the outer coast*
*** Rincon Island is an artificial offshore island built for oil and gas production*
**** Inactive*

Source: NOAA, 2021a

The general trend towards higher sea levels in California is consistent with global observations (IPCC, 2021). Global sea-level rise is the most obvious manifestation of climate change in the ocean (Griggs et al., 2017). Global mean sea levels have been rising at increasing rates: by 1.3 mm/year between 1901 and 1971; 1.9 mm/year (about 0.07 inch/year) between 1971 and 2006; and 3.7 mm/ year (about 0.1 inch/year) between 2006 and 2018. Human influence on the climate was very likely the main driver of these increases since at least 1971 (IPCC, 2021).

Why is this indicator important?

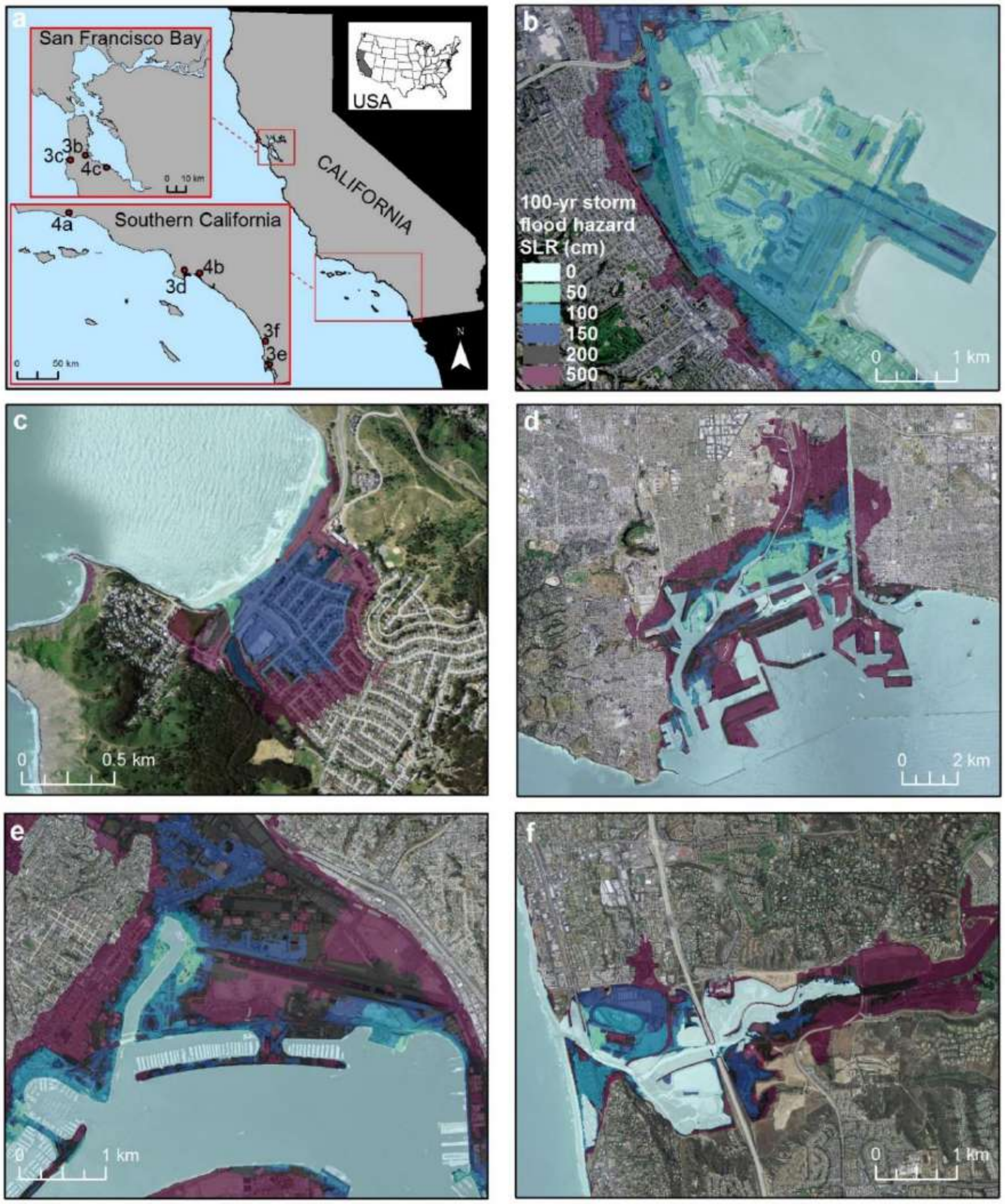
As sea level rise continues to accelerate throughout this century and beyond, coastal flooding, beach erosion, bluff retreat, loss of ecosystems, salinization of soils, ground and surface water, and impeded drainage will further increase along low-lying coasts worldwide without adequate adaptation efforts (IPCC, 2019).

Millions of residents, infrastructure, housing, natural resources, and economies in California's coastal counties face serious and costly threats from rising sea levels (LAO, 2020). The impacts of sea level rise will be amplified by storms, high tides, beach erosion and cliff retreat; flooding risks, in particular, will result from the combined effects of rising sea levels, heavy precipitation events, and shallower coastal groundwater (also due to sea level rise) (Barnard et al., 2019; Rahimi et al., 2020). Using a dynamic model (the Coastal Storm Modeling System or CoSMoS) that incorporates the effects of coastal storms in addition to estimates of sea level rise, projected areas of coastal flooding could impact over 600,000 people and $200 billion in property statewide over the next century (Figure 3; Barnard et al., 2019).

Critical infrastructure in many locations lies less than 4 feet above the high tide, including two international airports – Oakland and San Francisco – and about 172,000 homes (DWR, 2016). Rising sea levels place the airports, already vulnerable to storms and flooding, at greater risk (Griggs, 2020). Loss of service at either airport would result in major economic consequences regionally, nationally, and internationally (San Francisco Bay Conservation and Development Commission, 2012). Other critical infrastructure, such as ports, natural gas lines, and wastewater treatment plants, will also become more vulnerable to storms and flooding (Caldwell et al., 2013, CEC, 2017; Hummel et al., 2018). Notably, the areas projected to experience flooding events by 2100 contain at least 400 hazardous facilities including power plants, refineries, and industrial facilities. Sea level rise poses risks for such facilities experiencing flooding events that can potentially expose nearby residents to hazardous pollutants (UC Berkeley, 2021). Processes that result in significant short-term increases in water levels such as King tides (extremely high tides that typically occur a few times a year), seasonal cycles, winter storms, and patterns of climate variability (e.g., the Pacific Decadal Oscillation or the El Niño Southern Oscillation (ENSO)) cause the greatest impacts on infrastructure and coastal development due to the significantly higher water levels they produce compared to sea level rise alone (Griggs et al., 2017).

Low-income communities in California often are located in areas where infrastructure lack sufficient drainage capacity, making them particularly vulnerable to the impacts of flooding (Ramini et al., 2020). Climate-driven coastal hazards will amplify environmental justice-related inequities. Hazards in vulnerable areas disproportionately affect communities that are least able to adapt. For example, hazardous facilities at risk of flooding are disproportionately located in low-income communities and communities of color. Further, disadvantaged communities are over 5 times more likely to be located within 1 km of one or more hazardous facilities at risk of flooding in 2050, and over 6 times in 2100 (UC Berkeley, 2021).

Figure 3. Projected overland flood exposure over the next century in select locations across California based on results from the Coastal Storm Modeling System (CoSMoS)



Source: Barnard et al., 2019

(a) Study area for CoSMoS with insets. Examples of modeled flood extents for the 100-year coastal storm in combination with 0, 0.50, 1.00, 1.50, 2.00, and 5.00 meters of SLR; (b) San Francisco International Airport, (c) City of Pacifica, (d) Port of Los Angeles and Port of Long Beach, (e) Port of San Diego and San Diego International Airport, and (f) City of Del Mar. (Figure generated using ArcGIS v. 10.4.2, by Esri. Local base maps from ArcGIS Online, World_Terrain_Base, and ESRI_Imagery_World_2D, accessed 2 Oct 2018.) Projections can be viewed interactively and translated into socioeconomic exposure.

Compared to higher-income communities and property owners, people with lower incomes and residents of rental units face disproportionately greater impacts from sea level rise (CCC, 2015; LAO, 2020). They are more likely to be displaced by flooding or related impacts because they are not able to rebuild or are less able to prepare their residences for floods. They may be unable to evacuate and thus have less control over their safety. They may have less resources and are likely to not have insurance to replace lost or damaged property or structures. The loss of local public beaches and recreational areas would disproportionately affect low-income communities that have few options for low-cost recreation (CCC, 2015).

Figure 4. Cliff collapse at Isla Vista, California (taken 2005)

Credit: Patrick Barnard, USGS

Coastal erosion and cliff collapse (see Figure 4) threaten public safety, infrastructure, and property as they become more common with sea level rise (Vitousek et al., 2017; Limber et al., 2018; USGS, 2019). In Southern California, for instance, the projected sandy beach shoreline change indicates that 31 to 67 percent of Southern California beaches may become completely eroded by 2100 without human interventions (Vitousek et al., 2017). Further, sea cliffs could retreat at a rate nearly double that of the historical rate, causing an average total land loss of 19 to 41 meters (about 62 to 135 feet) by 2100 (Limber et al., 2018). As sea levels continue to rise, cliff collapses and the hazards they pose can also become increasingly common. In August 2019, three people were killed on a beach at Encinitas when the bluff above them collapsed, illustrating the damage a cliff collapse can cause.

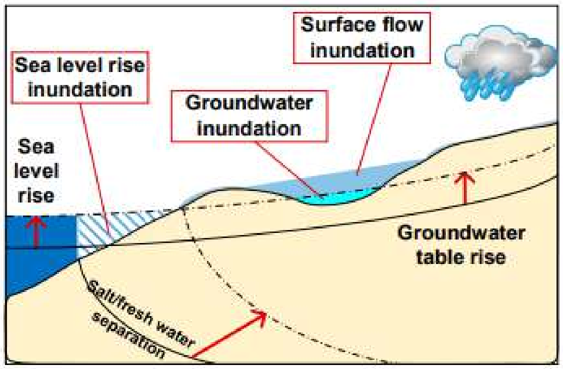
Figure 5. Olivella shells carved by the Chumash

Source: Science News, 2021

Coastal erosion and sea level rise, along with warming ocean temperatures and ocean acidification, collectively threaten cultural sites and resources along the shoreline for the Amah Mutsun and Chumash Tribes. Coastal erosion has damaged cultural sites, and as sea levels rise, sites previously used for gathering are no longer accessible (SCTLS, 2021; see Amah Mutsun and Santa Ynez Chumash Tribal reports). For example, traditional areas for the Chumash Tribe to gather Olivella shells (Figure 5), used in shell money, jewelry, and regalia, are often no longer accessible. Without access to traditional sites, knowledge can be disrupted, and the weight of that loss is felt by generations of tribal members (PBMI and SYBCI, 2021).

Furthermore, rising seas will result in shallower coastal groundwater, leading to emergent groundwater (when groundwater rises to or above the surface of the ground) in some places (Befus et al., 2020; USGS, 2020). This elevated groundwater can flood communities, damage infrastructure, and release pollutants, all before seawater overtops the beach. (Grant et al., 2021 May, 2020; Plane et al., 2019; Figure 6). Areas with emergent groundwater may occur progressively inland, expanding the area affected by sea level rise beyond what is anticipated solely from flooding caused by water flowing overland (May, 2020). A 2-meter rise in sea levels could lead to significant hazards from shallow and emergent groundwater in communities along California's coast, potentially affecting 4 million residents and $1.1 trillion in property, 33,000 km of roads, and 3,000 critical facilities (such as schools, police stations, and hospitals), with 6 to 9 times greater population, property, and infrastructure exposure than overland flooding (Befus et al., 2020; Jones et al., 2017; USGS, 2021). Under a changing climate, surface flooding – resulting from sea level rise and episodic storm-driven waves, surge, precipitation, and river flows – and sea level rise-driven elevated groundwater levels can interact with each other and worsen the overall flood risk on coastal communities (Rahimi et al., 2020).

Figure 6. Emerging sources of inundations in coastal areas with climate change



Source: Rahimi et al., 2020

Groundwater elevation can affect communities in other ways as well. As higher ocean water levels force up water levels underneath the ground, saltwater can intrude into fresh groundwater supplies, potentially affecting drinking water quality. Toxic contaminants can leak to the surface or flow through the subsurface to also compromise drinking water sources. Contaminated lands located along the coast and bay at risk of both surface and groundwater flooding include active and closed landfills, as well as "brownfields" which are undergoing or require cleanup. Moreover, raw sewage can seep into fresh groundwater aquifers or back up into streets and homes (LAO, 2020). Seawater intrusion into aquifers may require local communities to rely on other groundwater basins for their water supply (Coastal Resilience, 2020).

Coastal ecosystems in California are also threatened by sea level rise, including beaches, wetlands, estuaries, and fisheries. These wildlife areas provide flood protection, water treatment, carbon sequestration, biodiversity, wildlife habitat, and recreation (CEC, 2009). The coastal environment also supports economically valuable commercial and recreational fishing activities (Caldwell et al., 2013).

The health of two such coastal ecosystems in California, sandy beach and tidal marshes, may plummet by 2050 without adequate adaptation and resilience strategies (Barnard et al., 2021; Myers et al., 2019). Predictions suggest that sea level rise will completely flood the mudflats at the San Pablo Bay estuary over the next 100 years, for instance (May 2020). This wildlife refuge protects the largest remaining contiguous patch of pickleweed-dominated tidal marsh in the northern San Francisco Bay, which provides critical habitat to the endangered salt marsh harvest mouse (Smith et al., 2018; US FWS, 2013). The combined effect of increased inundation and salinity projected under most climate change scenarios can significantly compromise pickleweeds and other plants important to the wetland habitats of the salt marsh harvest mouse (Smith et al., 2018).

Rising seas also present serious threats to the Sacramento-San Joaquin Delta. During storms and high-water flood events, higher sea levels increase the likelihood of Delta island levee failures, resulting in potentially catastrophic flooding to island communities and infrastructure. Sea level rise will increase the Delta's salinity, particularly during periods of reduced freshwater outflows from snowmelt. This puts the water supply for over half of California's population and much of the Central Valley's agriculture at risk. As previously mentioned, saltwater intrusion into groundwater may also increase with sea level rise, putting further pressure on limited drinking water supplies (DWR, 2013).

To assist with local adaptation strategies, online coastal flooding hazard maps using data produced by the scientific and research community in California may be accessed at: CalAdapt, Our Coast Our Future, Hazard Exposure and Reporting Analytics (HERA), and CoSMoS. These maps include predicted flooding for the San Francisco Bay, Sacramento-San Joaquin River Delta and California coast resulting from storm events at different sea level rise scenarios. Multiple efforts throughout California are underway to plan for, prepare, and adapt to rising seas and protect coastal ecosystems, infrastructure and communities (for examples, see CNRA, 2018 and 2021; OPC, 2021).

What factors influence this indicator?

As previously mentioned, human influence has very likely been the main driver of global sea level rise since at least 1971 (IPCC, 2021). Water from melting mountain glaciers and ice sheets is the main source of global mean sea level rise today (IPCC, 2019; Slater et al., 2020). The ice sheets in Greenland and Antarctica, while not expected to melt completely even on millennial time scales, contain enough ice to raise global mean sea level by 24 feet and 187 feet, respectively. In addition, the accelerating rate of ice loss from these ice sheets is of particular concern (Griggs et al., 2017).

Heat-driven expansion (also known as the steric effect) was the single greatest contributor to global mean sea level rise over the past century, accounting for about half of the observed sea level rise (Griggs, et al., 2017). The ocean has absorbed more than 90 percent of the excess energy associated with anthropogenic greenhouse gas emissions, leading to ocean warming. As the ocean warms, water expands, and sea levels rise (IPCC, 2019).

Other sources of land-based water that contribute to sea level include anthropogenic activities. Groundwater that is pumped for agriculture, industry, and drinking ultimately drives more water to the ocean, thereby raising the sea level along the California coast (Griggs, et al., 2017). Conversely, dam building along rivers and associated reservoir impoundment can lower the sea level; however, estimates for the past few decades suggest that the effect of groundwater depletion and dam/reservoir contribution to sea level rise are secondary factors and largely cancel each other (Cazenave and Cozannet, 2014).

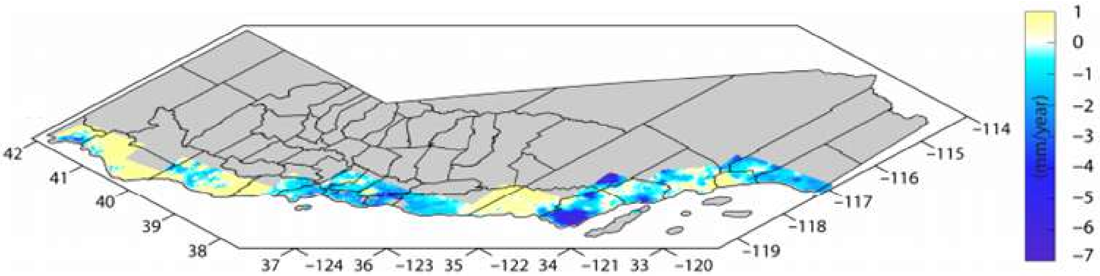
Global sea levels vary by region. Wind and water density gradients push sea levels higher in some places and lower in others. Climatic variability in different regions also affects local sea levels. ENSO in the eastern Pacific Ocean, for instance, produces alternating warm (El Niño) and cool phases (La Niña) that can bring sharp swings in sea level that are transient and typically last for only about a year. Additionally, ice sheets in Greenland and Antarctica, as well as mountain glaciers exert a gravitational pull on the ocean, resulting in a complicated distribution of sea level across the globe, called sea level fingerprints. When the ice melts, water that had once been pulled toward the ice mass due to gravitational attraction migrates away (NASA, 2017).

Understanding relative (local) sea level rise is important to understanding how low-lying coastal communities and ecosystems will be affected by flooding, wetland loss, and damage to infrastructure, and it can deviate from regional estimates of sea level rise, which typically don’t resolve finer scale shifts in land movement. (Blackwell et al., 2020). Episodically, local sea level is modulated by processes that produce higher-than-normal coastal water levels, such as storm surge, wave effects, and spring and King tides. Over the long term, glacial isostatic adjustment (GIA) due to crustal loading/unloading and plate tectonics can play a significant role in regional and local sea levels. Additionally, fluid withdrawals from the subsurface (e.g., due to groundwater pumping and hydrocarbon withdrawal), as well as sediment compaction, can lead to high rates of local subsidence, as in the California Bay-Delta, and along the San Francisco Bay shoreline. Much of California’s coast is subsiding due to regional changes in land levels.

A radar study of ~100 km wide swath of land along California’s coast during the years 2007-2018 estimated that between 4.3 million and 8.7 million people in California’s coastal communities live on areas of subsiding land (Figure 7; Blackwell et al., 2020). Many of the islands in the California Bay-Delta have dropped below sea level due to microbial oxidation and soil compaction caused by more than a century of farming (NASA, 2017). Conversely, plate tectonics can cause land uplift along the coast to outpace sea level rise, as is happening in Crescent City in northern California where

NOAA's records show a drop in sea level over time. The far north coast is the only area along California where sea level is dropping relative to land surface (Russell and Griggs, 2012).

Figure 7. Exposure to land subsidence along the coast of California



Map showing vertical land movement rates, in mm/year (2007-2018), along California's coast. Black lines identify California's counties.

Source: Blackwell et al., 2020

Technical considerations

Data characteristics

Sea level measurements came from federally operated tide gages located along the California coast which are managed by the National Water Level Observation Network, within NOAA, as well as from satellite altimetry operated by NASA. Data are available online at [NOAA's Tides and Currents webpage]() and [NASA's sea level webpage]().

Tide stations measure sea level relative to specific locations on land. Short-term changes in sea level (e.g., monthly mean sea level or yearly mean sea level) are determined relative to a location's Mean Sea Level, the arithmetic mean of hourly heights observed over a specific 19-year period called the "National Tidal Datum Epoch" (NTDE) established by NOAA's National Ocean Service. The NTDE accounts for the effect of the 18.6-year lunar nodal cycle on variations in the tidal range. The current NTDE is 1983-2001 (previous NTDEs were for the periods 1924-1942, 1941-1959, and 1960-1978); NTDEs are updated roughly every 20 years (NOAA, 2000; Szabados, 2008).

The U.S. federal government first started collecting measurements of sea levels in the mid-19th century to assist with accurate navigation and marine boundary determinations. Data from these early observation efforts and continued monitoring are used to assess long-term changes in sea level in multiple locations in California. Monitoring efforts have expanded over the years to include more locations with tidal stations, allowing for analysis of sea level trends at more regions, although for shorter time scales (NOAA, 2006).

Strengths and limitations of the data

Monthly mean sea levels tend to be highest in the fall and lowest in the spring, with differences of about 6 inches. Local warming or cooling resulting from offshore shifts in water masses and changes in wind-driven coastal circulation patterns also seasonally alter the average sea level by 8.4 inches (21 cm) (Flick, 1998). For day-to-day activities, the tidal range and elevations of the high and low tides are often far more important than the elevation of mean sea level.

As noted above, geological forces such as subsidence, in which the land falls relative to sea level, and the influence of shifting tectonic plates and glacial isostatic adjustment (GIA) complicate regional estimates of sea level rise. Much of the California coast is experiencing elevation changes due to tectonic forces and GIA. Mean sea level is measured at tide gauges with respect to a tide gauge benchmark on land, which traditionally was assumed to be stable. This only allows local changes to be observed relative to that benchmark. Additional data from global positioning systems (GPS) are useful to record vertical land movement at the tide gauge benchmark sites to correct for seismic activity and the earth's crustal movements. Satellites have been used since the 1990s to track sea level rise at the global scale with uniform coverage and provide an additional check on sea level rise rates derived from tide gauges alone (Abdalla et al., 2021; NOAA, 2020).

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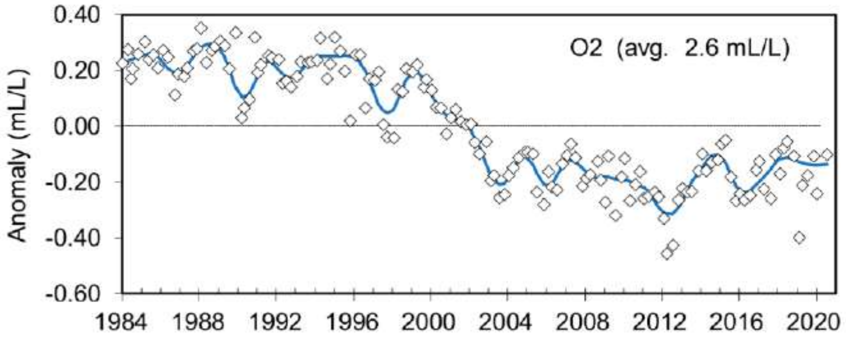
DISSOLVED OXYGEN IN COASTAL WATERS

Dissolved oxygen concentrations are declining in ocean waters off southern California.

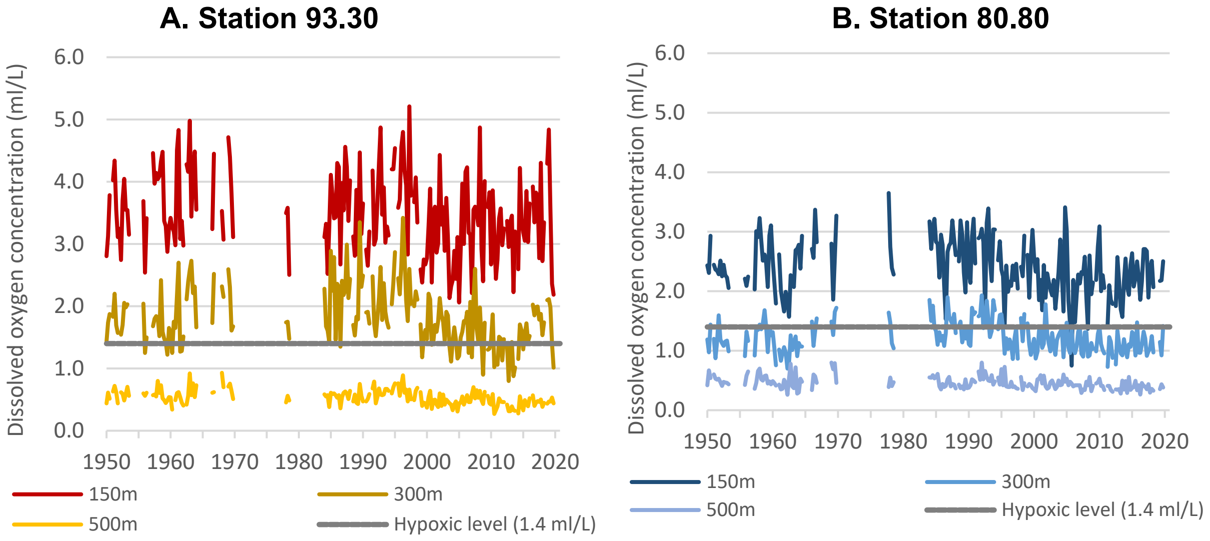
Figure 1. Dissolved oxygen concentrations across 66 monitoring stations in Southern California waters (1984-2020)



Source: Weber et al., 2021 Supplementary Figure 6

Each diamond on the graph represents the anomaly, or the difference between the average dissolved oxygen concentrations measured across 66 stations and the long-term average of 2.6 mL/L (based on values from a baseline period 1984 to 2013). The solid blue line connects annual averages. The stations are shown on the Figure 3 map; measurements were taken on the σ_θ*=26.4 kg/m*^{3} *isopycnal, the depth at which seawater is at a density of 1026.4 kg/m*^{3}*.*

Figure 2. Dissolved oxygen concentrations at two monitoring stations on the Southern California Coast (1950-2019)



A. Station 93.30

B. Station 80.80

Source: CalCOFI, 2021a

Quarterly averages of dissolved oxygen concentrations in milliliters per liter (ml/L) measured at three depths (150, 300 and 500 meters) at Line 93, station 30 and Line 80, station 80 (see map, Figure 3).

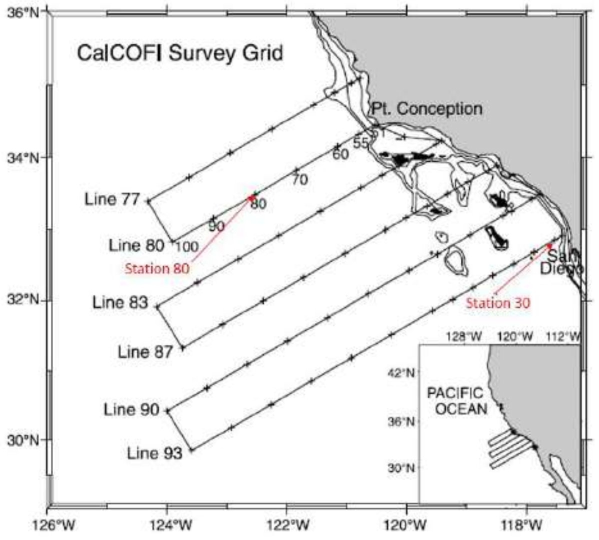
What does this indicator show?

Instrumental measurements of dissolved oxygen (DO) concentrations point to increasing deoxygenation of coastal waters within the California Current in recent decades (Figures 1 and 2; also Bograd et al., 2019; Evans et al., 2020; Weber et al., 2021). The California Current extends from British Columbia, Canada to Baja California, Mexico. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) has been taking measurements of DO periodically off southern California from San Diego to Point Conception since 1950, and consistently at a grid of stations four times per year since 1984 (see Figure 3 for locations). Figure 1 is based on measurements from the 66 core stations in the CalCOFI survey area. Figure 2 presents data collected from three depths at two stations: [A] Line 93, station 30 (93.30), and [B] Line 80, station 80 (80.80).

Throughout CalCOFI survey area, at depths corresponding to the "σ_θ-26.4 isopycnal" – the depth at which seawater is at a density of 1026.4 kg/m^3 – DO concentrations decreased significantly from about between the mid-1990s and the mid-2000s (Figure 1; also Bjorkstedt et al. 2012 as cited in Thompson et al., 2019). Following this decline, DO concentrations have been relatively constant, remaining below the long-term average since (Weber et al., 2021). Overall, DO concentrations in this region (to at least 500 m depth) have mostly declined to values lower than observed in the 1950's to 1960's (Bograd et al., 2008, 2015, 2019).

Figure 2A shows DO concentrations at three water depths at Station 93.30 offshore of San Diego. The data indicate overall mean decreases with minimal changes in the mean in the past 10 years. Since the mid-1990's, significant low-oxygen events have been observed: concentrations were below the hypoxic level (<1.4 ml/L), which can potentially cause physiological stress in marine organisms. This location is representative of the influence of the northward-flowing California Undercurrent, which is a major supplier of deeper source waters (200 to 500 meters (m)) to the region and has a large influence on oxygen content for much of the survey area. At 80.80 off Point Conception, within the core of the near-surface, southward-flowing California Current, DO concentrations have also declined sharply since the mid-1990's but have been generally increasing at 150-300 m in the past five years.

Figure 3. Sampling locations



Modified from Bograd *et al.*, 2008

Why is this indicator important?

Declining DO concentrations in ocean waters and the associated changes in the depth and extent of low oxygen zones can lead to significant and complex ecological changes in marine ecosystems, including wide-ranging impacts on diversity, abundance, and trophic structure of communities (e.g., Levin et al., 2009; Somero et al., 2015; Stramma et al., 2010). Changing ocean chemistry, in concert with changes in temperature, may lead to even greater and more diverse impacts on coastal marine ecosystems (e.g., Somero et al., 2015).

Globally since 1950, more than 500 coastal sites have been reported to have experienced hypoxic conditions. Fewer than 10 percent of these were known to have hypoxia before then (Breitburg et al., 2018). Separate from these episodic hypoxic events, coastal California is characterized by the presence of a zone of depleted oxygen concentrations (Oxygen Minimum Zone, or OMZ) at depths from 600 to 1100 meters. The OMZ near California is expanding both vertically (moving upward towards the ocean surface (e.g., Bograd et al., 2008)) and horizontally (Somero et al., 2015). The declines in oxygenation observed off California are consistent with an observed expansion of the low oxygen zones elsewhere around the world (Breitburg et al., 2018; Stramma et al., 2008).

The expansion of oxygen-deficient zones can lead to a compression of favorable habitat for certain marine species and an expansion of favorable habitat for others. For example, following the 1997-98 El Niño event, the Humboldt squid (*Dosidicus gigas*) — which thrives in low-oxygen environments — expanded its range northward from Baja California to southeast Alaska, a shift that may have been affected by changes in the extent of oxygen-deficient zones (Gilly and Markaida, 2007). Studies have indicated that low-oxygen waters can reach nearshore coastal habitats via upwelling, with potential impacts on these habitats (Chan et al., 2019).

Oxygen plays a role in the cycling of nutrients such as nitrogen, phosphorus and iron. As a result, changes in oxygen levels can influence nutrient budgets, biological productivity and carbon fixation. In oxygen-depleted waters, anaerobic microbial processes can produce chemicals such as hydrogen sulfide, which is toxic to other organisms, and methane, a potent greenhouse gas (Breitburg et al., 2018).

What factors influence this indicator?

DO levels reflect a complex interplay between physical and biological drivers in the marine environment, including currents, upwelling, air-sea exchange, and biological productivity, respiration and decomposition. Warmer waters hold less oxygen, as the gas becomes less soluble, and surface warming produces stratification that reduces the overturning circulation essential in ocean ventilation processes. Warming also accelerates the rate of oxygen consumption by marine organisms (e.g., Breitburg et al, 2018; Somero et al., 2015). In addition to these processes, DO is influenced by high surface productivity, regional circulation of the North Pacific Ocean, and anthropogenic nutrient inputs to the coastal ocean, as discussed below.

Upwelling is a wind-driven physical process wherein deep, nutrient rich waters move upward into the shallow surface ocean. There is evidence that upwelling has increased in some locations along the California coast due to anthropogenic impacts (García-Reyes and Largier, 2010; Wang et al., 2015). Upwelling brings nutrient rich waters to the surface, where it drives surface ocean productivity (photosynthesis). The amount of surface water productivity affects DO concentrations because as biological material sinks downward from the surface ocean and decays, oxygen is utilized in the decay and decomposition process. Thus, DO concentrations decrease in the subsurface below regions of high biological productivity.

DO concentrations are also controlled by regional and global oceanographic processes. For example, the Southern California Bight – the 400 miles of coastline from Point Conception in Santa Barbara County to Cabo Colnett, south of Ensenada, Mexico -- is impacted seasonally by the northward-flowing California Undercurrent. Much of the Bight is included in the CalCOFI survey region. Declining oxygen concentrations in this region imply a change in the properties of equatorial source waters (Bograd et al., 2015, 2019). A recent study estimated that equatorial waters transported via the California Undercurrent accounted for 81 percent of the deoxygenation trend in the CalCOFI region since 1993 (Evans et al., 2020).

Local nutrient inputs from human practices (e.g., agriculture, wastewater discharge) can also decrease oxygen concentrations in coastal waters. Fertilizers and nutrient enrichment from wastewater promote algal growth. As this material sinks and decays, it can create localized areas of low oxygen. Management of coastal pollution is an important aspect of minimizing changes in oxygen concentrations on a local scale.

Scientists estimate that about 15 percent of global oxygen decline between 1970 and 1990 can be explained by ocean warming and the remainder by increased stratification. In coastal areas, especially nutrient-enriched waters, warming is predicted to exacerbate oxygen depletion (Breitburg et al., 2018). In its Sixth Assessment, the Intergovernmental Panel on Climate Change concluded that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and that deoxygenation will continue to increase in the 21st century (IPCC, 2021).

Technical considerations:

Data characteristics

This indicator is based on data from the CalCOFI program. Established in 1949, CalCOFI conducts quarterly cruises (18 to 28 days long) to measure the physical and chemical properties of the California Current System and census populations of organisms from phytoplankton to avifauna. Data collected at depths down to 500 meters include temperature, salinity, oxygen, phosphate, silicate, nitrate and nitrite, chlorophyll, phytoplankton and zooplankton biodiversity, and zooplankton biomass (CalCOFI, 2021b).

DO measurements for CalCOFI Line 93.3, Station 30.0 (offshore of San Diego) and Line 80, Station 80 (within the offshore California Current core) were downloaded from the CalCOFI website. Quarterly averages were derived from oxygen concentrations reported for that calendar quarter. While sampling did occur between 1950 and1980, there are data gaps during this period.

Strengths and limitations of the data

Very few datasets describe DO conditions north of San Francisco and/or in coastal regions. One analysis suggests that 20-30 years of data are needed to robustly detect long-term declines in DO above natural variability (Henson et al., 2016). All of the CalCOFI datasets meet this criterion, thus CalCOFI currently represents the best resource for distinguishing long-term trends in DO from natural variability. CalCOFI has limited sampling availability in nearshore/coastal habitats, so establishing additional coastal monitoring sites may be critical for characterizing DO conditions in these areas.

These observations are limited by sites where oxygen concentration measurements are currently monitored along the coast and do not reflect oxygen declines that may be occurring across the entire California Current System. As described above, the observed DO concentrations could be influenced by both local thermodynamic or biological processes, as well as remote, large-scale changes. The oxygen concentrations can vary with the depth, temperature and time of year DO levels are measured.

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Impacts on Vegetation and Wildlife

Climate change has altered habitats and impacted ecosystems across the planet, threatening biodiversity. Adverse impacts on ecosystems, on both their biological and physical components, have been attributed to more frequent and intense extreme events such as droughts and marine heatwaves, as well as to long-term warming and changing precipitation patterns. The global evidence shows species responses that include poleward and elevational shifts in habitat range; changes in the timing of life cycle events (known as “phenology”); declines in the abundance of species; and changes in the makeup of species (or community composition) (IPCC, 2022).

Human well-being is dependent on the natural resources and services provided by ecosystems, which include carbon storage, flood protection, cultural resources, and the production of food, fiber, and other materials (IPCC, 2022; USGCRP, 2018). Many plant and animal species are important as food, medicine, and ceremonial materials to California Tribes, who are deeply affected by the impacts of climate change on these culturally significant resources.

Many of the same climate change impacts on ecosystems observed globally are happening in California. Warmer temperatures and changes in precipitation patterns are driving plants and animals to shift to elevations or latitudes with more favorable habitat conditions. Species that cannot adjust or move fast enough may experience declines in abundance; some may face local extinction. Along with observed changes in the distribution of plants and animals are changes in the timing of important biological events, such as bloom and fruit maturation in plants, and migration and egg-laying in animals.

Drought and warming temperatures have also contributed to large-scale tree mortality, which has fueled larger and more severe wildfires. The lack of moisture available to plants has also been associated with changes in the structure and composition of California’s forests and woodlands—changes that have been accelerated by wildfires. Warming ocean temperatures have amplified blooms of toxin-producing algae (“harmful algal blooms”) that have led to economically devastating fisheries closures. Changing conditions in freshwater, estuarine, and ocean habitats are threatening the survival of California Chinook salmon populations.

The threat to biodiversity posed by climate change is compounded by multiple other societal and environmental challenges intensifying risks and impacts (IPCC, 2022; USGCRP, 2018). This includes increasing development, habitat fragmentation and environmental pollution. Global initiatives, including the Paris Agreement, recognize the close interconnectedness between biodiversity, climate change, and human well-being, and have begun to jointly address these crises (Pörtner et al., 2021). California has committed to the goal of conserving 30 percent of the state's lands and coastal waters by 2030. This initiative, known as the 30x30 California initiative, is part of an international movement to conserve natural areas across our planet. Established by Executive Order (N-82- 20), this goal elevates biodiversity conservation as a priority and emphasizes the role of nature in the fight against climate change.

INDICATORS: IMPACTS ON VEGETATION AND WILDLIFE

VEGETATION

- Marine harmful algal blooms *(new)*
- Forest tree mortality *(updated)*
- Wildfires *(updated)*
- Ponderosa pine forest retreat (*updated)*
- Vegetation distribution shifts *(no update)*
- Changes in forests and woodlands *(updated)*
- Subalpine forest density *(updated)*
- Fruit and nut maturation *(updated)*
- Navel orangeworm abundance *(new)*

WILDLIFE

- Spring flight of Central Valley butterflies *(updated)*
- Migratory bird arrivals *(no update)*
- Bird wintering ranges *(no update)*
- Small mammal and avian range shifts *(updated)*
- Nudibranch range shifts *(no update)*
- Copepod populations *(updated)*
- Chinook salmon abundance *(updated)*
- Cassin's auklet breeding success *(no update)*
- California sea lion pup demography *(no update)*

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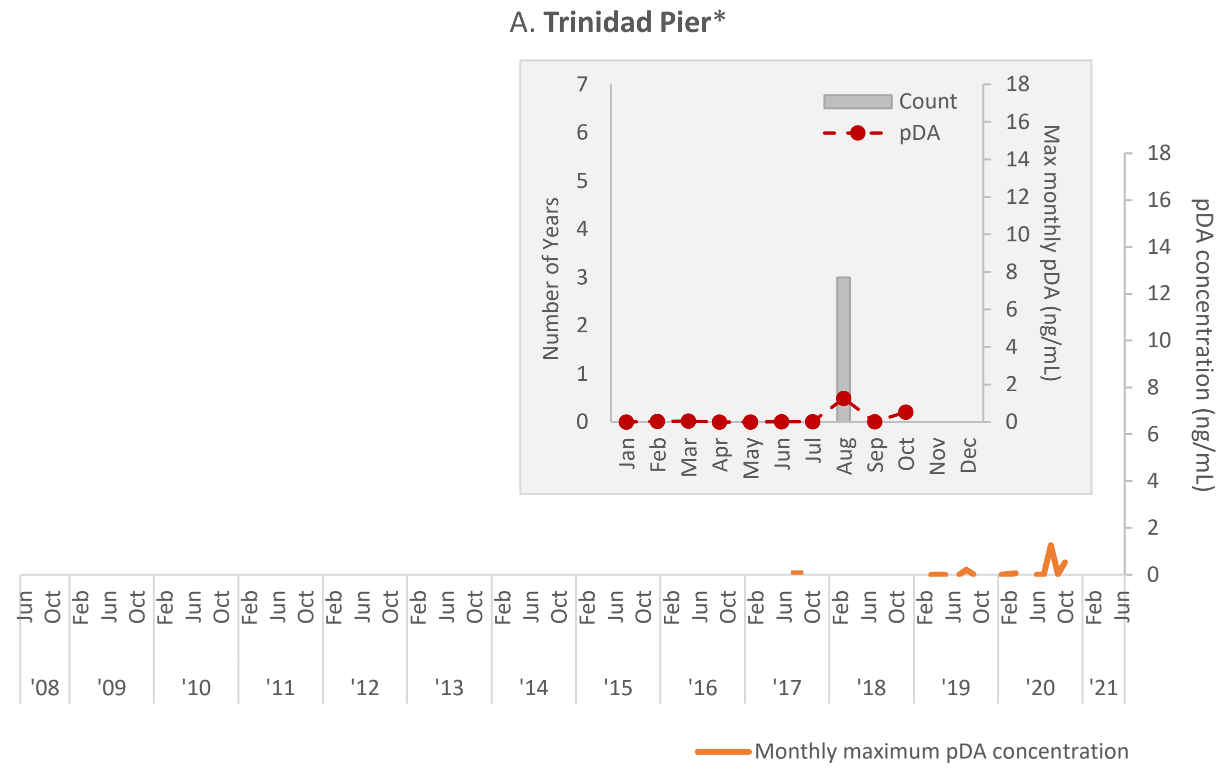
MARINE HARMFUL ALGAL BLOOMS

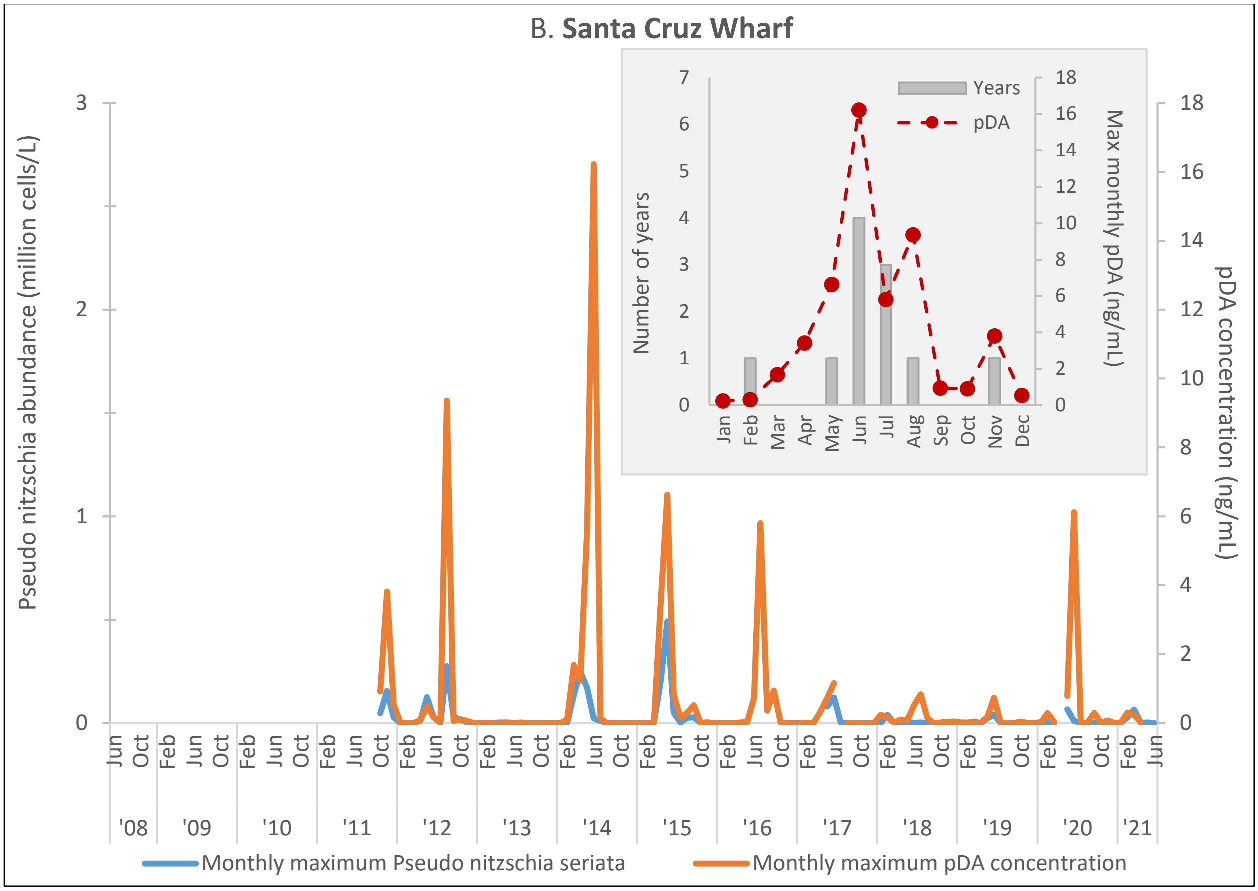
Patterns of blooms of certain types of algae in California coastal waters have been changing. While no trend is evident, blooms are known to be influenced in part by warming ocean temperatures. For example, red tide-forming dinoflagellates have been appearing more frequently since 2018. These harmful algal blooms (HABs) can produce biotoxins or otherwise disrupt marine ecosystems. Pseudo-nitzschia spp., a diatom which produces the toxin domoic acid, has been of particular concern due to its impacts on marine wildlife and fisheries in California.

Figure 1. Monthly maximum *Pseudo-nitzschia* seriata abundance and particulate domoic acid (pDA) concentrations

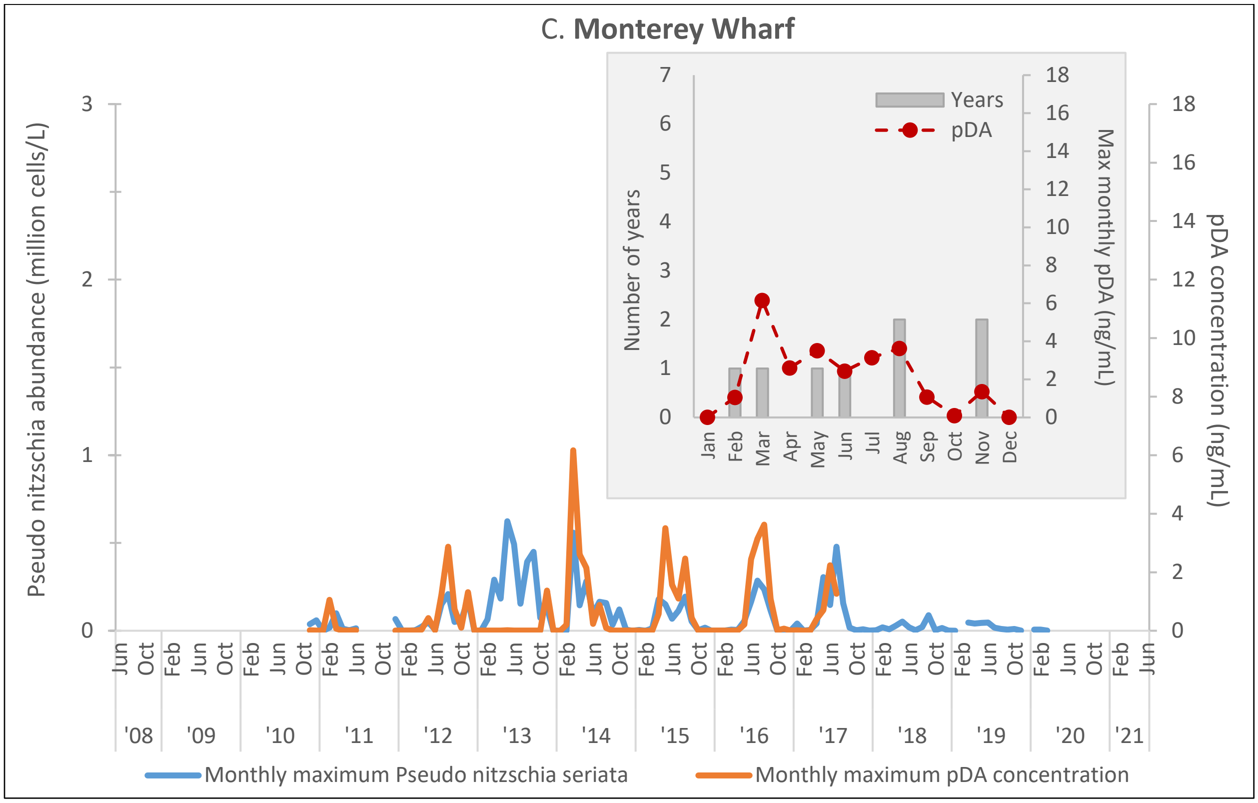
The eight graphs (Figure 1 A, Trinidad Pier to H, Scripps Pier) from the Harmful Algal Bloom Monitoring Alert Program (HABMAP) stations are displayed north to south. Gaps in the line graphs indicate no data were collected during that period. Inset graphs display the annual maximum pDA by month (across all years, line) and the number of years in which the annual maximum occurred in a given month (count, column). Pseudo-nitzschia seriata does not refer to a specific species (which cannot be visually distinguished) but to the larger, typically more toxic size of Pseudo-nitzschia.



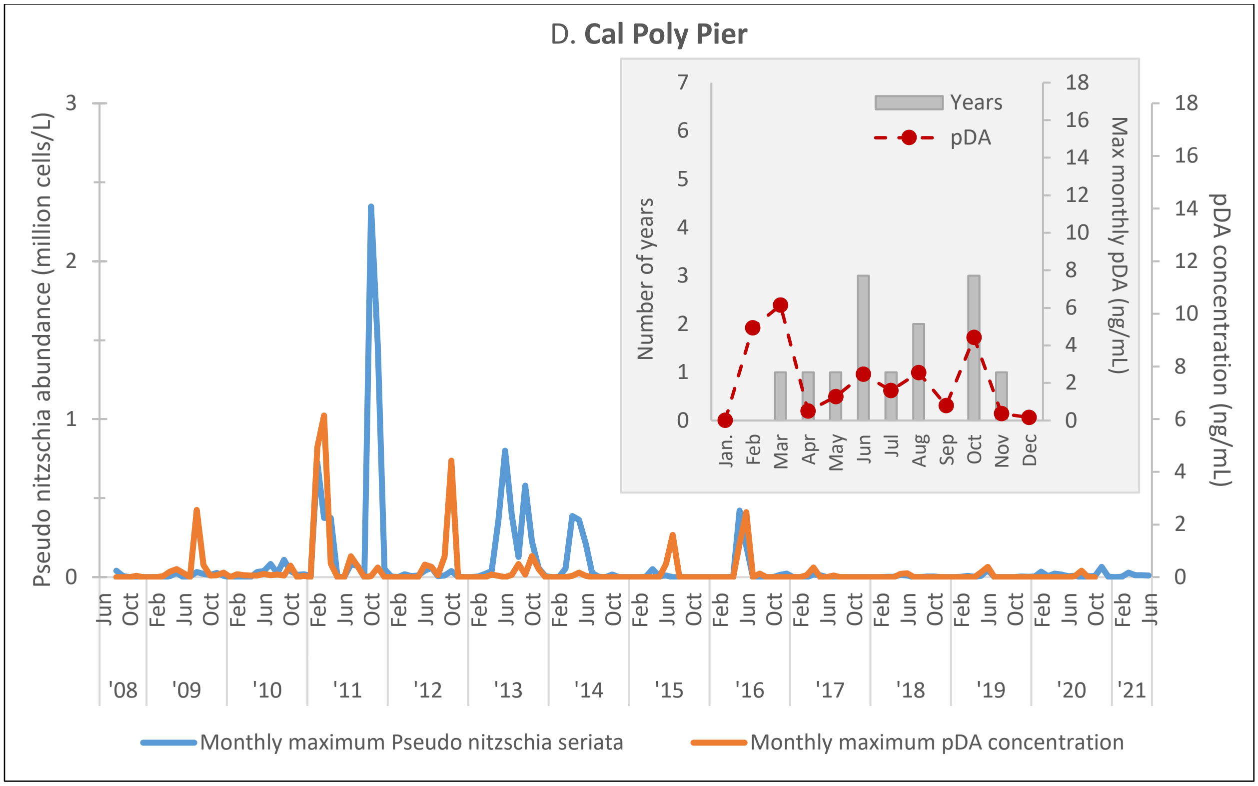
**Note: No cell counts are available, and pDA was intermittently collected starting in 2017.*



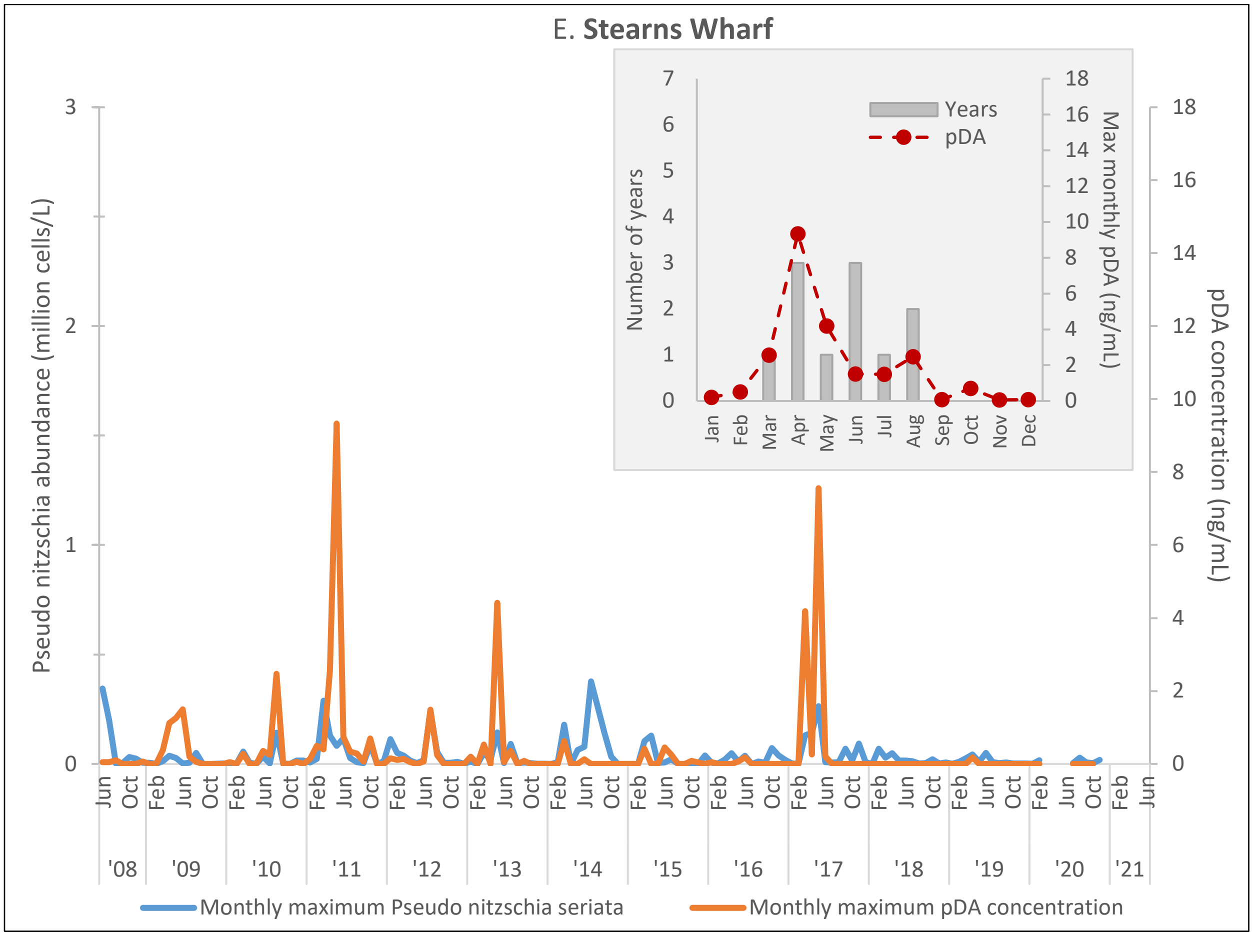
B. **Santa Cruz Wharf**



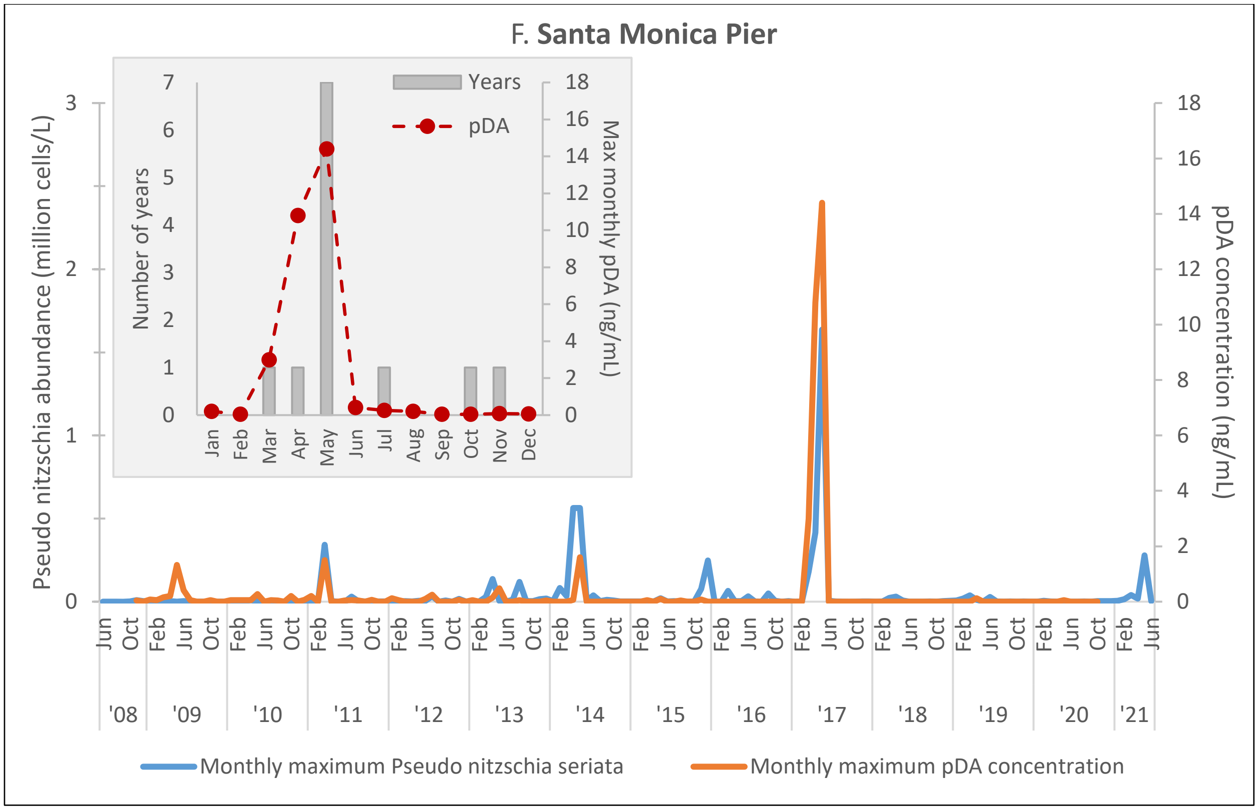
C. **Monterey Wharf**

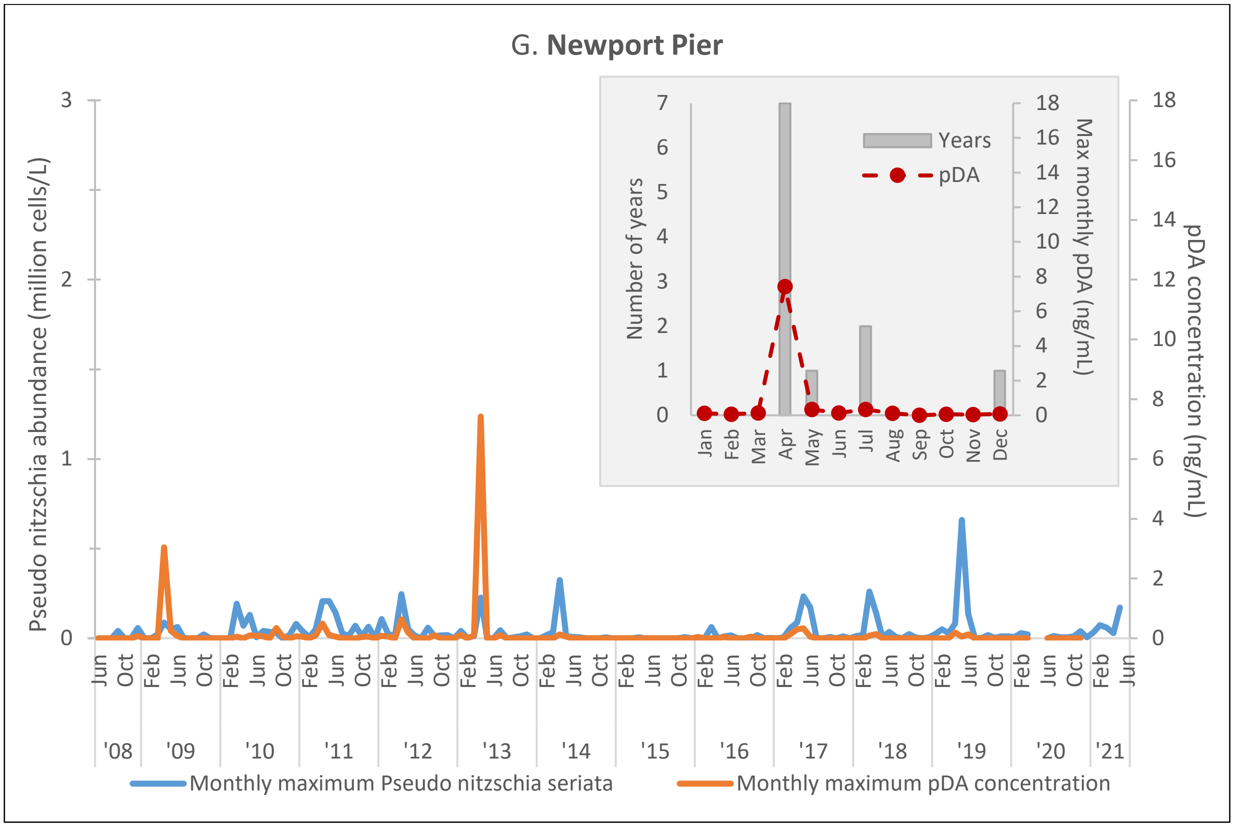


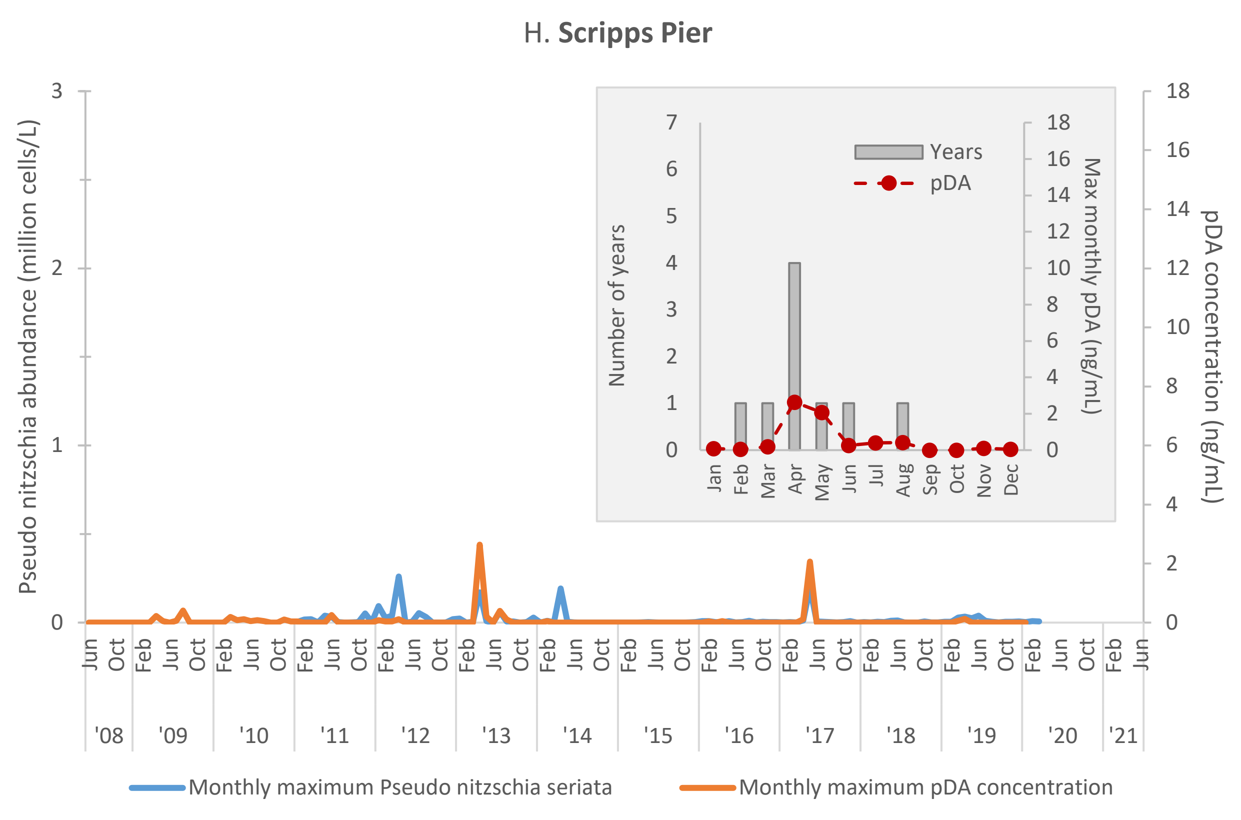
D. **Cal Poly Pier**



E. **Stearns Wharf**

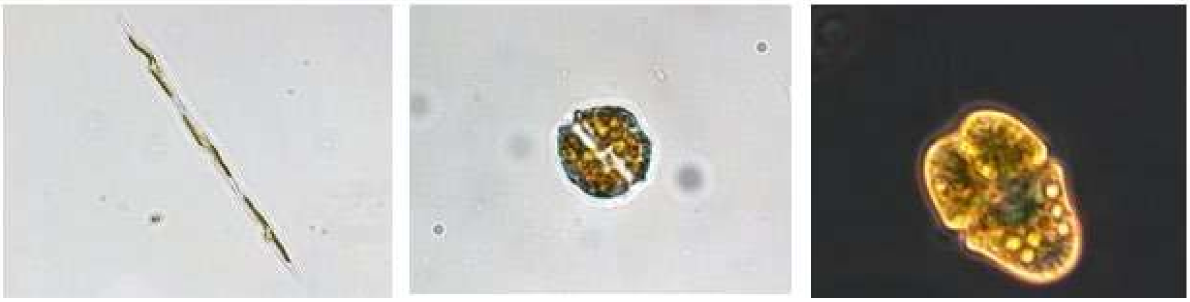

F. **Santa Monica Pier**
Pseudo nitzschia abundance (million cells/L)
0
1
2
3
pDA concentration (ng/mL)
0
2
4
6
8
10
12
14
16
18
Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Number of years
0 1 2 3 4 5 6 7
Max monthly pDA (ng/mL)
0 2 4 6 8 10 12 14 16 18
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


G. **Newport Pier**
Pseudo nitzschia abundance (million cells/L)
0
1
2
3
pDA concentration (ng/mL)
0
2
4
6
8
10
12
14
16
18
Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun Oct Feb Jun
'08 '09 '10 '11 '12 '13 '14 '15 '16 '17 '18 '19 '20 '21
Number of years
0 1 2 3 4 5 6 7
Max monthly pDA (ng/mL)
0 2 4 6 8 10 12 14 16 18
Years
pDA
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Monthly maximum Pseudo nitzschia seriata
Monthly maximum pDA concentration


H. **Scripps Pier**

What does the indicator show?

Figures 1 and 2 present data collected at nearshore sampling locations in California for two groups of phytoplankton that cause marine harmful algal blooms (HABs): diatoms and dinoflagellates. The data are from sampling locations that comprise the Harmful Algal Bloom Monitoring Alert Program (HABMAP) (see Figure 3 for locations; data for Bodega Pier are not available). Data for Santa Cruz Wharf in Figure 2A include earlier years not reported as part of HABMAP.



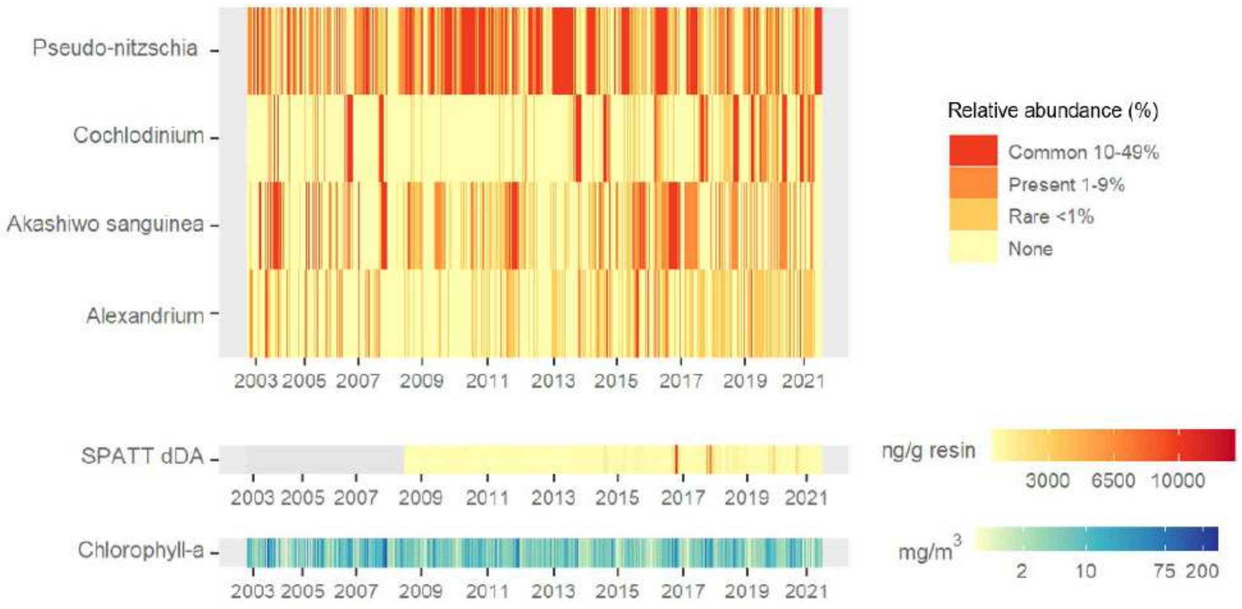
Source: Kudela Lab, UC Santa Cruz

Marine HABs in California are generally due to diatoms, such as Pseudo-nitzschia (left), or dinoflagellates, such as Alexandrium (center) and Akashiwo (right) (UCSC, 2022).

Figure 2. HAB organism abundance and toxin levels at selected locations.

Relative abundance index of Pseudo-nitzschia seriata and several dinoflagellates ("red tide" forming taxa: Alexandrium, Cochlodinium, Gymnodinium, Akashiwo), along with concentrations of dissolved domoic acid (dDA, measured with SPATT, Solid Phase Adsorption Toxin Tracking) (A, Santa Cruz) or particulate domoic acid (pDA) (B, Stearns and C, Newport) and chlorophyll-a concentrations. See Figure 3 for sampling locations.

A. Santa Cruz Wharf



Source: Radan, 2021 and Kudela pers. comm., 2021

Note: The scale for chlorophyll-a for Santa Cruz Wharf is different from the scale for Stearns Wharf and Newport Beach Pier.

B. Stearns Wharf

Source: HABMAP/SCCOOS, 2021

C. Newport Beach Pier

Source: HABMAP/SCCOOS, 2021

Figure 3. Location of HABMAP sampling locations

Source: SCCOOS, 2021

Figure 1, graphs A through H present monthly maximum cell count values for the diatom *Pseudo-nitzschia* seriata size class and for concentrations of domoic acid, the toxin it produces. *Pseudo-nitzschia* "seriata" does not refer to the actual species (which cannot be distinguished by light microscopy) but rather the larger size class of *Pseudo-nitzschia*, which is generally a more toxigenic group of species. The graphs present concentrations of particulate domoic acid or pDA, which is the intracellular domoic acid concentration in the bulk phytoplankton pool. Accumulation of domoic acid in fish and shellfish is thought to be primarily through ingestion of *Pseudo-nitzschia* cells containing intracellular DA.

There is considerable variability in both cell count and toxin concentration across and within sampling locations. *Pseudo-nitzschia* seriata abundance and pDA concentrations were lowest at the two sites located farthest south, Newport Pier and Scripps Pier, where sea surface temperatures are generally warmer than in the central and north coast. This is consistent with findings that high abundances of *Pseudo-nitzschia* have not been reported in the Southern California Bight when temperatures are above 20 degrees Celsius (°C) or 68 degrees Fahrenheit (°F), and that no substantive concentrations of pDA have been found above 19 °C

(66.2 F; Smith et al., 2018). There are also low pDA concentrations at the northernmost site, Trinidad, however data for this station are limited with no *Pseudo-nitzschia* seriata cell counts nor pre-2017 pDA data publicly available for Trinidad Pier. In general, peak *Pseudo-nitzschia* seriata abundance and pDA concentrations aligned, but there were some exceptions. For example, at Cal Poly Pier a large *Pseudo-nitzschia* seriata bloom event occurred in October 2011 without a corresponding peak in pDA concentrations; conversely, in October 2012 a relatively large spike in pDA concentrations was accompanied by comparatively low *Pseudo-nitzschia* seriata cell counts.

Across all sites, *Pseudo-nitzschia* seriata and pDA concentrations were lowest during the winter months (December to February). For most locations, the highest pDA concentrations occurred during the spring months (March to May), and the highest *Pseudo-nitzschia* seriata abundance during the spring and summer months (March to August). A seasonal signal is most evident at the southern stations – Scripps Pier, Newport Pier and Santa Monica Pier – where highest values for *Pseudo-nitzschia* seriata abundance and pDA concentrations were most common in the spring (April for the former two, and May for the latter). For Cal Poly Pier, the monthly maximum pDA most frequently occurred in June and October; however, the overall monthly maximum pDA across all years was in February and March, driven by a large pDA spike during those months in 2011.

The results of weekly HABs sampling at three of the monitoring sites are presented in Figure 2. Changes over time in the relative abundance of *Pseudo-nitzschia* seriata and the most commonly observed red tide-forming dinoflagellates (*Alexandrium, Cochlodinium, Gymnodinium* and *Akashiwo*) are presented as heatmaps. The colors represent the relative abundance index (RAI) for each species. This is the percentage of a species of interest compared to all other phytoplankton species in a given sample, reported as five categories/ranges: (1) none; (2) rare, less than 1 percent; (3) present, 1 to 9 percent; (4) common, 10 to 49 percent; and (5) abundant, greater than 50 percent (Radan, 2021). A longer time series of HABs is available from the Santa Cruz Wharf, where weekly sampling data for phytoplankton composition extends back to 2002 (Figure 2A). Data from Solid Phase Adsorption Toxin Tracking (SPATT) samplers are included from 2008 to present. SPATT samplers measure dDA over the seven-day deployment, integrating fluctuations due to water movement. As with the shorter time-series, there was no trend in the abundance of *Pseudo-nitzschia*, while the red tide dinoflagellates seem to be appearing more frequently since 2018.

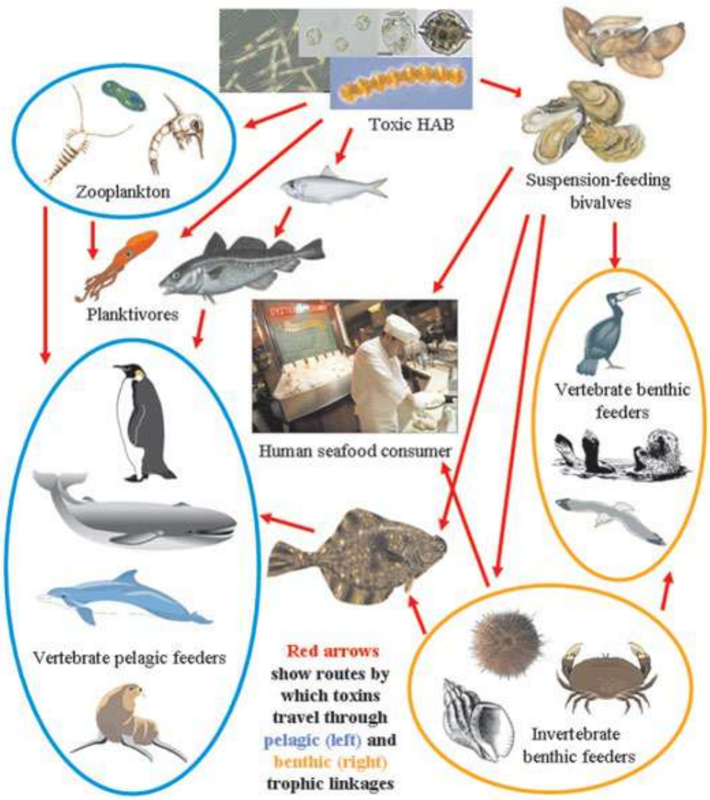
At Stearns Wharf, *Pseudo-nitzschia* seriata has been observed more often than not over the past 13 years, including at “abundant” levels in consecutive sampling periods prior to 2018 (Figure 2B); the diatom appears more frequently and at higher abundances at this location compared to Santa Cruz Wharf. Dinoflagellates were observed only intermittently over the same time period, and at “abundant” levels in only a few samples (monitoring for *Gymnodinium* spp. did not begin until 2019); these organisms occurred less frequently at this location compared to Santa Cruz Wharf. At

Newport Beach Pier (Figure 2C), both groups of HABs occurred less frequently and at lower levels than at either Santa Cruz Wharf or Stearns Wharf. Chlorophyll a concentrations at all three sites site are variable, and at times are high when *Pseudo-nitzschia* and red tide-forming organisms are relatively low. This indicates that other phytoplankton are present in high concentrations.

Why is this indicator important?

HABs can adversely affect marine organisms and their habitats. The diatoms and dinoflagellates associated with HABs can produce toxins that can move up the food chain (see Figure 4), and cause illness or death in fish, marine mammals and seabirds.

Figure 4. How HAB toxins move up the food chain

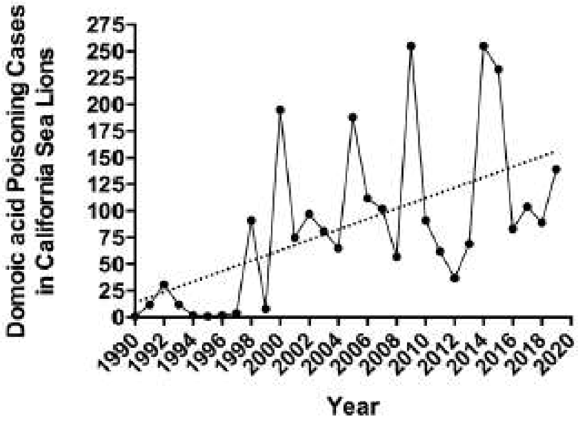


Source: [US National Office for Harmful Algal Blooms 2021]

Out of the roughly 50 different diatom *Pseudo-nitzschia* species, over 25 are known to produce domoic acid at differing concentrations (Bates et al., 2018). Ingestion of *Pseudo-nitzschia* cells containing domoic acid can result in its accumulation in mussels, oysters, clams, other filter-feeding organisms, and planktivorous fish such as sardines and anchovies. Other species may be exposed to domoic acid by feeding on toxin-contaminated organisms or residual cells and through domoic acid in sediment. Anchovies in particular are the dominant vectors of domoic acid and often have far higher concentrations of the toxin than bivalves and benthic feeders (Bernstein et al., 2021). This indicates that anchovies play a large role in aiding in the transfer of domoic acid up the food chain and are good indicators of domoic acid occurrence offshore. Human consumption of fish and shellfish containing domoic acid can result in Amnesic Shellfish Poisoning. Health impacts include symptoms such as nausea, vomiting, and diarrhea at lower doses and seizures, coma, irreversible memory loss at higher doses (OEHHA, 2021). To protect the public from exposures to domoic acid through seafood consumption, California fisheries are closed or have delayed opening when domoic acid is measured in razor clams, lobsters, crab and other seafood above the specified regulatory action limits (>30 ppm for crab viscera, ≥ 20 ppm for all other samples; FDA, 2021). Current biotoxin-related fishery closures are posted by the California Department of Fish and Wildlife.

Marine wildlife that consume domoic acid-contaminated organisms also exhibit signs of neurotoxin exposure. In California, domoic acid was first recognized as a threat to marine mammals in 1998 when hundreds of California sea lions stranded along beaches in central California exhibiting seizures, head weaving, and other neurological signs (Scholin et al. 2000). Retrospective analyses of veterinary records at The Marine Mammal Center in Sausalito revealed cases of domoic acid poisoning since 1990 (see Figure 5; Anderson et al., 2021). Cases increased beginning in 1998 with a notable spike in 2015 coinciding with a widespread coastal bloom. Toxin concentrations in bivalve and fish vector species, while high enough to cause documented illness and mortality in marine mammal and seabird predators, have not been associated with acute health impacts or die-offs among these vectors (Anderson et al., 2021). Between March and November 2015, domoic acid was detected in whales, dolphins, porpoises, seals, and sea lions ranging from southern California to northern Washington—the largest geographic extent of domoic acid detection in marine mammals ever recorded globally (McCabe et al., 2016).

Figure 5. California Sea Lions diagnosed with domoic acid poisoning



Source: Figure 7 from Anderson et al. 2021

Annual number of cases recorded at The Marine Mammal Center in Sausalito CA. Dotted line shows the significant regression (p<0.05).

For California, adverse impacts from marine HABs are also associated with blooms of dinoflagellates, which typically occur in the fall. Dinoflagellates are phytoplankton that can swim via their two flagella. As a result they can migrate vertically in the water column, while other phytoplankton such as diatoms cannot. When conditions are favorable, one or more populations of dinoflagellate may begin growing exponentially, resulting in up to millions of cells per liter of seawater. This 'bloom' can alter the appearance of water color to red, orange, or brown (Dierssen et al. 2006), hence these organisms are considered “red tide formers.” As with many HABs, visible indications of a bloom do not distinguish whether toxins are also present. The majority of red tides in California are nontoxic (Kudela et al., 2015); conversely, toxins may be present in the absence of water discoloration.

In the United States, dinoflagellates known to produce saxitoxins – also known as paralytic shellfish toxins (PSTs) – are in the genera *Alexandrium, Gymnodinium,* and

Pyrodinium. Alexandrium is one of the extremely toxigenic genera: a couple hundred cells in a liter of water can cause unhealthy concentrations of toxins even if no bloom is visible (CDPH 2021). PSTs can lead to numerous health impacts, including facial numbness, nausea, vomiting, respiratory failure and death (Anderson et al., 2021). PSTs were recognized as a serious health risk in California in 1927 when a major outbreak near San Francisco led to more than 100 illnesses and multiple deaths (Price et al., 1991). This led to the establishment of a monitoring program for PSTs in shellfish, the first in the U.S.

Other impacts of marine HABs include fish kills by clogging or lacerating fish gills, *Akashiwo* bloom-derived seafoam destroying the waterproofing of seabird feathers, and indirect effects including dying phytoplankton depleting oxygen or large blooms reducing light penetration (UCSC, 2021).

In addition to the human health and wildlife impacts of HABs, the economic impact of HABs is significant. The closure of commercial and recreational fisheries can cause significant economic loss. When the Dungeness crab season was delayed by several months due to a West Coast-wide algae bloom, the estimated economic loss was over $43 million (Holland and Leonard 2020).

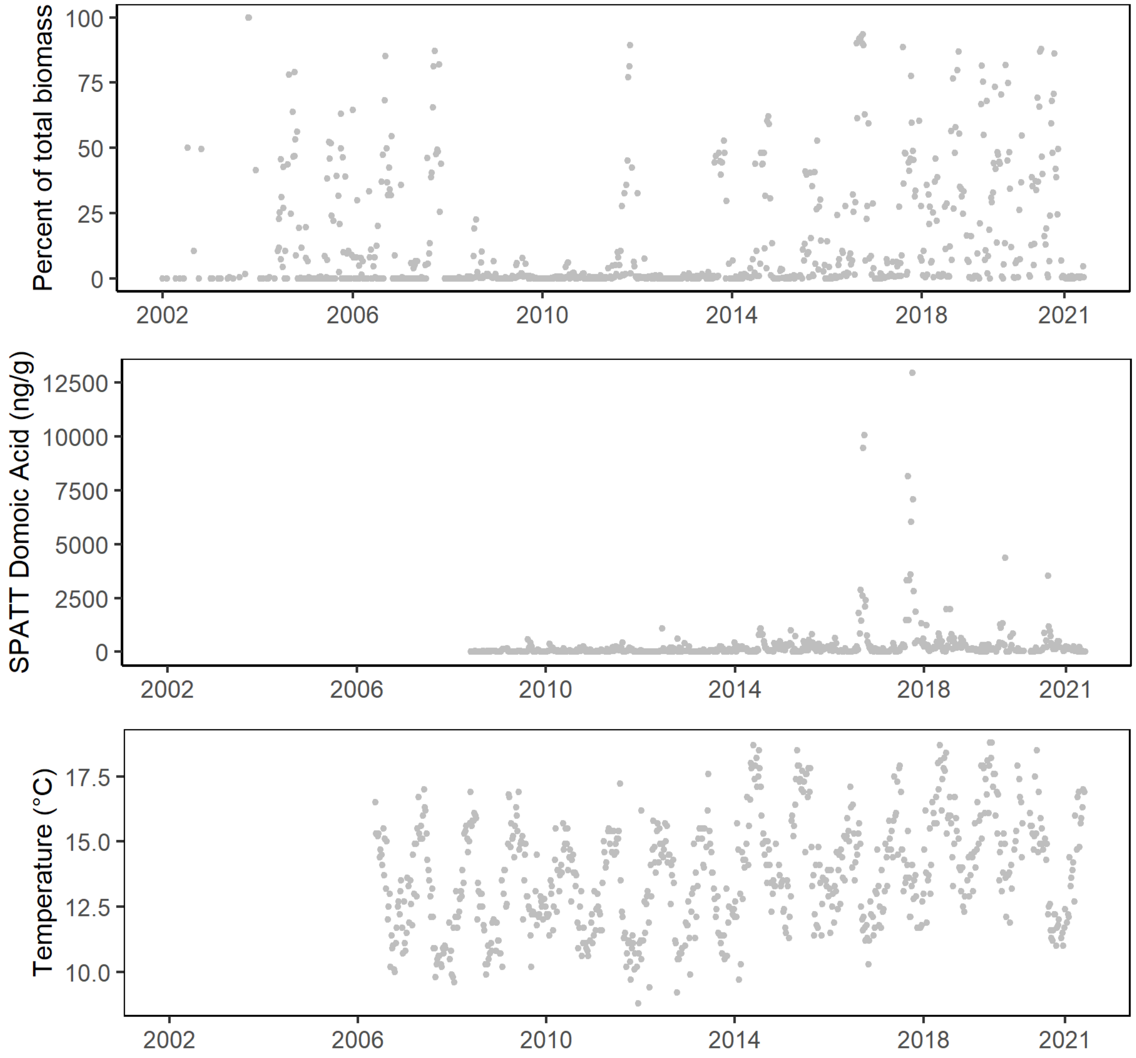
What factors influence this indicator?

Globally, observational and experimental evidence show that shifts in marine HABs distribution, increased abundance, and increased toxicity of marine HABs in recent years have been partly or wholly caused by warming and by other, more direct human drivers (Bindoff, et al., 2019). Marine HAB patterns in California have been associated with multiple factors including both natural and anthropogenic nutrient loading, decadal oscillations, and events such as marine heat waves. With climate change, California coastal waters have warmed over the past century (see *Coastal ocean temperature* indicator), and marine heat waves, such as the one which affected the West Coast of the United States from 2014 to 2016, have become more frequent over the 20th century, and more intense and longer in duration since the 1980s (IPCC, 2021).

All phytoplankton are influenced by light, temperature, nutrients, and physical forcing such as upwelling/downwelling which modulates (e.g.) temperature, salinity, and physical mixing. Water temperature, salinity, upwelling, advection are factors used in the California Harmful Algae Risk Mapping (C-HARM) model to estimate probability of *Pseudo-nitzschia* abundance above 10,000 cells/L and cellular and pDA production above their respective thresholds (see Anderson et al. 2009, 2011, 2016 for more details). C-HARM model predicts these probabilities at the current time ("nowcast") and three days into the future ("forecast") (see https://sccoos.org/california-hab-bulletin/).

Figure 6 presents time series for dinoflagellates, dDA, and temperature in Santa Cruz Wharf. Analyses indicated that both dinoflagellates abundance and dDA concentrations were positively correlated with temperature (not shown; Kudela pers. comm. 2021). These results indicate that with warming oceans, domoic acid concentrations and dinoflagellate abundance, particularly within Central and Northern California, will increase.

Figure 6. Santa Cruz Wharf relative abundance index of several "red tide" forming taxa combined (*Alexandrium*, *Cochlodinium*, and *Gynmnodium*/*Akashiwo*) compared to overall total phytoplankton biomass (top panel), dissolved domoic acid with Solid Phase Adsorption Toxin Tracking (SPATT) (middle panel), sea surface temperature (bottom panel) data over time.

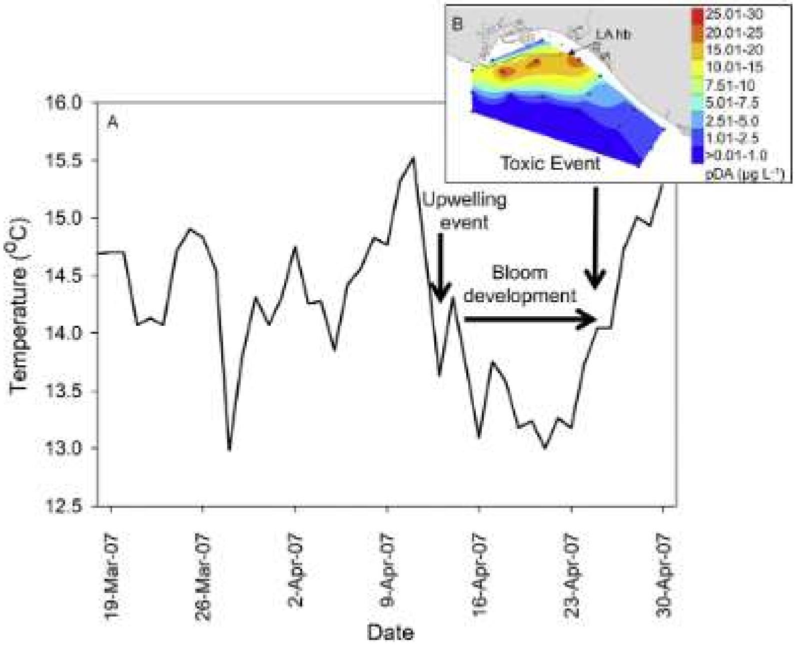


Source: HABMAP and Kudela pers. comm. 2021

A recent analysis of the increase in dinoflagellates concluded that the primary driver at the event-scale is changes in the intensity and direction of local winds (Fischer et al. 2018). It is unclear whether long-term increases in temperature and upwelling intensity will favor or inhibit dinoflagellate blooms, and inter-annual variability is still the dominant pattern in this record. However, the correlation between increasing sea surface temperature, dinoflagellate blooms, and dDA suggest that some HAB species will become increasingly problematic in these Northern and Central California regions in the near future, at least until the apparent thermal maximum (20 °C) for domoic acid production is reached (Fischer et al. 2018; Smith et al. 2018).

Kudela et al. (2003) looked at the correlation between nutrient runoff and *Pseudo-nitzschia* bloom events in Monterey Bay, and did not find a relationship between the two. Lane et al. (2009) developed several models for *Pseudo-nitzschia* in Monterey Bay and Pajaro River discharge was a key negative factor in the Fall-Winter model, meaning discharge resulted in fewer fall blooms. However, Kudela et al. (2008) suggests that urea may be a key variable in bloom events associated with runoff; higher urea concentrations at the Santa Cruz Wharf correlate with higher *Pseudo-nitzschia* abundance. Urea is not often measured in water quality samples, and the lack of this data may be the reason past studies in California have not found a positive correlation between nutrient runoff and blooms.

Figure 7. Influence of upwelling on subsequent bloom of *Pseudo-nitzschia* in Southern California. Data from San Pedro, CA in Spring of 2007



Source: Smith et al., 2018

Umhau et al. (2018) studied the role of upwelling in occurrences of *Pseudo-nitzschia* and pDA in the Santa Barbara Basin. At Stearns Wharf and Goleta Pier, *Pseudo-nitzschia* abundance and pDA concentrations were higher during upwelling versus non-upwelling periods, but due to high variability, these relationships were not significant for the offshore stations. Smith et al. (2018) provides another example of the relationship between upwelling of nutrient-rich water into the nearshore environment and subsequent *Pseudo-nitzschia* bloom in Southern California (see Figure 7).

Warmer sea surface temperatures and upwelling are also shown to be correlated with elevated domoic acid concentrations; within Northern California, maximal domoic acid events coincided during warm periods with upwelling (McKibben et al., 2017).

Furthermore, *Pseudo-nitzschia* and domoic acid are also found within the water column and marine sediment (Umhau et al., 2018). The subsurface populations are believed to act as a seeding population; during upwelling events this population may cause surface blooms (Smith et al., 2018). During the spring of 2015, the largest outbreak of domoic acid was recorded along the west coast. This event coincided with a marine heatwave and the start of the seasonal upwelling period (McCabe et al., 2016). During this marine heatwave, a research cruise that samples waters off the coast of Trinidad found high concentrations of domoic acid and *Pseudo-nitzschia* in water, and record high domoic acid concentrations within razor clams (McClatchie et al., 2016). While warmer water conditions generally favor marine HABs, there appears to be an upper maximum for current strains of *Pseudo-nitzschia* (20°C; Smith et al., 2018) such that in typical years, water temperatures in some areas of Southern California, such as Scripps Pier, may exceed this threshold. In 2015-2016, most impacts were seen north of Los Angeles County, suggesting a northward shift of suitable habitat for toxin-producing *Pseudo-nitzschia* species (McCabe et al., 2016).

More specific factors that are associated with toxin production are certain nutrients and nutrient ratios. Silicate and phosphorus limitations are the two factors most consistently correlated with pDA (Smith et al., 2018). The ratio between silicate and phosphorous also is significantly correlated with pDA, however this correlation is not significant across all years (Anderson et al., 2013). A change in the silica concentrations within upwelling waters of Southern California was associated with an increase in *Pseudo-nitzschia* bloom frequency (Bograd et al., 2015).

Ocean circulation patterns also may influence algal blooms. As the name implies, Pacific Decadal Oscillation (PDO), occurs on a decadal cycle, and the positive phase typically brings lower biological productivity in California. PDO mainly influences sea surface height anomalies (SSHa) and sea surface temperature anomalies (SSTa). PDO has a larger influence on marine life north of San Francisco. The North Pacific Gyre Oscillation (NPGO) also occurs on decadal time scales, affecting SSTa and SSHa, with most influence on regions south of San Francisco. A positive NPGO is associated with an increase in upwelling-favorable winds. El Niño Southern Oscillation consists of two phases – El Niño and La Niña – and occurs on timescales from months to years. El Niño is associated with a warming phase, where California ocean temperatures are typically warmer while La Niña is associated with a cooling phase. In Southern California, PDO has no significant effect on pDA production, while median pDA production increased during periods of negative North Pacific Gyre Oscillation (Smith et al., 2018). Furthermore, pDA production increased during La Niña in Southern California (Smith et al., 2018). These observations suggest that the warm waters within Southern California may exceed the upper temperature limits for *Pseudo-nitzschia* and domoic acid. Within Northern California where water temperatures are generally below the apparent thermal maximum, researchers found that domoic acid concentrations were positively correlated with a positive PDO and El Niño (McKibben et al., 2017). Research near Cal Poly Pier found a significant relationship between PDO and phytoplankton composition, with diatoms and dinoflagellates found to be the dominant phytoplankton in the fall during periods of negative and positive PDO phases, respectively (Barth et al., 2020).

Technical Considerations

Data characteristics

Phytoplankton and pDA data were obtained via the Environmental Research Division's Data Access Program (ERDDAP) in July 2021. SPATT dDA data for Santa Cruz was obtained from Dr. Kudela.

Weekly phytoplankton samples are collected by the Harmful Algal Bloom Monitoring and Alert Program (HABMAP) at nine pier locations throughout California; seven of these stations have historical data. In addition to phytoplankton, water quality samples are taken to measure: algal toxins, temperature, salinity, and nutrients. Surface water samples were taken from each station and a 100-mL water sample preserved to analyze phytoplankton abundance. To calculate the relative abundance index, the Utermöhl method was used to subset the sample and count phytoplankton under a dissecting microscope. The phytoplankton were categorized into nine genera: *Alexandrium*, *Ceratium*, *Cochlodinium*, *Dinophysis*, *Gymnodinium*, *Lingulodinium*, *Prorocentrum*, *Pseudo-nitzschia* delicatissima group, and *Pseudo-nitzschia* seriata group, and two “other” groups, namely other diatoms and other dinoflagellates. Since *Pseudo-nitzschia* is difficult to visually identify to species with light microscopy, the genus is broken up into two groups based on size class. *Pseudo-nitzschia* seriata is the larger and more toxigenic group while *Pseudo-nitzschia* delicatissima is the smaller and typically non-toxigenic group. Relative abundance was calculated by looking at the abundance of the genera compared to the total phytoplankton population (Barth et al., 2020). The relative abundance is then reported as: (1) none; (2) rare, less than 1 percent; (3) present, 1 to 9 percent; (4) common, 10 to 49 percent; and (5) abundant, greater than 50 percent (Radan, 2021).

Grab water samples were filtered and the domoic acid content of all material collected on the filter was analyzed for pDA. Grab samples represent the pDA within the sample at the time of collection. There is a more robust and broadly available dataset for pDA than for dDA via SPATT. Between 2001 and 2008, pDA concentrations were measured using liquid chromatography-tandem mass spectrometry (LC-MS/MS). From 2008 to the present, pDA concentrations were measured using a domoic acid specific enzyme-linked immunosorbent assay (Danil et al., 2021).

SPATT samplers were deployed for seven days and the dDA adsorbed onto the resin at the time of collection was analyzed using LC-MS (Lane et al., 2010). SPATT samplers provide a cumulative measure of domoic acid dissolved in water during the sampler deployment period.

Strengths and limitations of the data

Most of the long-term, consistently collected marine HAB data for California is for surface waters from near-shore structures in Central and Southern California. The HABMAP nearshore station data included above are robust, collected at consistent intervals, and with similar methods since 2008, providing a valuable time series dataset for those areas that is publicly available. The limited publicly available data for Northern California (i.e., Trinidad Pier and Bodega Bay) makes it difficult to analyze trends in that region.

Furthermore, these nearshore, surface water data may not be representative of what is happening offshore or in deeper waters. Umhau et al. (2018) found that offshore stations often had higher domoic acid concentrations than nearshore stations. These nearshore data do not always correspond with C-HARM predictions for the open coast. C-HARM output may be more closely correlated with marine mammals that strand along the coast due to "domoic acid toxicosis" (Anderson et al., 2016). In addition, species such as lobster and crabs that feed on the ocean bottom offshore and are mobile may accumulate domoic acid differently from attached, shoreline bivalve species. For example, Bernstein et al. (2021) found that anchovies had higher domoic acid concentrations than mussels.

As noted above, the *Pseudo-nitzschia* abundances are for two size classes (not individual species) due to the lack of microscopic species-specific identifiers. Availability of rapid, low-cost genetic identification of *Pseudo-nitzschia* species may inform potential relationships between individual *Pseudo-nitzschia* species abundance and domoic acid concentrations and changes with environmental conditions such as temperature and nutrients (Lema et al., 2019).

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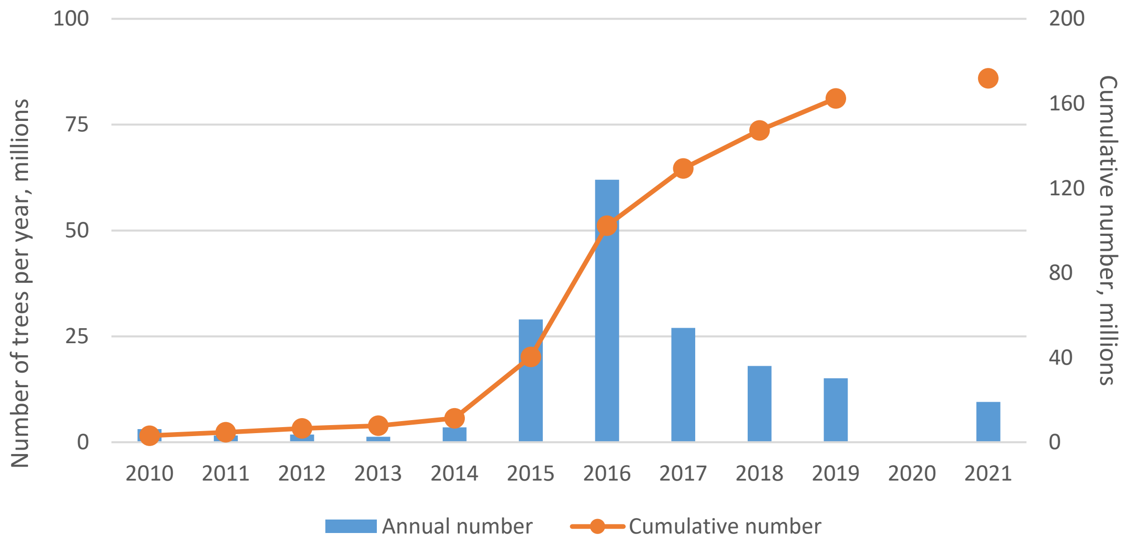
FOREST TREE MORTALITY

Since the 2012-2016 drought — California's most severe since instrumental records began — tree deaths in California forest lands increased dramatically. An estimated 170 million trees in forest lands died between 2010 and 2021. Most of these trees were stressed from higher temperatures and decreased water availability, making them more vulnerable to insects and pathogens.

Figure 1. Estimated number of dead trees (Based on aerial detection surveys)*



Source: USFS, 2020a and b, 2021a

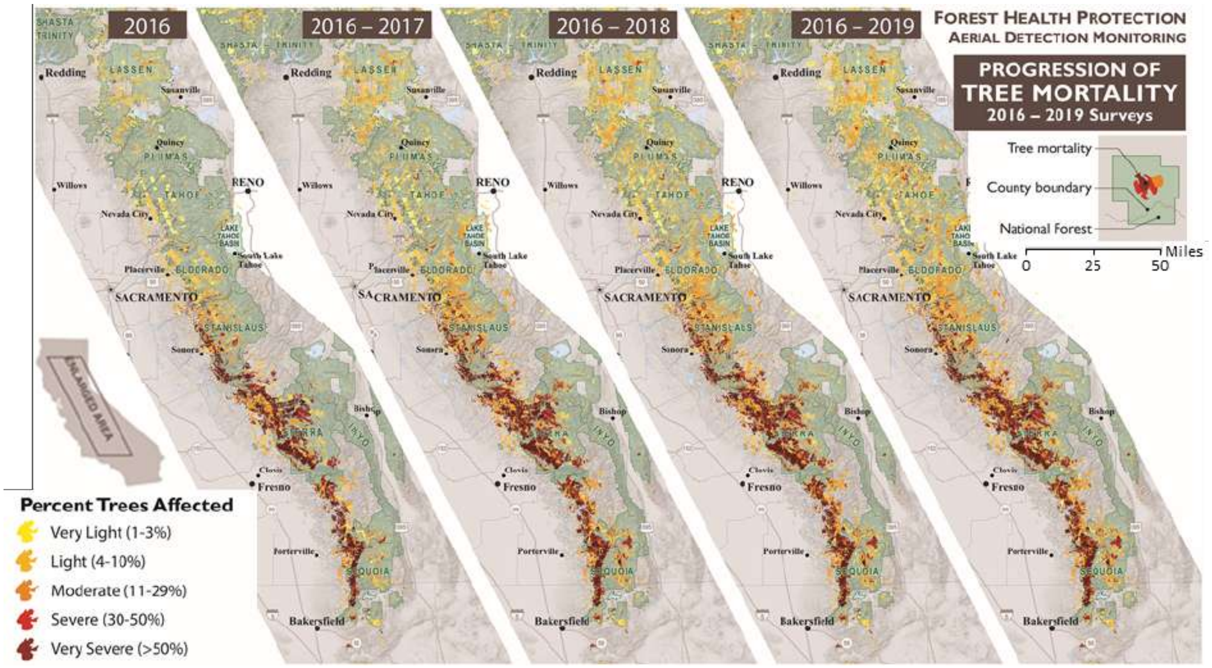
**Aerial surveys were suspended in 2020 due to COVID-19 pandemic. Estimate for 2021 is based on slightly different methodology and is not directly comparable to prior years.*

What does the indicator show?

Figure 1 shows the estimated annual number of dead trees in California forests, based on US Forest Service Aerial Detection Surveys (ADS). The estimates include trees killed by a variety of agents including drought and drought-related insect activity, but not wildfire. Annual tree mortality in California forests showed a steep increase in 2015 (USFS, 2016), as the 2012-2016 drought progressed. The largest number of tree deaths in any one year (62 million, more than double the previous year's estimate) was recorded in 2016, the fourth year of the drought. Relatively wet water years (October – September) followed in 2017-2018 and 2018-2019. Tree deaths during these years were lower than during the drought, but still six to nine times higher than in the beginning of the decade.

California again entered into drought in 2020. Since ADS were suspended in 2020, however, no estimates are presented for that year. While the methodology used in 2021 differed from, and thus yielded estimates not directly comparable to earlier years', the estimated 9.5 million dead trees suggest a decrease although the mortality rate still remains above pre-2012-2016 drought levels (USFS, 2021d). Figure 1 also shows the cumulative number of dead trees in forested areas between 2010 and 2021 at more than an estimated 170 million (USFS, 2021d and e).

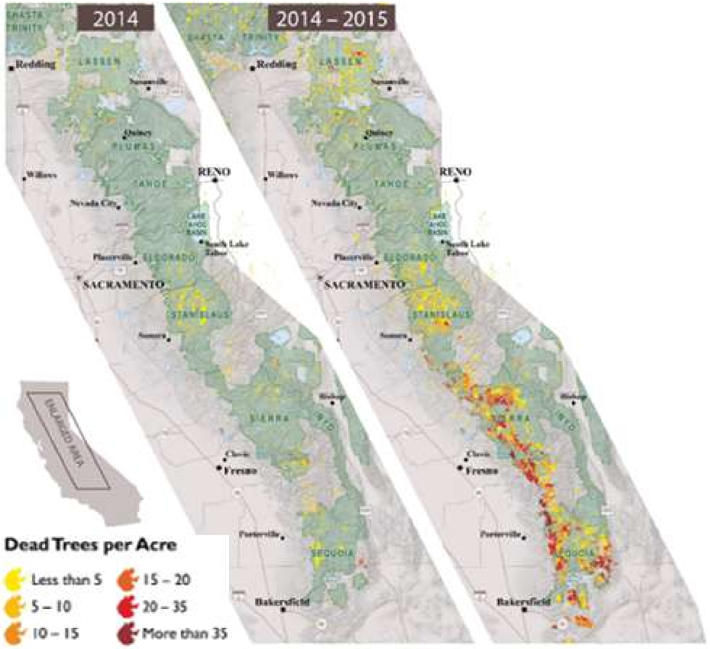
Figure 2. Maps showing progression of tree mortality, 2016 to 2019



Source: USFS, 2021b

The maps in Figure 2 show the progression of cumulative tree mortality between 2016 and 2019 in California's Sierra Nevada Mountains, where mortality has been the most severe. For comparison, Figure 3 shows mortality between 2014 and 2015. The extent and severity of tree mortality increased substantially in 2016, especially in lower elevation forests of the Southern Sierra Nevada where the drought was most severe and prolonged (USFS, 2017). Extensive mortality became evident farther north and into higher elevations beginning in 2016.

Figure 3. Tree mortality in the Sierra Nevada Mountains, 2014 to 2015



Source: Modified from USFS 2021c

California’s pattern of tree mortality corresponds with global trends: increasing tree mortality has been documented on all vegetated continents and in most bioregions over the past two decades. Tree mortality has been linked to increasingly dry and hot climatic conditions (Allen et al., 2010).

As noted in the Tribal section of this report, many Tribes have noticed an increase in tree mortality. Tribes participating in the Eastern Sierra and Southern California listening sessions including Bishop, Big Pine, Mono Lake Kutzadika’a, Santa Ynez, Pala, Barona, and others have witnessed increased tree mortality of conifers, oaks and pine nut trees. During the Lake, Sonoma and Mendocino listening session, the Middletown Rancheria shared this image of local trees (Figure 4) that are dying or already dead. The Kashia Band of Pomo Indians are also experiencing tree mortality and now refer to these stands or dead and dying trees as “match sticks”.

Figure 4. Dead and dying trees at Middletown Rancheria

Photo credit: Mike Shaver, Environmental Director, Middletown Rancheria

Why is this indicator important?

Forests occupy almost one-third of California and are a vital resource for the state, providing important ecosystem services, including water and air purification, carbon sequestration, building materials, renewable energy, cultural resources, wildlife habitat, and recreational opportunities (CNRA, 2016). Accelerating tree mortality and the increasing frequency of large-scale and high mortality events (known as forest dieback) could have profound effects on these ecosystem services. The loss of large trees, in particular, represents a significant reduction in the capacity of forests to store carbon, further exacerbating climate change.

Additionally, there is evidence that increased tree mortality amplifies other climate change-related phenomena such as forest type conversion (a change in tree species or group of species present, for example, from conifers to hardwood; see *Changes in forests and woodlands* indicator) and increased wildfire risk (see *Wildfires* indicator). If forest tree mortality levels continue at elevated rates, changes in the species comprising the state's forest ecosystems, conversion of forests to vegetation types with fewer trees, or even the outright loss of forests are anticipated (Larvie et al., 2019; Lenihan et al., 2003; Millar et al., 2015; Thorne et al., 2008). The unprecedented scale of tree mortality and the increased fuel loads present increased risks of large, severe fires in the coming decades (Stephens et al., 2018).

A state of emergency was proclaimed in October 2015 to address the impacts of the unprecedented tree deaths to communities in affected regions (Brown, 2015). Among other things, the proclamation directs state agencies to take action to minimize the risks to public safety associated with the large number of dead trees, and to address the increased threat of wildfires and erosion in the affected areas. A state task force developed in response to this emergency order has since evolved to broadly address forest health issues, including tree mortality and increasing wildfire risk. In 2021 the task force released the California Wildfire and Forest Resilience Action Plan, establishing State strategies and identifying key actions for the coming years (FMTF, 2021).

What factors influence this indicator?

Tree mortality is a complex process that often involves a chain of events and a wide range of factors, making it difficult to assign a single cause of death. Various pathogens contributing to tree mortality spatially overlap with drought, wildfire, insects and diseases that in combination result in large stand-level forest dieback, changes in the composition of forest trees, and shifts in tree species ranges in the western United States (Clark et al., 2016).

The death of over 170 million trees over the last decade can be attributed to the combined effects of extreme drought and forest management that suppressed wildfires. Fire suppression practices, which started in the 1930s, resulted in increasing tree densities, as shade-tolerant and fire-sensitive tree species were able to establish (Stephens et al., 2018). California and most of the western United States ecosystems are fire-dependent and fire-adapted; for millennia, periodic fire was critical to maintaining ecosystem integrity. Forest densification has increased competition among trees for water and other resources, leaving them increasingly susceptible to mortality from drought and bark beetles.

The 2012-2016 drought in California may foreshadow an increasingly common condition in which warming temperatures coincide with dry years, creating hotter or more frequent droughts. Using tree ring data, researchers estimated 2014 to be the worst single drought year in at least the last 1,200 years in the state, as seen in the tree rings of blue oak — the result of unusually low (yet not unprecedented) precipitation and record high temperatures (Griffin and Anchukaitis, 2014). Such hotter droughts increase the physiological stress in trees (Diffenbaugh et al., 2015; Young et al., 2017). In fact, rising global temperatures have contributed to droughts of a severity that is unprecedented in the last century (Millar et al., 2015). Regional warming and drought change the hydrology at landscape scales (Thorne et al. 2015). Less precipitation falling as snow, declining snowpack water content, and earlier spring snowmelt and runoff have impacted old growth western forests (van Mantgem et al., 2009). The 2012-2016 drought occurred at a time of record warmth — 2014 was, at that time, the warmest year on record, followed by 2015 — accompanied by record low snowpack (DWR, 2017) (also see the *Air temperatures, Drought,* and *Snow-water content* indicators).

Large scale, drought-induced tree mortality events also create feedbacks that exacerbate the threat of wildfires (Stephens et al., 2018). Across the west, drier conditions have also amplified the occurrence and extent of wildfires (Abatzoglou and Williams, 2016) that directly kill trees and burn trees that previously died due to other factors. Techniques to assess the overall levels of tree mortality associated with increasingly intense wildfires are emerging (for example, the Monitoring Trends in Burn Severity Program and the Rapid Assessment of Vegetation Condition After Wildfire Program); however, a comprehensive study for California is not yet available. An example of a smaller-area study estimated that about 2,300 to 3,600 giant sequoias (*Sequoiadendron giganteum*) over four feet in diameter were killed or will die in the next three to five years following the 2021 KNP Complex and Windy Fires (Shive et al., 2021). These estimates correspond to approximately 3 to 5 percent of the entire sequoia population in the Sierra Nevada. In the prior year, an estimated 7,500 to 10,600 large sequoias (about 10 to 14 percent of Sierra Nevada population) were lost in the Castle Fire (Stephenson and Brigham, 2021).

Competition for resources is also a factor influencing tree mortality. Most of California's coniferous forests have higher densities of trees now than 100 years ago, a consequence of fire suppression (McIntyre et al. 2015; Stephens et al., 2018). Denser vegetation increases the demand for water, and tree mortality associated with the drought increased disproportionately in areas that were both dry and dense (Young et al., 2017).

Drying in the deep rooting zone has been closely tied to tree mortality in the Sierra Nevada Forest (Goulden and Bales, 2019). From 2012 to 2015, cumulative evapotranspiration exceeded precipitation by the equivalent of nearly 60 inches of rainfall, and the subsurface moisture was exhausted to depths of 15 to 60 feet. This stress on trees was further intensified due to the higher-than-historical density of trees. The combination of the dense canopy and warm temperatures in the southern Sierra Nevada forests may have increased die-off by 55 percent (Goulden and Bales, 2019).

Tree mortality during the drought correlated with increases in climatic water deficit (CWD) (Young et al., 2017). CWD is used as a measure of water stress experienced by plants (Stephenson, 1998). CWD can be thought of as the amount of additional water that would have been transpired by plants had it been present in the soil; it integrates plant water demand relative to soil moisture availability. Increases in CWD are associated with a warming climate, as plant water demand for evapotranspiration increase as temperatures rise (Flint et al., 2013; Thorne et al., 2015). Reduced precipitation and earlier snowmelt also contribute to a higher CWD by decreasing available soil water. Under increased CWD conditions, trees could lose their ability to convey water from root to leaf via a tree's xylem — a direct mechanism that has been shown to lead to drought-induced tree mortality (Adams et al., 2010).

In addition to creating vegetative stress, warming temperatures provide favorable conditions for the growth and reproduction of insects and pathogens, increasing the threat of tree infestations and diseases (van Mantgem et al., 2009). Temperature-driven insect population increases in combination with water deficit can have disproportionate consequences on tree mortality than would have occurred due to drought or insects alone (Anderegg, 2015). The majority of conifer deaths involved trees weakened by drought succumbing to beetle outbreaks, rather than direct physiological stress from drought (Moore et al., 2016). In recent decades, the outbreaks of insects and pathogens have resulted in extensive forest defoliation, canopy dieback, declines in growth, and forest mortality in western North America. Some widespread dieback events were concomitant with infestation outbreaks where the insect populations increased due to warmer winter temperatures (Bentz et al., 2010).

Some of the predominant pests and diseases affecting California's forests are:

> **Western pine beetle (*Dendroctonus brevicomis*).** The western pine beetle is one of several native bark beetle species of the western United States. In California's Sierra Nevada, drought and attacks by pine beetles have contributed to large proportions of ponderosa pine mortality (Fettig et al., 2019). Overall, about 49 percent of the trees in the region died between 2014 and 2017. Ponderosa pine and sugar pine were most affected, with 90 and 48 percent mortality, respectively. During the 2012–2015 drought, warmer temperatures increased the bark beetle–induced tree mortality by thirty percent (Robbins et al., 2022). Specifically, the warming increased the maturation rate of the beetles and decreased the beetle's mortality during winter. This led to a larger beetle population during periods when trees were more susceptible due to drought. Large extents of beetle-killed trees have increased the fuel loads for wildfire, which in turn leads to higher levels of additional tree mortality during the fire (Wayman & Safford 2021).
>
> **Sudden oak death (*Phytophthora ramorum).*** In coastal northern California, sudden oak death (SOD) is the most important cause of tree mortality. The SOD organism, an invasive pathogen, was first detected in California around 1990. *P. ramorum* affects a broad host range of over 130 species of trees, shrubs, herbs, and ferns, many of which are moved long distances via the nursery industry (Cobb et al, 2020). The pathogen can kill three of four species that comprise an important part of California's northern coastal forests: tanoak (*Notholithocarpus densiflorus*), coast live oak (*Quercus agrifolia*), and California black oak (*Q. kelloggii*); the fourth

species, California bay laurel (*Umbellularia californica*), is a carrier of the disease. Using a demographic model, Cobb et al. found that SOD has killed at least 48 million trees and infected about 150 million more since 1995, while about 1.8 billion remain at risk. (Cobb et al., 2020). The SOD pathogen benefits from warmer rainy temperatures, and although a direct connection has not been established, historical warming of air temperature in the wet winter months of California's north coast ecoregion has been observed, with mean air temperature warming of 1.33 +/- 0.29°F from 1951-1980 (33.63°F) to 1981-2020 (34.95°F) (Flint et al. 2021, analysis by Thorne, personal communication).

Shot Hole Borers (*Euwallacea* spp.). Some urban and natural forests in southern California have been severely affected by beetle-related tree mortality. Two beetle species of Invasive Shot Hole Borers (ISHB) introduce a fungus that causes Fusarium dieback (FD) that can infect 137 species of trees (UCANR, 2021). ISHB-FD has killed thousands of trees in Southern California, and can impact riparian, agricultural and urban tree species (Boland 2018; Eskalen et al., 2018). ISHB-FD has also moved into riparian systems in Southern California, including the Tijuana River and the Santa Clara River riparian forests (Bennett, 2020).

Goldspotted Oak Borer (*Agrilus auroguttatus*). Also in Southern California, a beetle called the Goldspotted Oak Borer, is a serious threat that was introduced from Arizona. It can kill a range of oak species in California, including coast live oak and black oak (Coleman et al., 2017). In the highly infested area of eastern San Diego County, oak mortality levels have approached 45 percent (Coleman et al., 2017). The beetle is killing trees on federal, state, private, and local Native American lands in many areas of San Diego County (University of California Cooperative Extension, 2021). The Iipay Nation of Santa Ysabel and the Barona Band of Mission Indians have reported the death of oak trees on their reservations, located in San Diego County (PBMI and SYBCI, 2021). The 2021 ADS detected 19,000 dead trees on 4,000 acres in the same area (USFS, 2021e).

Climate change, however, may not always worsen diseases or pathogens. A recent study found that favorable climate conditions for a pathogen, white pine blister rust (WPBR; *Cronartium ribicola*), had shifted to higher elevations over 20 years, due to the hotter and drier climate (Dudney et al., 2021). The pathogen attacks five-needle pines, or white pines, and is considered a cool-weather disease. While the estimated range of the pathogen expanded in the colder, higher elevation areas of Sequoia and Kings Canyon National Parks (by 780 km^2), its actual observed presence decreased by 33 percent between the 1996 and 2016 surveys. One explanation begins with the fact that WPBR depends on the host (a white pine species) and an alternate host (plants and shrubs from the genera *Ribes*, *Castellja* and *Pedicularis*). Because of the drought, there were fewer of the alternate host species, and that may have suppressed the spread of the pathogen. However, there is concern that several species of white pine that inhabit high-elevation subalpine conditions may now be exposed to this pathogen.

Technical considerations

Data characteristics

The aerial tree mortality surveys are based on annual small plane reconnaissance over California's forested lands. Forested areas are mapped on a one-acre basis, and the following are recorded: (a) damage type, (b) number of trees affected, and (c) affected tree species. Generally, areas with <1 tree per acre of mortality are considered to have "background" or "normal" levels of mortality and are not usually mapped during the flight. If low levels of mortality are indicative of a localized pest-related event, the areas are supposed to be mapped; however, it is usually not possible to systematically discern the cause of such low-level mortality using visual aerial surveys.

For the aerial surveys, lands dominated by hardwood and conifer tree species are considered forest lands. Affected tree are recorded to species level if possible (sugar pine and white fir), or to genus level (pine, fir). In areas where two or more tree species are affected, the surveyor will designate the proportion of damage affecting each species (e.g., 25 percent sugar pine, 75 percent white fir), or preferably, an estimate of trees per acre for each species affected is recorded. Lands characterized as urban, orchards, and windbreaks are not mapped. Tree injuries that are recorded are typically defoliation, discoloration, dieback or more commonly death. Survey results provide a reasonable estimate of dead trees that aid in the understanding of the mortality event (USFS, 2019b). There will be some level of error in the density estimates, however, over large areas, the results should show the correct trends.

Strengths and limitations of the data

Aerial surveys cannot detect mortality until the trees have been dead some months and the foliage has dried out and faded from green to a red or yellow color. Thus, currently infested, but alive trees that still look healthy from a distance may not be counted in the aerial survey. Unfortunately, the aerial detection survey program was suspended in 2020 due to the COVID 19 pandemic. The 2021 ADS did not include all areas covered by past aerial survey operations; instead remote sensing was used to analyze some of the areas. Thus, after 2019, tree mortality data comparable to earlier years are not available to assess the impacts of next wave of drought that began in 2020.

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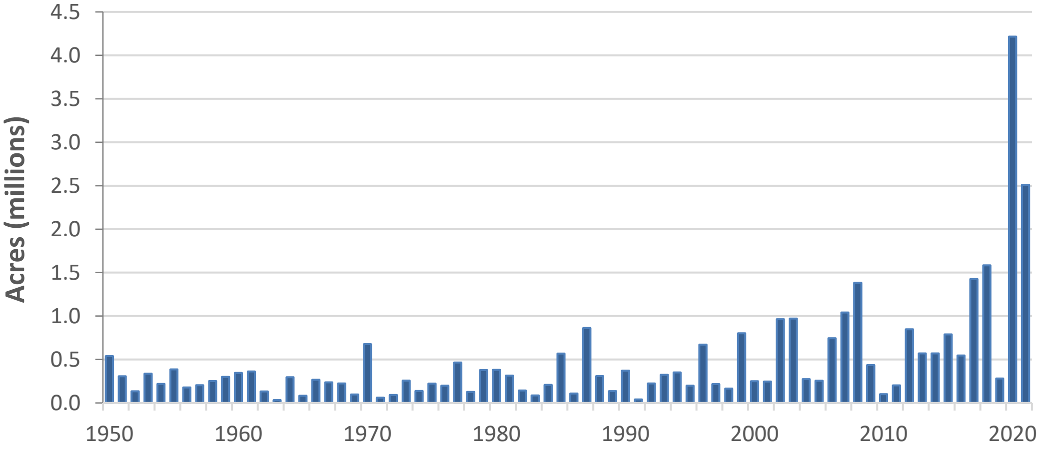
WILDFIRES

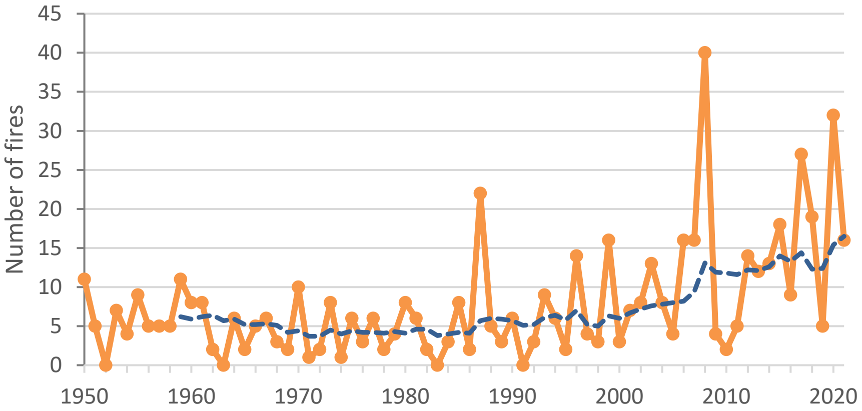
The area burned by wildfires and the number of large fires (10,000 acres or more) across the state have increased markedly in the last 20 years—trends influenced by altered fuel conditions and climate change. Wildfires in 2020 burned an unprecedented 4 million acres across California. In 2021, about 2.6 million acres burned, making it the second highest year, followed by 2018, with 1.5 million acres burned.

Figure 1. Statewide annual acres burned, 1950-2021



Source: CAL FIRE, 2022

Figure 2. Annual number of large wildfires (≥ 10,000 acres), 1950-2021*



Source: CAL FIRE, 2022

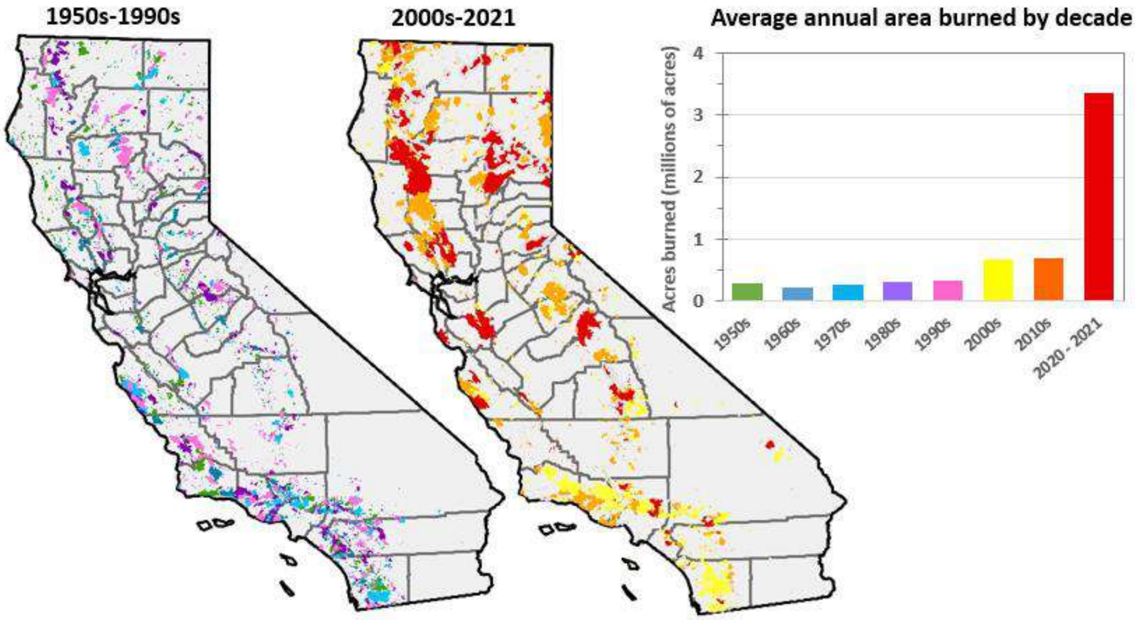
Dotted line is 10-year running average.

What does the indicator show?

The data presented in Figure 1 show the number of acres burned by wildfires statewide each year. The total area burned annually since 1950 ranged from a low in 1963 of 32,000 acres to a record high in 2020 of 4.2 million acres – more than 4 percent of the state's roughly 100 million acres of land. The year 2021 ranks the second highest in acreage burned by a wide margin: wildfires consumed about 2.6 million acres, compared to about 1.6 million in 2018, the third highest year. The number of large fires (10,000 acres or more) has similarly increased in the past two decades (Figure 2).

Figure 3 shows areas of the state burned by wildfires by decade. The average area burned each year in the last two full decades is at least double the acreage in the earlier decades; the annual average in 2020-2021 is about five times higher than in the 2010s. Until the 2010s, the largest fires occurred in Southern California. In the past several years, most of the largest fires have occurred in the north, including the August Complex fires in 2020 (in Mendocino, Humboldt, Trinity Tehama, Glenn, Lake and Colusa Counties) and the Dixie Fire in 2021 (in Butte, Plumas, Lassen, Shasta and Tehama counties), which shattered previous fire size records (see Figure 4).

Figure 3. Fire history, 1950-2021

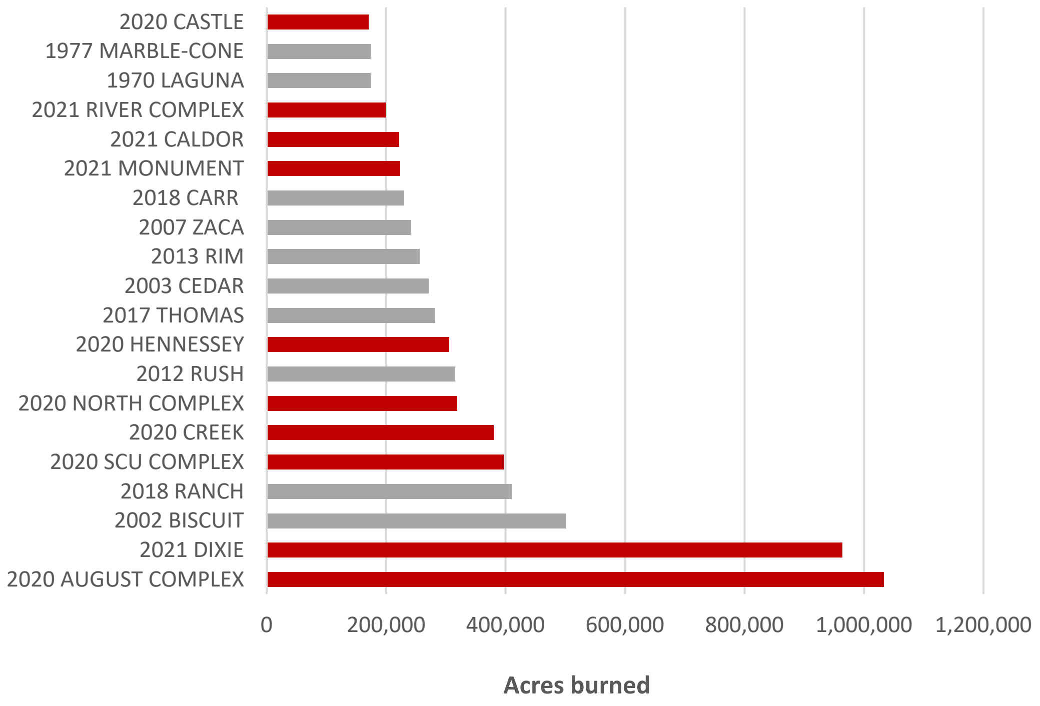


Source: CAL FIRE, 2022

Maps showing areas burned in 1950 to 1999 (left) and in 2000-2021 (right). The colors on the maps correspond to decade burned, as presented on the bar graph showing the average annual acreage burned by decade.

As shown in Figure 4, all but two of the largest wildfires have occurred since 2000, including ten that burned in 2020 and 2021 (CAL FIRE, 2022). The increasing prevalence of very large fires (>10,000 acres) in California and across the West has led many experts to describe the US as having entered into an era of “mega-fires” or, when also considering recent large-scale tree mortality events, an era of “mega-disturbances” (CAL FIRE, 2018).

Figure 4. Top 20 California fires since 1950



Source: CAL FIRE 2022

Red bars denote fires that occurred in 2020 and 2021.

Notable fires in the past five years include:

- The October 2017 wildfires in Sonoma and Napa counties that devastated the affected communities: 44 deaths, more than 100,000 residents evacuated, and over $9 billion in residential and commercial insurance claims (CDI, 2017).

- The Thomas Fire that swept through Ventura and Santa Barbara counties in December 2017 and occurred outside of what has traditionally been considered the state’s fire season. Following the Thomas Fire, debris flows in 2018 in Montecito resulted in 23 deaths and nearly 1 billion dollars in damages (Oakley, 2021). Santa Ynez Chumash firefighters helped battle this blaze and additionally worked to protect cultural sites (Shankar, 2017).

- The Mendocino Complex and Carr fires in 2018, which totaled $148.5 billion (roughly 1.5% of California’s annual gross domestic product), with $27.7 billion in capital losses, $32.2 billion in health costs, and $88.6 billion in indirect losses (e.g., manufacturing and supply chain impacts) (Wang et al., 2021). Indirect costs often affect industry sectors and locations distant from the fires (for example, 52% of the indirect losses—31% of total losses—were outside of California). During the Lake, Sonoma and Mendocino listening session and in the Big Valley climate change report, Tribes detailed the impacts of this fire on their Tribes (Big Valley and Middeltown, 2021).

- The Camp Fire in 2018, the deadliest and most destructive wildfire in California history: 85 deaths, nearly 19,000 buildings destroyed, and most of the town of Paradise burned down. The fire generated a large plume of heavy smoke that traveled thousands of miles. The smoke caused dangerously high levels of air pollution in the Sacramento Valley and Bay Area in particular, for a period of about two weeks (CARB, 2021).

- The August Complex fire in 2020, described as the state's first "gigafire," having burned more than one million acres. The fire crossed seven counties comprising an area larger than the state of Rhode Island (CAL FIRE, 2021a).

- The 2020 Creek Fire in Fresno and Madera Counties, fueled by trees stressed from years of exceptional drought in the heart of the tree mortality zone (CAL FIRE, 2021b). The largest single fire as of that date, the fire burned almost 380,000 acres in an area that has no recorded fire history in the Sierra National Forest. Rising warm air from the fast-moving fire carried water vapor up into the atmosphere, creating a "pyrocumulonimbus" cloud—one of the largest ever observed in the United States (NASA, 2020). The Creek Fire had a direct impact on the North Fork Band of Mono Indians of California as it burned historic lands and came within five miles of the reservation (NFRMIC, 2022).

- The CZU Complex fire in 2020, which burned about 86,500 acres in Santa Cruz and San Mateo Counties, destroying about 1,500 structures and damaging 140 others (CAL FIRE, 2021c). The fire burned the majority of the 18,000 acres in the state's oldest park, Big Basin Redwood State Park (CalOES, 2021). The park is home to the largest continuous stand of ancient coast redwoods south of San Francisco, most of which fortunately survived the fire (CDPR, 2021). The Amah Mutsun Tribal Band suffered direct losses as a result of this fire (Amah Mutsun, 2022).

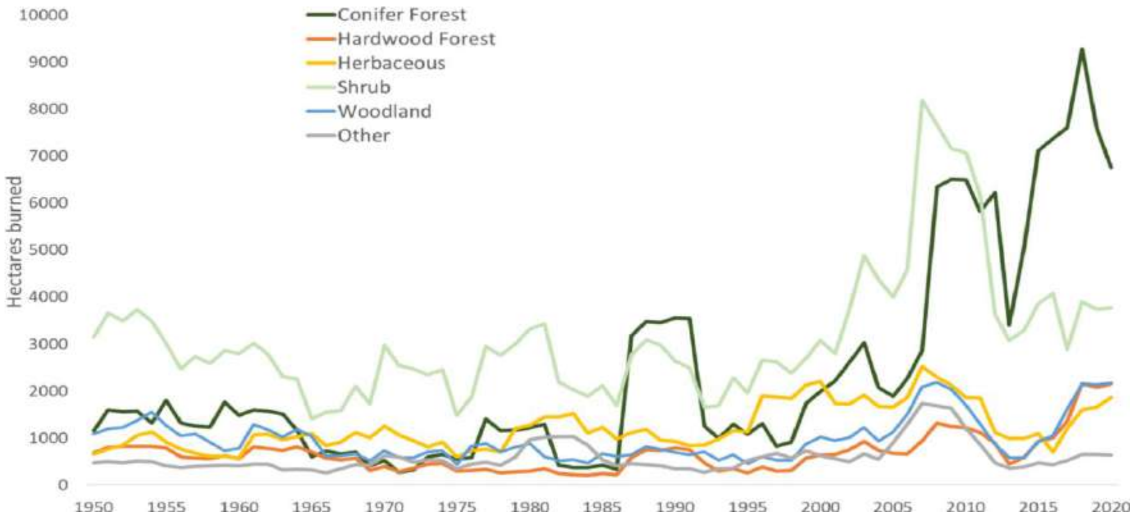
- The Dome Fire in 2020 burned over 43,000 acres in the Mojave National Preserve, through one of the densest and largest Joshua Tree forests in the world. An estimated 1.3 million Joshua trees were killed in the fire (NPS, 2022).

- The Castle Fire in 2020 and the KNP Complex and Windy Fires in 2021 led to the loss of an unprecedented number of giant sequoias: an estimated 9,800 to 14,000 trees that made up about 13 to 19 percent of the large sequoia population in the Sierra Nevada. Giant sequoias are highly valued trees that occur in about 70 distinct groves covering only about 12,000 hectares. An iconic species, giant sequoias are the most massive trees on earth with exceptional longevity, and the center piece of many state and national parks (Shive et al., 2021 and 2022).

- The Dixie Fire started on July 13, 2021 in Butte County. It burned across four other counties –Lassen, Plumas, Shasta and Tehama – and on the Plumas National Forest, Lassen National Forest, and Lassen Volcanic National Park. It is the largest single fire in modern history to date, consuming more than 960,000 acres, and was the first fire known to cross the crest of the Sierra Nevada, followed a month later by the Caldor Fire (Inciweb, 2022a and b).

In addition, changes in the type of vegetation burned have been observed in recent decades. Figure 6 presents the annual area burned by wildfires across the state by five categories of vegetation: herbaceous, shrubland, woodland, hardwood forest, and coniferous forest; the sixth category, “other,” includes partially vegetated areas of lower flammability such as barren, urban, wetland, agriculture and desert (Schwartz and Syphard, 2021). Most vegetation types have seen increases in area burned since 2000, with, conifer forests showing the greatest increase. In most years between 1950 and the mid-2000s, shrubland accounted for the largest area burned in California; cumulatively, fires in shrubland made up more than 50 percent of the area burned since 1950.

Figure 6. Area Burned by Vegetation Type, 1950-2020



Source: Figure 2 from Schwartz and Syphard, 2021

Area burned is smoothed over a five-year window for five vegetation types (coniferous forest, hardwood forest, woodland (consisting of hardwood and coniferous woodland) shrub, herbaceous vegetation, and “other” (lower flammability and partially vegetated areas).

Why is this indicator important?

Wildfires threaten public health and safety, property, and infrastructure, as well as ecosystems and the services they provide. The economic costs associated with fire prevention, mitigation and response, and post-fire rebuilding and restoration have been substantial in recent years (CCST, 2020).

Wildfires severely impact air quality both locally and in areas downwind of the fire (Nolte et al., 2018). Wildfire smoke contains hazardous constituents including fine particulate matter, carbon monoxide, ozone precursor compounds, polycyclic aromatic hydrocarbons, and volatile organic compounds (CDPH, 2019; Black et al., 2017). Exposures to wildfire smoke have been associated with general respiratory illnesses and exacerbations of asthma and chronic obstructive pulmonary disease (Liu et al., 2017; Reid et al., 2016;). As an example of the remote impacts of wildfires, the Camp Fire in 2018 affected air quality 88 miles downwind in Sacramento County, which experienced eleven consecutive days of “unhealthy” air and an increased number of emergency department visits for respiratory-related health conditions (CDC, 2021). (See *Wildfire smoke* indicator)

The rapid growth of wildfire is consistent with predicted increases in property damage that will occur in wildland/urban interfaces proximate to major metropolitan areas in coastal southern California, in the San Francisco Bay Area, and in the Sierra foothills northeast of Sacramento (Westerling and Bryant, 2008). Between 2000 and 2018, the largest number of structures burned in locations classified as “other”—this includes residential areas along the wildland-urban interface (Figure 6; Schwartz and Syphard, 2021). Among lands with natural vegetation types, the largest fraction of destructive fires (those that destroyed structures) occurred in woodlands and hardwood forests; these forests make up only 4 percent of all vegetation types statewide, yet accounted for 16 percent of destructive fires. Only 12 percent of destructive fires occurred in conifer forests.

Wildfires are a serious threat to California’s Tribes. More information specific to each Tribe is presented in the *Impacts on Tribes* section. For example, in the Klamath Basin, the Karuk Tribe has experienced more frequent, large-scale, high-severity intense fires in recent years (Karuk, 2022). Although a historically fire-adapted system, large high-severity wildfires in this region threaten many species, alter the habitat, and disrupt ecosystem dynamics. During the Eastern Sierra listening session Tribes shared that as the Owens Valley is losing native vegetation, invasive plants are less resistant to wildfire. (Bishop Paiute, 2020 and 2022). Wildfire is considered a high-risk exposure for the Pala Tribe also. Nearly a third of Pala’s population lives in a high-risk wildfire area (Pala, 2022).

Less than three months after the Eastern Sierra listening session during which the Tribes discussed the vulnerability of their area to wildfire. The home of the Cultural Monitor for the Coleville Paiute Tribe, Grace Dick, burned to the ground in the Mountain View Fire, which burned over 20,000 acres in the Antelope Valley.

Substantial economic impacts are associated with damage to infrastructure, loss of property, disruption of businesses and jobs, and firefighting and post-fire cleanup. Larger and more extreme wildfires could be especially challenging for rural, low-income households residing in fire prone areas. Property loss is more likely to occur in smaller, more isolated housing clusters that are difficult for firefighters to reach and suppress (Syphard, 2012). Rural, low-income residents often have less capacity to protect themselves and recover from fire impacts than people living in more affluent communities (CAL FIRE, 2018). Wildfires on or near native lands threaten the health, safety, and economy of those Tribes, culturally important species, medicinal plants, traditional foods, and cultural sites (Jantarasami et al., 2018).

As large wildfires increase in size and number and the fire season has grown longer, firefighting has consumed more of the annual resource management budgets for federal and state lands that otherwise could be spent on sustainable programs for fuel management and forest health. The increased threat to losses of property, lives, and natural resources has made fire suppression in California an increasingly higher priority for federal, state, and local land management agencies. In response, the Governor's *California and Forest Resilience Action Plan* provides a strategy to improve wildfire resilience and forest health throughout the state (Governor's Forest Management Task Force, 2021).

Wildfires in forests can lead to long-term changes in forest area, composition, or structure. Forest conversion to shrub or grassland will have adverse impacts on soil productivity, water quality, wildlife habitat, and carbon storage (CAL FIRE, 2018). Recovery of plant communities following a fire determines biodiversity, ecosystem services, future fire activity and other ecosystem conditions. Fires cause injury or death to animals, and lead to immigration or emigration; the habitat changes resulting from a fire (such as altered physical habitats, changes in food availability, and disruptions to landscape processes) can have more profound impacts on animal communities (Smith, 2000). Larger "megafires" kill small mammal, reptile and amphibian species that have evaded or survived smaller, less severe natural historic fires by seeking shelter in burrows (CAL FIRE, 2018). Animals exhibit a wide range of strategies in dealing with fires, and recovery of animal communities is affected by the nature of the fire, the type of vegetation burned, the availability of refugia, and habitat fragmentation outside the burned area (Keeley and Safford, 2016).

Fires affect the physical, chemical and biological properties of soils (Neary et al., 2008). Relatively low temperatures can reduce the organic matter in soils, increasing its bulk density and reducing its porosity. These changes make the soil more vulnerable to post-fire runoff and erosion, leading to damaging floods (Oakley, 2021). Healthy forests play an important role in the hydrologic cycle, promoting infiltration, holding soil on slopes, and maintaining the delivery of high-quality water to streams and downstream uses (CAL FIRE, 2018). Fires affect aquatic habitat and aquatic organisms by altering streamflow, depositing sediment, and introducing fire debris, ash and other water contaminants, including heavy metals from soils and geologic sources and fire retardants into surface waters (Neary et al., 2008). These contaminants have compromised the quality of drinking water sources (Alizadeha et al., 2021). In watersheds, vegetation destroyed by severe wildfire can reduce stream shade and increase water temperatures, threatening species such as Chinook salmon (see *Salmon River water temperature* indicator).

Forests play an important part in regulating levels of atmospheric carbon (Gonzalez et al., 2015; Settele et al, 2014). Trees remove carbon dioxide, a greenhouse gas, from the atmosphere and store it through natural processes. California's forests function as net carbon sinks, sequestering about 25 million metric tons of carbon dioxide equivalent per year (Christensen et al., 2021). However, the long-term sustainability of forests to continue to operate as net sinks is at risk. The increasing frequency of large wildfire events and the increasing loss of conifer and hardwood forests to wildfires, along with pest infestations and associated tree mortality have the potential to drastically impact the quantity, quality and stability of carbon storage in affected areas.

What factors influence this indicator?

A natural element of California's landscape, wildfires play a critical role in shaping the state's wildlands. Prior to Euro-American settlement, an estimated 4.5 to 12 million acres burned annually, ignited naturally by lightning and intentionally by Native Americans to manage the landscape (Stephens et al., 2007). For example, the Karuk Tribe in the mid-Klamath River region of northern California and the Amah Mutsun Band in the central coast have relied on fire to protect ecological and cultural resources and to build wildfire resilience (*Impacts of Climate Change on the Amah Mutsun Tribal Band* and *on the Karuk Tribe* chapters). These patterns of recurring, primarily low and moderate severity fires were disrupted following the depopulation of Native Americans and the implementation of more than a century of fire suppression that led to the accumulation of fuels in California's forests (Taylor et al., 2016).

Changes in population and land use can have immediate and dramatic effects on the number and sources of ignitions and on the availability and flammability of fuels. For example, the escalation of fire losses at the wildland-urban interface is often attributed to new housing development within or adjacent to wildland vegetation (Li et al., 2021; Mass et al., 2019; Syphard et al., 2012). Population growth has brought the suppression of fire and attendant growth in fuel availability, as well as the spread of highly flammable, nonnative plant species. In addition, the expansion of the electrical distribution system, much of it vulnerable to strong winds, provides multiple points of wildfire initiation (Mass et al., 2019).

The size, severity, duration, and frequency of wildfires are greatly influenced by climate. High precipitation years promote the growth of vegetation that then dry up the following spring or summer under warm, low moisture conditions. In largely grass- and shrub-dominated foothills of the Sierra Nevada and across southern California landscapes, the amount of prior-year rainfall has been positively linked to area burned by fire in the following year (Keeley and Syphard, 2017). In western US forests, warmer spring and summer temperatures, reduced snowpack and earlier spring snowmelt have been associated with increased wildfire activity beginning in the mid-1980s: more frequent large wildfires, longer wildfire durations, and longer wildfire seasons (Westerling et al., 2006 and 2016; Williams et al., 2019). Climate change-linked increases in temperature and in vapor pressure deficit (VPD, a measure of dryness, is the difference between the amount of water vapor in air and the maximum amount it can hold) have been shown to significantly enhance fuel aridity over the past several decades, creating a more favorable fire environment (Abatzoglou and Williams, 2016). As summertime temperatures increased by approximately 1.4°C in California since the early 1970s, VPD has likewise increased (Williams et al., 2019). The warming-driven increase in VPD has been found to be the largest wildfire-relevant climate trend in the summer. Warming-driven fuel drying is the strongest link between climate change and increased wildfire activity across the Sierra Nevada (Chen et al., 2021).

In recent years, California has experienced extreme drought intensified by unusually warm temperatures, known as a hotter drought (see *Drought* indicator). With hotter drought come very low precipitation and snowpack, decreased streamflow, dry soils, and large-scale tree deaths. These conditions create increased risk for extreme wildfires that spread rapidly, burn with a severity damaging to the ecosystem, and are costly to suppress (Crockett and Westerling, 2017). A study of wildfires in the western US across ecoregions that represent a wide range of vegetation types, latitudes and precipitation regimes found the largest increases in fire activity in ecoregions where temperatures trended hotter and precipitation trended drier, coinciding with trends toward increased drought severity (Dennison et al., 2014). A disproportionate increase in burned areas in the past two decades have occurred in regions of the western US where vegetation is more sensitive to moisture deficits and prone to drying out (Rao et al, 2022). Tree mortality associated with the severe 2012-2016 drought in California significantly altered forest structure, composition and fuels for wildfire, particularly in the central and southern Sierra Nevada (Stephens et al., 2018). Historical records indicate that in the 1920s, drought also coincided with increased large fires (greater than 10,000 hectares (approximately 25,000 acres) (Keeley and Syphard 2021).

In the fall, warming temperatures and decreasing precipitation statewide over the past four decades have contributed to extreme fire weather (that is, weather conditions conducive to wildfires) across most of the state; the frequency of autumn days with extreme fire weather was estimated to have more than doubled since the early 1980s (Goss et al., 2020). Recent autumn wildfires – notably the Camp Fire in Butte County and the Woolsey Fire in Los Angeles and Ventura Counties, both in 2018 – occurred during periods of extreme fire weather that coincided with strong offshore winds. These fires burned vegetation rendered unusually dry by anomalously warm conditions and late rainfall. As the onset of California's rainy season has become progressively delayed over the past six decades (Luković et al., 2021; Swain, 2021), wildfire risk has increased with the temporal overlap between extremely dry vegetation conditions and fire-promoting winds in late autumn.

Large and damaging wildfires in California are often associated with significant wind events, especially fast-moving downslope winds such as the Santa Ana winds (in Southern California) and Diablo winds (in Northern California). In Southern California, the influence of Santa Ana winds on wildfires is evident; a study found that non-Santa Ana fires, which occur mostly in June through August, affected higher elevation forests, while Santa Ana fires, which occur mostly in September through December, spread three times faster and occurred closer to urban areas (Jin et al., 2015). Recent examples of Santa Ana wind-driven fires include the destructive Thomas Fire in Ventura and Santa Barbara Counties (December 2017 to January 2018) and the Woolsey Fire, mentioned above. Catastrophic wildfires in Northern California, including the series of "Wine Country" fires in Napa and Sonoma Counties in October 2017 and the 2018 Camp Fire, were driven by Diablo winds. These fires burned over non-forested landscapes of shrubs, grasses, and woodlands (Keeley and Syphard, 2019).

Fire severity is affected by climate. The area burned by high severity fires from 1985 to 2017 in western US forests showed an eightfold increase, corresponding with warmer and drier fire seasons (Parks et al., 2020). Among the potential consequences of high severity fires is the growth of vegetation types other than those originally in the burned area, potentially altering forest ecosystems.

Higher altitude forests are buffered against the effects of warming to some extent by available moisture from colder conditions. Snowpack and abundant spring runoff provide moisture to soil and vegetation, reducing the flammability of these forests. However, a study of a 105-year data set (1908 to 2012) found that fire frequency in the Sierra Nevada has been increasing since the late 20th century, as has the upper elevational extent of those fires (Schwartz et al., 2015). Prior to 1950, 7 of 1531 recorded fires burned at elevations above 3000 meters; since 1989, 30 of 1534 fires burned above this elevation. Changes in fire management (such as reduced fire suppression at high elevations), climate (warming temperatures, especially at night, and earlier snowpack melt), fuels (from increasing tree densities) and ignitions (both lightning and human-caused) are recognized as factors influencing the trend. These factors are not mutually exclusive and may have synergistic effects.

The upslope advance of Sierra Nevada wildfires in recent years was corroborated by a study which found that fire is increasing disproportionally at high-elevation compared to low-elevation forests in the western United States (Alizadeh et al., 2021). The largest increased rates in burned area during 1984 to 2017 occurred above 2500 meters. High-elevation fires advance upslope with a cumulative change of 252 meters; the greatest advances were observed in the Southern Rockies, Middle Rockies and Sierra Nevada ecoregions at 550, 506 and 444 meters, respectively. The upslope advancement was consistent with the increase in VPD. The upward migration of wildfire may play a role in fundamentally changing the landscape at higher elevations, and make these areas even more prone to burning in the future.

Technical considerations

Data characteristics

Data on statewide annual acres burned (Figure 1) were downloaded from a fire perimeter database made publicly available online through CAL FIRE. CAL FIRE works with the USDA Forest Service (USFS) Region 5 Remote Sensing Lab, the Bureau of Land Management (BLM), and the National Park Service (NPS) to track fires on public and private lands throughout California. The data for the period 1950 to 2001 include USFS wildland fires 10 acres and greater, and CAL FIRE fires 300 acres and greater. In 2002, BLM and NPS fires of 10 acres and greater were added, as were CAL FIRE timber fires of 10 acres and greater, brush fires of 50 acres and greater, grass fires of 300 acres and greater, wildland fires destroying three or more structures, and wildland fires causing $300,000 or more in damage. Further details are available at the CAL FIRE fire perimeters webpage.

For the graph in Figure 5, the alarm date of the first large fire, and the containment date of the last large fire of the calendar year in the fire perimeter datafile were plotted as the start and end dates, respectively, for each year.

Strengths and limitations of the data

The CAL FIRE database contains the most complete digital record of fires in California. However, some fires may be missing for a variety of reasons (e.g., lost historical records, inadequate documentation). The containment date for many of the fires is missing, but a large majority of the fires have alarm dates. In addition, although every attempt is made to remove duplicate fires, some duplicates may still exist. Overgeneralization may also be an issue, in which unburned regions within old, large fires may appear as burned.

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PONDEROSA PINE FOREST RETREAT

Ponderosa pine forests in the Sierra Nevada have retreated uphill since the mid-1930s.

Update to 2018 Report

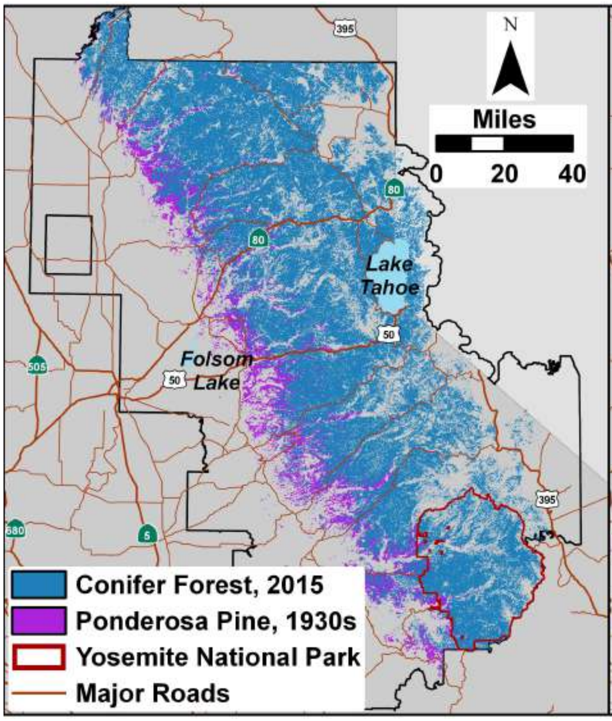
Ponderosa pine in California's Sierra Nevada occupies the western lower edge of the montane conifer forest. As noted in the 2018 indicator report, the death of adult trees and the inability of seedlings to survive unfavorable conditions are driving the upslope retreat of the lower edge of the ponderosa pine in this area. During the 2012-2016 drought, tree mortality in these mountains was concentrated in the lower half of the elevations of the conifer belt, particularly in the southern Sierra.

Recent studies have advanced the understanding of factors affecting conifer mortality, particularly the role of moisture deficit. One study using field measurements and remote sensing products linked tree die-off across the Sierra Nevada to the drying of the deep rooting zone (Goulden and Bales, 2019). This loss of soil moisture in 5 to 15 meter depths is due to a combination of drought, heat and increased evaporative demand. It occurred in dense forests where fire suppression practices have been in place since at least 1980. Conifer mortality was highest in the Southern Sierra and at elevations below 2,300 meters. Another study documented a retreat in the lower edge of ponderosa pine in 90 sites across the western United States (Davis et al., 2019). Using tree ring analysis from 2,935 trees in the footprints of 33 wildfires, the study focused on factors that limit the regeneration of trees after a fire, including vapor pressure deficit, soil moisture and maximum surface temperatures. Climate conditions in the last 20 years in dry sites were found to be "increasingly unsuitable for regeneration."

The studies that follow present findings relating drought conditions to western pine beetle (WPB) infestations, and forest structure (the size and density of trees, which often reflect the influence of forest management). A study of ponderosa pine in the Sierra Nevada Mountains focused on interactions between broad-scale environmental factors (climatic water deficit, a measure of water stress associated with hotter, drier conditions) and local-scale host tree size (Koontz et al., 2021). Using drones to map 450,000 trees at 32 dry sites at around 1,000 meter elevation, the authors found that sites with larger, denser ponderosa pine trees (which facilitated WPB colonization and expansion) amplified tree mortality rates in hot, dry conditions. Similarly, field observations in the southern and central Sierra Nevada showed that mortality rates increased with size, density and proportion of ponderosa pine trees, and with climatic water deficit (Restiano et al., 2019). In contrast, another study in the southern Sierra Nevada found that while ponderosa pine mortality in the first two years of the 2012-2016 drought was high, large trees that survived were thereafter more stable (Pile et al., 2019). These recent mortality events, in combination with a number of large wildfires that have traversed the lower edge of montane conifers, have likely contributed to ongoing upslope retreat of ponderosa pine.

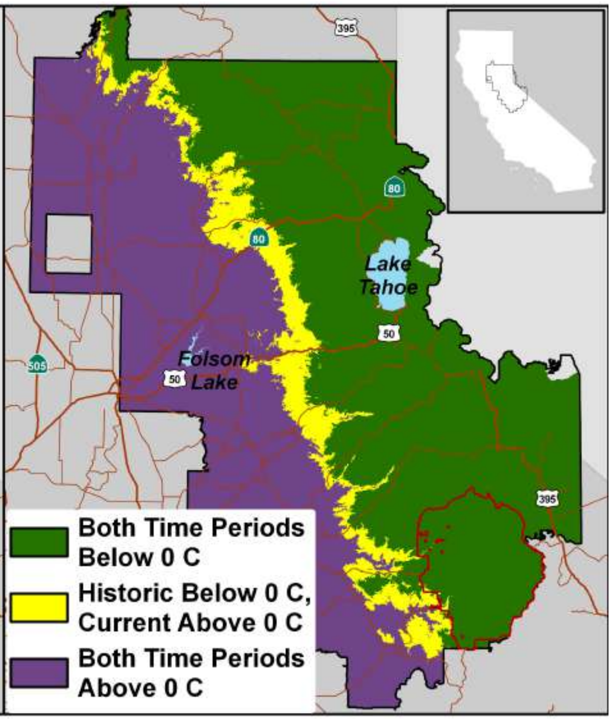
The sections below are unchanged from the 2018 report.

Figure 1
Ponderosa Pine Forest Retreat in the Sierra Nevada Mountains since 1934



Source: Thorne et al., 2008 (updated 2017)

Figure 2
Change in Winter Freeze Line
The change in winter temperatures between 1921-1950 and 1988-2015



Source: Thorne et al., 2015

What does the indicator show?

The lower edge of the conifer-dominated forests of the Sierra Nevada has been retreating upslope over the past eight decades. The dark blue areas in Figure 1 are the regions that still are dominated by the Sierran conifer forests, including the well-known forests leading up to the Lake Tahoe Basin. The area in purple was historically occupied by ponderosa pine (*Pinus ponderosa*), the pine that extends the lowest of the group of conifers making up the mixed conifer forests of the Sierra Nevada Mountains (Thorne et al., 2008). This lower edge is contracting along a 186-mile long front, which is consistent with predicted forest response to future climate change (Lenihan et al., 2003) – that is, an expansion of broadleaf-dominated forests in this elevation zone, with the accompanying loss of conifer-dominated forests.

Figure 2 shows the change in winter nighttime freezing temperatures (that is, minimum temperatures during December, January and February) (adapted from Thorne et al., 2015) over the past several decades. Winter nighttime temperatures were historically below freezing in the 4015-square kilometer (km^2) area in yellow, but are currently above 0°C on average. The purple region to the west represents the area where winter average minimum temperatures have always exceeded 0°C, while the green region to the east is the area that had, and on average still has, freezing winter nighttime temperatures.

The area that no longer has freezing nighttime winter temperatures (the yellow area in Figure 2) occupies elevations from 476 to 1861 meters (m). These elevations fall within those from which ponderosa pine has retreated — between 92 and 2310 m (shown in purple in Figure 1).

Why is this indicator important?

Since plant species are adapted to environmental conditions, changes in the distribution of dominant plants can be both an indicator of, and a response to, climate change. As conditions warm, species are generally expected to move towards the poles and to higher elevations. At the lower edge of the Sierra Nevada Mountains' conifer forests, there has been a transition to oak-dominated and chaparral vegetation concurrent with the uphill retreat of ponderosa pines.

The shift in vegetation from needle-leafed to broad-leafed trees and chaparral is a significant change, with consequences for the species of this region. Birds, mammals and other species that rely on acorns and oaks for food and habitat will find more of this type of habitat available, while species that depend on pine nuts and pine trees will find fewer resources. Increasing temperatures and the change to oak-dominated ecosystems means these areas will dry out more quickly due to both increased plant evaporative demand (Goulden and Bales, 2014) and earlier onset to the summer seasonal drought (see *Snow-water content and Snowmelt runoff* indicators). The vegetation transformation may also lead to more frequent wildfires (see *Wildfires* indicator). Moreover, the temperature of microenvironments will also be different, due to the differing amount of shade and the physical structure of the trees and shrubs making up the majority of the area.

The upslope retreat of conifers is a clear biological signal that conditions are changing. Since the snowpack of the Sierra Nevada is a vitally important resource for people, plants and animals, and the lower edge of the snowpack is also associated with the conifer belt, the upslope retreat of conifers may be a visible measure for monitoring what regions of the Sierra can still support a snowpack.

What factors influence this indicator?

The Sierra Nevada foothills have a Mediterranean climate that includes a summer seasonal drought, and the mixed conifer forests found higher upslope do not often occur in this zone. As temperatures warm, these drought-dominated conditions are moving upslope, as evidenced by the upslope movement of the freezeline. This change in the freezeline means that, should a rare winter storm drop snow in the yellow zone, it will likely melt within a few days, and not accumulate in a snowpack. In turn, this means that the countdown to summer drought conditions starts from the last precipitation event of the year, since there is no stored water in a snowpack to be released through melting. Therefore, summer drought conditions begin earlier, as also evidenced by the advancing spring snow melt, which has been documented throughout the western United States (Stewart et al., 2005) and in the Sierra Nevada (see *Snowmelt runoff* indicator). The uphill retreat of the ponderosa pines in the Sierra Nevada roughly corresponds to the upward migration of the freezeline shown in Figure 2.

Vegetation changes occurring along elevation gradients are linked to changes in climate as well as many other factors such as species competition, topographic conditions, and land use (Macias-Fauria and Johnson, 2013). The discovery of tree seedlings recently established in alpine areas above the tree line suggests that those trees had found some suitable condition and moved upslope into the area. This phenomenon is a leading edge dynamic — that is, successful establishment of seedlings at the advancing edge of a species' range. An increase or decrease in the area of a vegetation type within its elevational limits is reflective of the population changes among the dominant plant species of that type. At the retreating, lower end of a species' range, as shown here, change is likely driven by mortality of adults, along with the inability of seedlings to survive under unfavorable conditions.

This rise in temperature and associated drying in the Sierra Nevada is not likely to kill adult ponderosa pine trees directly. This tree species is resistant to heat and drought, and a gradual warming may not kill the adult trees. However, if the seedling establishment conditions have changed enough, the sequence of events is likely to proceed as follows: 1) A disturbance occurs on a site; this can be a fire that kills the adult trees (fires are increasing throughout the western US (Westerling, 2016) and in California [see *Wildfires* indicator]), a logging clear cut or other land use change, or disturbances such as a bark beetle outbreak or a disease that affects the adult trees; 2) Subsequent to the adults being killed off, the seeds and seedlings are not able to survive long enough to allow a new stand of trees to establish. Seedlings may be susceptible to a number of causes of mortality: desiccation due to increased aridity; root competition for water by other species, particularly chaparral shrubs and non-native grasses; or increased fire frequency, which kills all the seedlings. Long-term vegetation plot studies corroborate the trend that this map analysis illustrates, by documenting an increase in seedling mortality in Sierra Nevada conifers (van Mantgem and Stephenson, 2007). The upslope retreat of ponderosa pine overlaps but is also slightly lower than the upslope movement of the freezeline, suggesting a lag time during which forest tree species are adjusting to the new climate conditions.

Technical considerations

Data characteristics

This indicator is based on a study that compared vegetation maps made in two time periods spanning 80 years: the Wieslander Vegetation Type Survey of the 1930s, and the California Department of Forestry and Fire Protection's 2015 landcover map (FRAP, 2015). The climate trend information depends on reconstructions of historical climate from weather stations in the study area. The climate data comparison uses 30-year averages of winter nighttime low temperature (1921-1950 for the historical period and 1986-2015 to represent the current time period). These temperature values are derived from the monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1997) 800-meter (m) data, downscaled to 270 m (Flint et al., 2013). The mean minimum monthly temperatures for December, January and February were combined to represent the winter quarter and the average of the 30 years used to track changes in winter freezing conditions.

The Wieslander Vegetation Type Mapping (VTM) project was a US Forest Service survey program that began in the late 1920s and ended in the early 1940s, and was meant to inventory the forests of California (Wieslander, 1935a and b). Directed by Albert Wieslander, project surveyors would ascend to ridge lines and draw the patterns of the vegetation they observed on topographic maps, coding the polygons they drew with symbols representing the dominant species in each mapped unit. Maps were drawn for about half of the state, including most of the Sierra Nevada Mountains, the Coast Ranges from the San Francisco Bay Area to the Mexican border, and scattered quadrangles in the far northwest of the state. They also surveyed over 16,000 vegetation plots, took over 3,000 landscape photographs, and left notes associated with each quadrangle surveyed. University groups have digitized the survey (Kelly et al., 2005 and 2016): UC Berkeley digitized the photographs and the vegetation plots; UC Davis digitized the vegetation maps (Thorne et al., 2006; Thorne and Le, 2016). The Sierra Nevada VTM maps used here were surveyed from 1934-1937, meaning that this dataset provides a potential for assessing change in vegetation over the past 80 years. The analysis presented here compares parts of the central and northern Sierra Nevada which were mapped in both time periods and comprise 25 30' quadrangles and 47,955 km^2 (11,849,939 acres; Figure 1).

The Wieslander maps were compared to a 2015 digital vegetation map. Because the level of spatial detail in each map was different, a 200-m grid was created for the study area. Vegetation types occupying the most area were identified within each grid cell (about 1,198,887 cells for this study), and assigned to that cell. Once the dominant vegetation from each time period was identified for each cell, those cells that had been listed as ponderosa pine forest but had become a non-conifer vegetation type, were identified, and the pattern of loss at the lower edge was revealed.

The VTM survey data are used in two other indicators in this report. In the *Subalpine forest density* indicator, vegetation plots were revisited to see how tree size and the composition of species of trees at a particular location have changed since the original VTM survey; and in the *Changes in forest and woodlands* indicator, plots from independent surveys were summarized to describe changes in forest structure and composition since the VTM survey.

Strengths and limitations of the data

Historical reconstructions, whether of climate or vegetation, are dependent on the quality of the data. In the case of the Wieslander maps, the historic maps upon which the vegetation was surveyed have spatial inaccuracies of up to ~300 m. Registration methods allow the historical base maps and digitized vegetation maps to be registered to contemporary topography with an average RMSE of 98 m. This permitted the comparison between times at 200 m grid resolution. The Wieslander Vegetation Type Map survey was one of the most complete and thorough efforts to document the forests of California. The use of these data is a unique opportunity. The general trend is consistent across the entire western flank of the Sierra Nevada, which also lends credence to the findings.

Generally, the high elevation zones of the Sierra Nevada are the least well represented by weather stations that were used in generating the monthly climate maps. This study reports phenomenon more than two-thirds of the way down from the peaks of the Sierra, an area where there are more weather stations. Hence, while the historical climate maps of California as a whole may have some areas of high uncertainty, the region reported here was fairly well documented.

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VEGETATION DISTRIBUTION SHIFTS (NO UPDATE)

The distribution of vegetation across the north slope of Deep Canyon in the Santa Rosa Mountains has moved upward 213 feet in the past 30 years.

Figure 1. Change in mean elevation (in meters)* of plant species in the Deep Canyon Transect

Common Name	Mean elevation, 1977	Mean elevation, 2006-2007	Change (meters)
White Fir	2,421	2,518	96
Jeffrey Pine	2,240	2,267	28
Canyon Live Oak	1,987	2,033	47
Sugar Bush	1,457	1,518	61
Desert Ceanothus	1,602	1,671	70
Muller's Scrub Oak	1,485	1,522	37
Creosote Bush	317	459	142
Burrobush	630	748	118
Brittlebush	574	674	100
Desert Agave	693	643	-50
Mean change in elevation		**65 m (213 ft)**	
95% confidence interval		34 m (112 ft)	

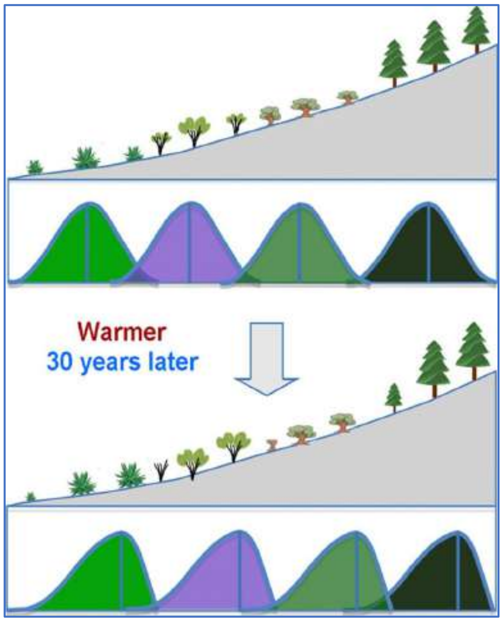
** Change in cover-weighted mean elevation of ten most widely distributed species in the Deep Canyon Transect*

What does the indicator show?

The mean elevation of nine of the ten dominant plant species in the Deep Canyon Transect of Southern California's Santa Rosa Mountains (see map, Figure 3) have moved upslope in the past 30 years (Kelly and Goulden, 2008). A comparison of two vegetation surveys of plant cover — one in 1977 and the other in 2006-2007 — along an 8,400-foot elevation gradient found that the average elevation of the dominant species rose by 65 meters (213 feet) between the surveys. All vegetation types moved upward, including small desert shrubs, chaparral, Canyon oak, and large conifers.

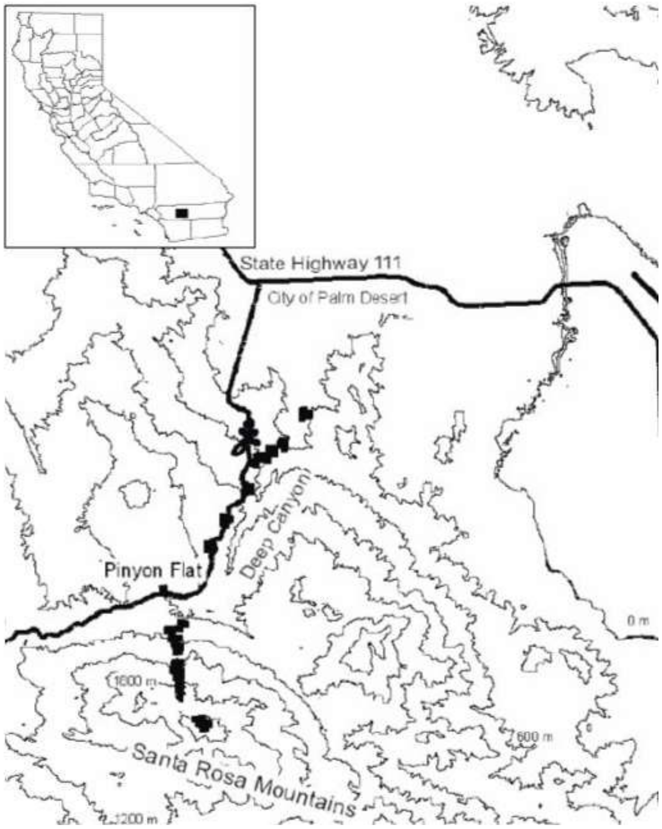
Although the species distribution moved upslope, the upper and lower range limits of these species have not changed. At the lower half of the species' ranges, individual plants have pruned limbs or completely died, reducing their dominance. An increase in cover was observed at the upper half of the species' ranges, where mature plants have reproduced and grown in size, increasing their dominance.

Figure 2. A conceptual diagram: Vegetation distribution shifts



Source: Breshears et al., 2009

Figure 3. The sites of the Deep Canyon surveys and their location in California



Source: Kelly and Goulden, 2008

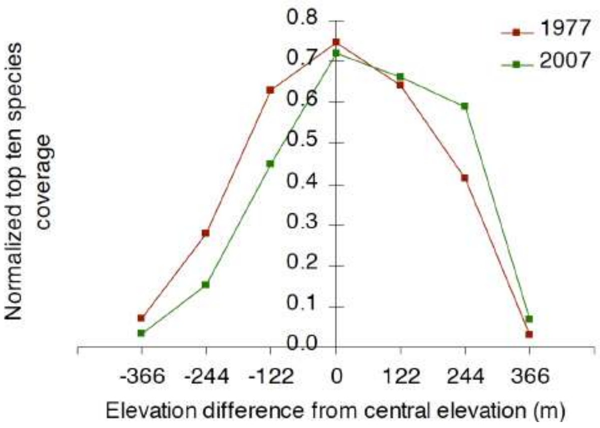
The conceptual diagram above illustrates these changes. Vegetation species along the mountain slope were distributed in a bell curve along the slope in 1977, with the highest abundances at the middle of each species' range. After 30 years of warming and drought, vegetation experienced die-off at the lower edges of each species' range, while plants at the cooler, wetter, upper elevations increased in dominance.

Vegetation distribution changes at Deep Canyon can be compared to the conceptual diagram using the graph in Figure 4. A detailed discussion of the derivation of the metrics presented is beyond the scope of this narrative (see Kelly and Goulden, 2008 for details).

In simple terms, Figure 4 shows plant coverage (which represents the percent of ground surface covered by vegetation) plotted against elevation, with “0” representing the “center elevation” (the midpoint of the lowest and highest elevations where each species was found.) (The y-axis of the graph shows “normalized” coverage, derived by dividing each species’ coverage at each elevation in 2007 by its maximum coverage at any elevation in 1977 and averaging across the ten dominant species.)

Figure 4 shows that the ten dominant species in the survey area had a symmetric normalized distribution in 1977. This changed to an upwardly skewed distribution in 2007. From 1977 to 2007, cover declined in the lower parts of the

Figure 4. Vegetation distribution, ten dominant species at Deep Canyon



Source: Kelly and Goulden, 2008

species' original ranges (by a median of 46 percent) and increased in the upper parts of the original ranges (by 12 percent).

Why is this indicator important?

Plant ranges are limited by environmental conditions. On a mountain slope, the climate of the lower extent of a species' range experiences warmer and drier conditions, while the upper extent of a species' range is cooler and wetter. Climate warming or drought is expected to increase stress on plants at lower elevations, pushing them upward into the cooler, wetter climates higher on the slope. Recent climate warming and drying has been found to be pushing conifers upslope across the Southwestern United States by killing the trees at the lower, warmer, drier edges of their ranges (Allen and Breshears, 1998; McDowell et al., 2010).

The climate and vegetation gradient of Deep Canyon's slopes is analogous to the south-to-north gradient of California. Deep Canyon's climate ranges from hot desert at the mountain base, stretching upward through warm chaparral, and finally into mild conifer forests at the mountain peak. This vegetation and climate gradient is similar to the transition along the state of California, from the southern deserts, northward through chaparral-covered foothills and mountains, and into the mild evergreen forests of northern California. Understanding the effects of local climate change on Deep Canyon's vegetation gradient will help to predict how California's vegetation will respond to a warmer or drier climate.

This indicator is consistent with biological range shifts seen around the globe (Chen et al., 2011). Plant, bird, mammal, and insect ranges are retreating away from the equator and up mountain slopes, generally tracking the temperature changes observed within each species' range. There is major uncertainty surrounding any individual species' ability to migrate in response to climate change. In Deep Canyon, no species were found outside their historic range. If species are not able to establish in new locations, this study might be revealing the beginning of a local extinction of each species and local ecosystem collapse.

What factors influence this indicator?

The climate of Deep Canyon has become warmer and drier in the past 30 years. Temperatures have increased 1.1 ^{0}F from 1977 to 2007, and droughts have intensified. The combination of warming and drying has effectively moved the climate zones of Deep Canyon upslope about 200 feet, similar to the amount the vegetation has shifted upslope.

The change in plant distribution observed in Deep Canyon may be attributed in part to a severe drought from 1999 to 2002. This drought caused marked vegetation mortality throughout Southern California, directly through drought stress and indirectly through insect attack, and many recently dead plants were observed during the survey. However, recent mortality alone cannot explain the elevation shifts. Many plants that had died before the 1999–2002 drought were also noted, as well as an increase in cover in the upper half of the species' ranges. These trends indicate that warming and/or drying of climate has been stressing the lower elevation plants and providing more favorable conditions for plants at higher elevations over the 30-year period. These changes are consistent with predictions of the effects of climate warming and drought on mountain ecosystems.

Four considerations provide evidence that the observed vegetation redistribution is attributable to climate:

- Vegetation shifts were uniform across elevation, implying that the ultimate causal factor was uniformly distributed. Recent climatic trends in Southern California do not appear to vary strongly with elevation.
- The vegetation shifts are consistent with the expected bioclimatic effects of most of the observed climatic shifts. Increased temperature, longer frost-free period, increased elevation of the snow line, and occurrence of severe drought should increase plant stress in some years. This increased stress would be expected to decrease a species' ability to survive in the drier, warmer, lower parts of its range and increase its ability to survive in the wetter, cooler, upper parts of its range.
- The change from a symmetrical vegetation distribution to an upwardly skewed distribution (see Figure 4), when averaged across species and elevation, can be interpreted as a sign of the impact of climate change on vegetation distribution.
- The vegetation shifts resulted in part from mortality during the 1987–1990 and 1999–2002 droughts. The connection between mortality and drought is consistent with a fingerprint of climate change.

Two alternative explanations for the vegetation redistribution, changes in fire frequency or air pollution, merit consideration. The wildfire regime in Southern California has changed over the last century, resulting in plant demographic shifts, especially in montane forest. However, the fire regime in Deep Canyon is similar to its historical norm, and fire effects would not produce uniform changes across the elevation gradient. Schwilk and Keeley (2012) claim that the upslope redistribution of one species in Deep Canyon, *Ceanothus greggii*, was due to elevational differences in historic fires and not by climate warming. However, observations of postfire recovery of *C. greggii* outlined in Zammit and Zedler (1993) support the conclusion that an influence stronger than fire history is redistributing Deep Canyon's dominant species upwards. Air pollution as an explanation is similarly problematic: ozone-related mortality is concentrated only at higher elevations, and would not produce the uniform changes that were observed across the elevation gradient.

The upward movement of the dominant species at Deep Canyon in just 30 years can also be attributed to recent changes in the local climate. The establishment of species at locations well above their previous ranges appears to have been minimal, and the observed upslope movement is a result of shifting dominance within existing communities, rather than the expansion of ranges to new elevations. The climate factor most influential on species redistribution could not be determined. In fact, the various observed climatic changes may interact and reinforce each other; climate warming coupled with increasing climate variability intensifies the effects of extreme yet unexceptional droughts.

The local changes could be caused by regional urban heat island effects or long-term climate fluctuations, such as the Pacific Decadal Oscillation. Nonetheless, the climate changes observed are similar to climate changes that have been predicted with or attributed to greenhouse gas-forced global climate change. The study results imply that surprisingly rapid shifts in the distribution of plants can be expected with climate change, at least in areas where seed dispersal is not a major constraint, and that global climate change may already be influencing the distribution of vegetation.

Additionally, the exact mechanisms of the plant mortality are unknown. How a tree dies in response to drought is a surprisingly difficult question that the scientific community continues to discuss (Waring, 1987; Breshears et al., 2009; van Mantgem et al., 2009). Drought and warming have caused forest mortality worldwide and no other plausible explanation for the vegetation shifts were observed.

Technical considerations

Data characteristics

This indicator is based on a re-survey of an initial vegetation study conducted in 1977 (Zabriskie, 1979). Zabriskie's survey consisted of 22 belt-transect surveys 400 yards long, at 400' elevation intervals, from 0' to 8400' elevation along the north face of the Santa Rosa Mountains. These surveys counted live perennial vegetation crossing the 400-yard transect and noted species and coverage amount.

The exact location of Zabriskie's original surveys is lost. The study investigators were able to relocate the surveys within 10-20 yards of the original location using the original selection criteria: north-facing slopes, with transects centered on north-facing ridgelines and following the 400' interval isocontour. Jan Zabriskie also toured the sites with the investigators to explain his original sampling strategy and point out original locations.

Strengths and limitations of the data

A common problem in revisiting historic studies is finding the exact location of the original sites. Discussion with Zabriskie, original maps, careful and consistent site location criteria, and a relatively small geographic area, provide confidence in the investigators' accuracy in relocating the original survey sites. Location inaccuracy is the largest source of uncertainty in the data. The vegetation coverage methodology was identical to Zabriskie's and could result in biases of less than a few percent per transect. Year-to-year fluctuations could be a problem in extrapolating one survey to a 30-year trend. A major strength of this survey is that the species evaluated in this survey are generally long-lived, thus the vegetation changes observed are the result of long-term trends and not short-term variability. Species in the survey such as yucca, white fir, creosote, and California lilac have lifespans of decades to centuries, and thus high mortality rates within 30 years are considered significant changes. Finally, weather station data do not come from within the survey site; the climate data come from nearby stations around the Southern California desert mountains.

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CHANGES IN FORESTS AND WOODLANDS

Compared to 80 years ago, California's forests today have more small trees, fewer large trees, and less biomass. The areas occupied by pines have decreased in all regions studied, while the areas occupied by oaks have increased in the Sierra Nevada but have decreased in the South and Central Coast. These changes are associated with decreased water availability driven by warmer temperatures.

Update to 2018 Report

The forest domination by pines has decreased in some areas of California compared to the 1930's, while the proportion of oaks in mixed conifer-hardwood forests has increased in parts of the state (McIntyre et al., 2015). Studies since the 2018 report have provided a better understanding of the mechanisms by which the shift from pines to oaks is progressing. One study reported increased oak dominance compared to conifers in 93 vegetation plots located within and adjacent to areas that burned twice in the Lassen National Forest: first in the 2000 Storie Fire, and subsequently in the 2012 Chips Fire (Nemens et al., 2018). In plots where the first fire was severe, no conifers reestablished, while oaks either survived the fire or subsequently re-sprouted. In the second fire, re-seeded conifers were killed in plots that burned at moderate and high severities; surprisingly, black oak showed vigorous regrowth following the fire, indicating that the carbohydrate reserves in the root stock were either not depleted after the initial re-sprouting, or had been replenished in the intervening years. Although these results suggest that California black oaks are resilient in the face of multiple fires, the increasing frequency of fires raises the question of how long black oak could continue this process, and whether its capacity to regenerate is fire interval-dependent. This study is a further confirmation of the findings in an earlier study (Goforth and Minnich, 2008) that pine-oak forest and woodlands are susceptible to disturbance-initiated conversion, and that this trend has been amplified by climate trends over the past 80 years.

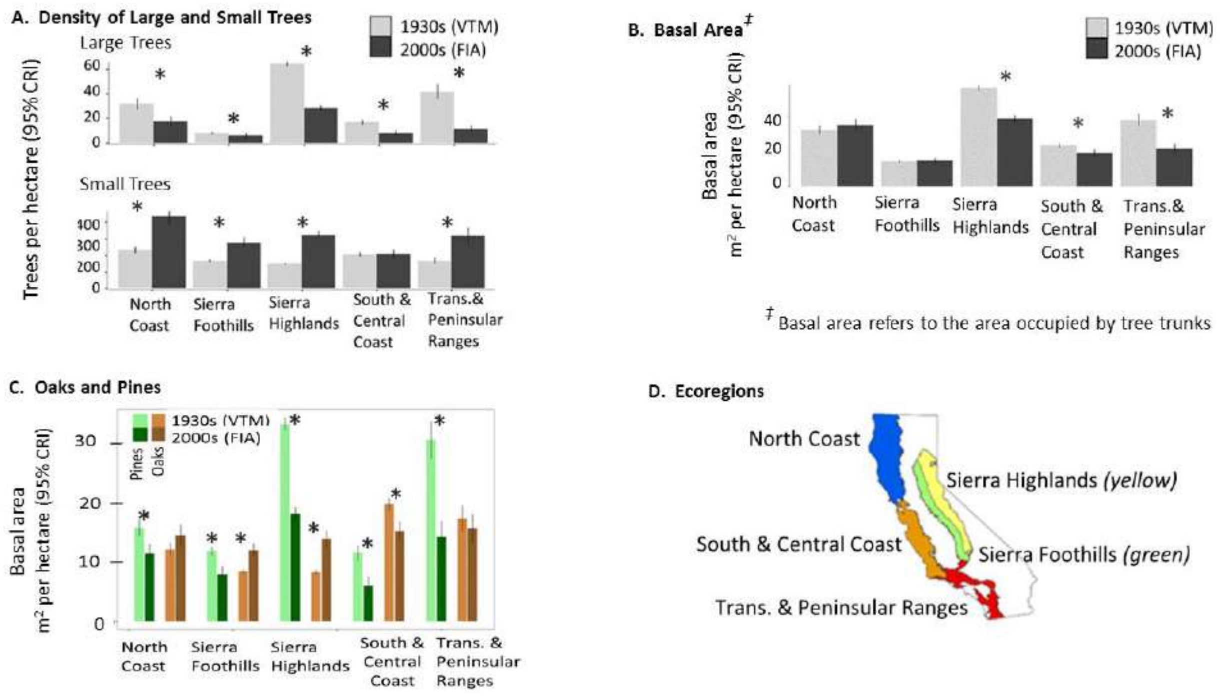
In the Klamath Mountains at the northern end of the state, a study of 36 square miles in the Six Rivers National Forest found a decrease in the proportion of oaks, along with an increase in the proportion of pines and Douglas fir based on a comparison between a historical (1872 – 1884) and a modern (2008 – 2017) inventory (Knight et al., 2020). The study also found an increase in small trees. The authors attribute the decrease in oaks and increase in fir to fire suppression. Amplified by climate conditions, these changes have increased the risk of stand-replacing fires: the area burned gradually increased through the 1970s, 80s and 90s, but quadrupled from about 75,000 hectares (185,000 acres) in the 1990s to 325,000 hectares (800,000 acres) in the 2000s. Over 500,000 hectares (about 1.2 million acres) have burned since 2000, a trend well outside the previous scales of wildfire.

A remote sensing study of spatial patterns of tree mortality for about 2 million trees in the Sierra Nevada over eight years, including the drought of 2012-2016, found that large trees died at twice the rate of small trees (Stovall et al., 2019). The mortality patterns arrayed along environmental gradients of temperature, water and competition, which agrees with other tree mortality assessments that associated canopy water loss with tree mortality (Goulden and Bales, 2019; Asner et al., 2016; Brodrick and Asner, 2017). A study of tree size patterns by land ownership found declines in large trees and increases in forest density across the state. This pattern is most pronounced on private timberlands, which experienced up to 400 percent regional increases in small tree (<10.2 cm) density since 1930 (Easterday et al., 2018). In the northern coastal areas, an additional factor affecting the balance of oak and pine is mortality driven by Sudden Oak Death (SOD), caused by a water mold (*Phytophthora ramorum*) (Cobb et al., 2020; also *Forest Tree Mortality* indicator).

Increasingly large wildfires, with six of the largest seven fires on record occurring in the last two years (CAL FIRE, 2022; also see *Wildfires* indicator), may make further tracking of temperature and moisture driven effects on proportions of tree species more difficult.

The sections below are unchanged from the 2018 report.

Figure 1. Changes in forest structure and composition
Historical (1929-1936) vs. Contemporary (2000-2010)§



Source: McIntyre et al., 2015

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§ *Historical from Wieslander Vegetation Map (VTM); Contemporary from Forest Inventory Analysis (FIA)*

* *Statistically significant differences*

What does this indicator show?

The structure and composition of California's forests have changed, and this is associated with climate change related water availability. This indicator consists of three metrics tracking changes in the structure and composition of forests across five regions in California. These metrics are based on a comparison of data from a 1930s survey of the state's vegetation (documented in the Wieslander Vegetation Type Map, or VTM) with data from surveys conducted between 2000 to 2010 (as part of the US Forest Service's Forest Inventory Analysis, or FIA) (McIntyre et al., 2015). Forest structure refers to the distribution of small, medium, and large-sized trees, while species composition refers to the diversity of tree species present.

Figure 1A displays the first metric, which shows changes in the density of large and small trees. Large trees are defined as greater than (>) 61 centimeters (cm), or >24 inches (in), in diameter at a height of 4.5 feet ("diameter at breast height," or dbh), and small trees are defined as 10-30 cm, or 4-12 in, dbh. Decreases in large tree density were observed in all regions studied (top row). The greatest decrease occurred in the Transverse and Peninsular ranges of Southern California, where large tree density in the contemporary period was less than 30 percent of the density in the historical dataset (40.8 vs. 10.6 trees per hectare (trees/ha)). Declines of about 50 percent in large tree densities were observed in the Sierra Nevada highlands (64.3 vs. 28.03 trees/ha), the Coast Ranges of southern and central California (16.6 vs. 7.5 trees/ha), and northern California (30.6 vs. 16.7 trees/ha). Declines in large trees were lowest in the Sierra Nevada foothills (7.6 vs. 5.7 trees/ha), the region where large tree densities are lowest.

From the historical to the contemporary period, densities of small trees increased over two-fold within the Sierra Nevada highlands (149 vs. 315 trees/ha), and over 50 percent in the Sierra Nevada foothills (165 vs. 268 trees/ha), the North Coast region (229 vs. 412 trees/ha) and the Transverse and Peninsular ranges (165 vs. 301 trees/ha) (Figure 1, bottom row). The density of small trees was unchanged in the South and Central Coast Region (200 vs. 197 trees/ha). Patterns of change for intermediate-sized trees (31–60 cm or 12-24 in dbh) were variable across the two time periods (not shown).

Figure 1B illustrates the second metric, which shows changes in basal area — the amount of area occupied by tree trunks within a given area (here expressed in units square meters per hectare (m^2/ha)). Basal area, which reflects biomass, decreased in three of the five regions: up to 40 percent in the Transverse and Peninsular Ranges Region (37.8 vs. 21.6 m^2/ha, 30 percent in the Sierra Nevada Highlands Region (55.9 vs. 38.5 m^2/ha), and 18 percent in the South and Central Coast Region (23.3 vs. 19.0 m^2/ha). In the North Coast and Sierra Nevada Foothills Regions, the reductions in basal area due to large tree declines were balanced by increases in smaller size classes, hence no decline in overall basal area was observed.

The third metric is displayed in Figure 1C, which compares historical and contemporary basal area occupied by pines and oaks. Changes in the relative abundance of these tree species represent changes in forest composition. Pines have declined in all regions, whereas oaks increased in two Sierra Nevada regions but decreased in the South and Central Coastal ranges.

Why is this indicator important?

The pine and oak-dominated forests and woodlands of California provide ecosystem benefits such as erosion control, water provision and carbon sequestration, as well as wildlife habitat, timber, and opportunities for recreation. Changes in forest structure and tree species composition can impact these functions.

This indicator describes how forest conditions have changed relative to historical climate change by comparing the 80-year old VTM survey with modern-day observations. It shows that the state's forests are transitioning from one set of species to another. Since these changes may be a natural ecosystem response to warming and drying conditions, monitoring them provides valuable insight into future forest responses to climate change. There is evidence that wildfires at elevations up to about 5,000 feet where pines and oaks grow together can initiate this shift in species dominance by removing the dominant conifers (including pines but also other needle-leafed trees), allowing resident oaks and chaparral to establish and become the dominant vegetation. Another VTM-based study estimates that 13.5 million acres in California are at risk of this conversion (Goforth and Minnich, 2008). Decreases in large coniferous trees, including pines and firs in California montane (mountainous) forests have also been documented in other studies (van Mantgem and Stephenson, 2007; Dolanc et al., 2013; Lutz et al., 2009); furthermore, dieback of trees has been reported on all continents (Allen et al., 2015) and across the western USA (van Mantgem et al., 2009).

Despite a nearly 40 percent overall increase in tree density, the decline in large trees has resulted in about a 20 percent decline in basal area and associated biomass (not shown).

What factors influence this indicator?

Statewide, the decline in large trees and increases in the relative abundance of oaks compared to pines are associated with climatic water deficit (CWD), while changes in small tree densities are not (McIntyre et al, 2015). CWD is the cumulative annual excess of potential versus actual evapotranspiration of water from plants. It can be thought of as the amount of additional water that would have evaporated or been transpired by plants (beyond what was actually evaporated or transpired) if the water had been present in the soils for the plants to take up. CWD is a useful metric because it integrates plant water demand relative to soil moisture availability, and provides a measure of potential plant drought stress. Increases in CWD, which reflect decreases in soil moisture, are associated with a warming climate because increased air temperatures increase plant water demand (Thorne et al., 2015). CWD can be further increased if there is less precipitation under future conditions, and if snowpack melts sooner, leading to drier soils during summer months. CWD has been associated with patterns of forest mortality and vegetation distributions in a number of studies. Following four years of severe drought (2012-2015) in California, areas with high CWD experienced substantially more tree mortality than areas with low CWD (Young et al., 2017). Much of the mortality was caused by beetle attacks on trees weakened by the drought (see *Forest tree mortality* indicator).

The ratio of oak to pine basal area was correlated with estimates of CWD in the time periods of both forest surveys (McIntyre et al., 2015). In addition, the contemporary survey shows an increased relative dominance by oaks that was associated with increases in CWD. The paleological record is consistent with this: in the past 150,000 years, oaks dominated in warmer, drier interglacial periods, and pines in colder, more mesic (characterized by moderate or well-balanced supply of moisture) glacial periods (Heusser, 1992).

The changes in forest species composition and basal area described here are occurring in California forest and woodland areas at elevations that are subject to seasonal drought; these areas represent water-limited ecosystems throughout the low to mid-elevations of the state, from the southern coastal and transverse mountains to near the northern end of the foothills of the Sierra Nevada Mountains. Although there are several potential causes for these dynamics at lower elevations, hotter drought conditions are the lead environmental cause.

That conifer trees are potentially at higher climatic risk than broadleaf trees is supported by the findings of Lutz et al. (2010). The authors mapped the climate occupied by 17 Sierra Nevada tree species in Yosemite National Park relative to the entire range of climate conditions each species encounters in its geographic range. They found seven species, all except one of which is a conifer, occupy the arid end of their North American climate distributions: *Pseudotsuga menziesii*, *Pinus ponderosa*, *Calocedrus decurrens*, *Pinus lambertiana, Abies concolor*, *Abies magnifica,* and *Quercus kelloggii.*

Other factors potentially contributing to shifts in the oak: pine ratio include fire suppression, wildfires, and logging practices. Widespread fire suppression in the western USA has led to the buildup of forest litter and increased density of small trees, including the establishment of the highly flammable white fir (*Abies concolor*) — changes which have potentially contributed to the more frequent and larger wildfires today. Further, a warming climate is contributing to the increasing frequency and intensity of wildfires in the western US (Westerling et al., 2006) (see *Wildfires* indicator).

As noted above, wildfires can initiate the conversion of coniferous to broadleaf forests and woodlands or chaparral by removing dominant conifers. A large stand-replacing fire at Cuyamaca Rancho State Park near San Diego (the Cedar fire, October 24-28, 2003) happened after eight decades of fire suppression. A seedling census four years after the fire found that while various oak species had re-established, few to no conifer seedlings had done so, resulting in the conversion of a mixed conifer-oak forest to one dominated principally by oaks (Goforth and Minnich, 2008). The authors did not examine changes in climatic conditions. The authors predict this transition is to be expected for the ~13.6 million acres of this forest type in California, including large swaths of the Sierra Nevada foothills and most of the forests and woodlands near coastal urban areas. This prediction is also in line with change documented on the western slope of the Sierra Nevada Mountains where lower elevations of coniferous forests are retracting upslope (Thorne et al., 2008; see *Ponderosa pine forest retreat* indicator). This is corroborated by a recent study that examined post-fire seedling regeneration after 14 large wildfires in Northern California. Welch et al. (2016) found that in 10 of the 14 fires, conifer regeneration was not high enough to meet US Forest Service stocking standards, indicative of a return of the site to a conifer forest.

Technical considerations

Data characteristics

The indicator is based on a study comparing forested plots from the Wieslander Vegetation Type Map (VTM) survey (between 1929 and 1936) with US Forest Service Forest Inventory Analysis (FIA) plots (between 2000 and 2010). Across California, 9,388 VTM plots and 5,198 FIA plots were identified as forested (having at least one tree >10.2 cm dbh, the cutoff for a tree in the VTM data). Only plots occurring within 5 km of a plot from the other time period were selected, resulting in 6,572 VTM and 1,909 FIA focal plots. The plots were similar in slope, aspect, and elevation, as well as location across latitudinal and longitudinal gradients.

A modified version of the Jepson Manual eco-regions of California was used in identifying plots by region, as follows: South and Central Coast; Transverse and Peninsular Ranges; North Coast; Foothills of the Sierra Nevada and southern Cascades; Highlands of the Sierra Nevada and southern Cascades. (The Central Valley and desert regions are not included because they did not have a sufficient number of forested plots). Changes in tree density were compared with changes in CWD between 1910–1940 and 1981–2010 using 30-year averages from each time period. CWD is the seasonally integrated excess in potential evapotranspiration (PET) versus actual evapotranspiration. Details on the methodology are described in McIntyre et al. (2015).

Strengths and limitations of the data

Historical reconstructions, whether of climate or vegetation, are dependent on the quality of the data. In the case of the 1930s historical vegetation survey, the plot areas surveyed were not permanently marked, and this comparison used contemporary US Forest Service plots to compare densities of trees in similar locations as paired plots that had similar slope, aspect and elevation. The VTM survey only classed trees to size classes, so the modern survey, which has actual diameter at breast height values for every tree was re-classed to the same size classes. This reduced some of the precision with regards to tree size. However, the historical VTM was one of the most complete and thorough efforts to document the forests of California, and the use of these data was a unique opportunity to examine shifts statewide.

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SUBALPINE FOREST DENSITY

Subalpine forests in the Sierra Nevada have more small trees and fewer large trees than they did in the early decades of the 20th century.

Update to 2018 Report

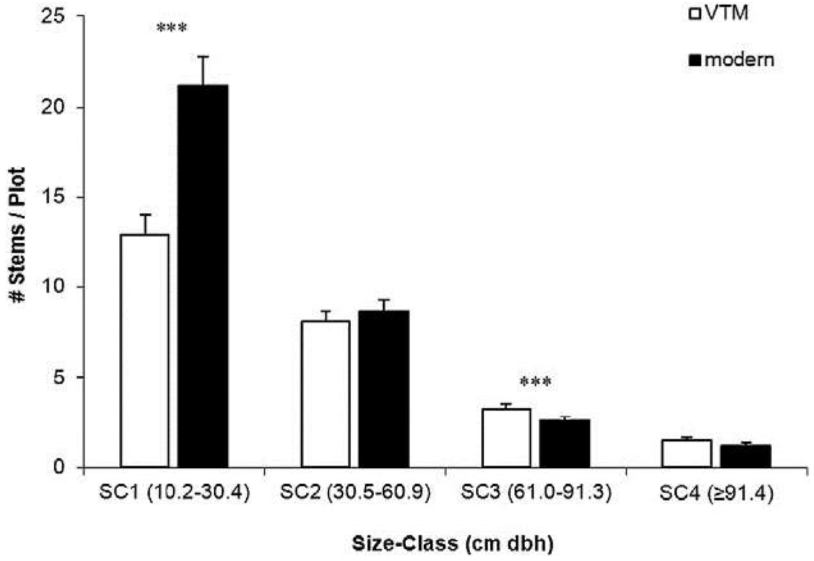
Subalpine tree species dwell in cold-limited ecosystems just below treeline, at 7,500 to 11,000 feet elevation (Das et al. 2013). In addition to the increased tree density discussed in the 2018 indicator report, recent studies have quantified the changing dynamics of subalpine conifers. More specifically, studies have examined how changes in forest structure, composition, and elevational and latitudinal ranges are influenced by warming temperatures and increasing moisture deficits due to climate change and by disturbance events such as wildfires and attacks by beetles and pathogens.

At high elevations in the Rocky Mountains, where conditions are similar to those in California's subalpine forests, the mortality rate among subalpine conifers tripled between 1982 and 2019 (Andrus et al 2021). This increase was found to be related to warmer and drier summers and bark beetle infestations. The sites at greatest risk are those at the lower extent of their elevation distribution, where warming temperatures can exacerbate water deficit. Another study found that over the past 30 years, seedling establishment on north-facing slopes has fared increasingly better than on the warm and dry south-facing slopes in the southern Rocky Mountains, and that beetle-induced mortality has occurred at the treeline (Elliot et al., 2021). This study concluded that "hotter drought" could be enveloping the upper treeline, such that unless warming abates and precipitation increases considerably, the evidence does not support model projections that the treeline will advance upslope.

As seedings fail to establish and more large trees die in existing forests, climate change is expected to cause subalpine conifer species to move to higher elevations or latitudes where a short growing season, heavy winds, deep snowpack and other factors have made conditions unfavorable for them in the past. A better understanding of the importance of "microsites" created by boulders, krumholz trees, shrubs, and other features that can protect seedlings and facilitate their establishment will allow more reliable prediction of future changes in the elevation and extent of conifer mountain forests (Brodersen et al., 2019). In the northern Sierra Nevada, three of twelve tree species showed significant shifts to higher elevations (averaging 112 to 119 meters) in an 80-year period: red fir (*Abies magnifica*), western white pine (*Pinus monticola*), and mountain hemlock (*Tsuga mertensiana*) (Wright et al. 2016). Contrary to predictions of northward spread, these same species also shifted southward by about 16 kilometers; this is likely due to the higher elevations in the southern Sierra relative to the north. A review of Northern Hemisphere treeline movement from 1901 to 2018 found that while an upward shift was observed in almost 90 percent of the sites studied, this ascent occurred at rate about half of that expected from climate warming alone (0.354 meter/year) (Lu et al. 2020). Precipitation was a more important factor: in the temperate region, a combination of warmer temperatures and higher autumn precipitation accelerated rates, whereas wetter springs reduced them. Increasing mortality at the lower edge of subalpine conifers and limited recruitment at the upper treeline limit have been identified as factors driving range contractions in subalpine forests (Conlisk et al., 2017).

The sections below are unchanged from the 2018 report.

Figure 1. Change in subalpine tree density
(by size class, based on diameter at breast height or dbh)
Historical vs. Modern, Central Sierra Nevada



Source: Dolanc et al., 2013

*White bars - Vegetation Type Mapping (VTM) historical plots, 1929-1936; Black bars - modern plots, 2007-2009. Statistically significant differences are indicated by ***p<0.0001*

*Change in tree density (# stems/plot) by **size class**, as follows:*
***SC1** – 10.2 to 30.4 cm diameter at breast height (dbh); **SC2** - 30.5 to 60.9 cm dbh; **SC3** – 61.0 to to 91.3 cm dbh*

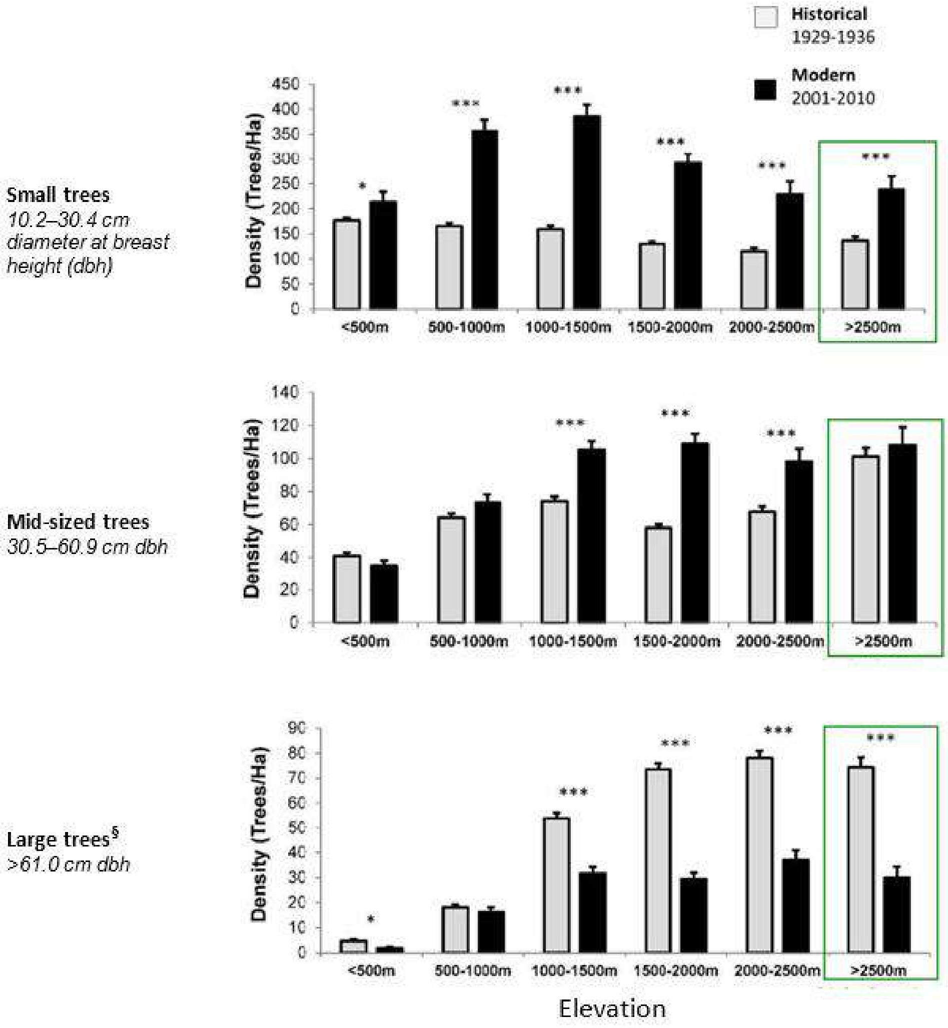
What does the indicator show?

Figure 1 shows an increase in the density of small trees (measured as the number of stems in each plot) in higher-elevation (subalpine) forests in the central Sierra Nevada since the 1930s. The figure compares the densities of trees by size class in historical plots (based on Vegetation Type Mapping (VTM) data collected between 1929 and 1936), with modern-day plots (based on resampling data between 2007 and 2009).

There are now many more small trees (categorized as SC1, with diameters measuring 10.2 to 30.4 centimeters (cm) (4 to 12 inches) at a height of 1.4 meters (4.5 feet) – a measurement referred to as “diameter at breast height,” or dbh. Also, there are fewer large trees (those categorized as SC3 and SC4, exceeding 61 cm (24”) dbh). Thus, in the subalpine zone, the density of small trees increased by 62 percent while large tree densities decreased by 21 percent — a net increase of 30 percent more trees present today than in the 1930s. These shifts are ubiquitous throughout the subalpine zone (2300 to 3400 meters (m) or approximately 7,500 to 11,000 feet elevation) of the central

Sierra Nevada (see map, Figure 3); further, the shifts occurred to a surprisingly consistent degree for the eight most common tree species native to this zone.

Figure 2. Change in tree density by elevation* and size class: Historical vs. Modern, North and Central Sierra Nevada



Source: Dolanc et al., 2014a

Gray bars *- Vegetation Type Mapping (VTM) historical plots, 1929-1936.* ***Black bars*** *- Forest Inventory and Analysis (FIA) modern plots, 2001-2010 The last set of bars (outlined in green) show changes at the subalpine elevation (>2500m) Statistically significant differences are indicated by *p<0.05, **p<0.001, and ***p<0.0001*

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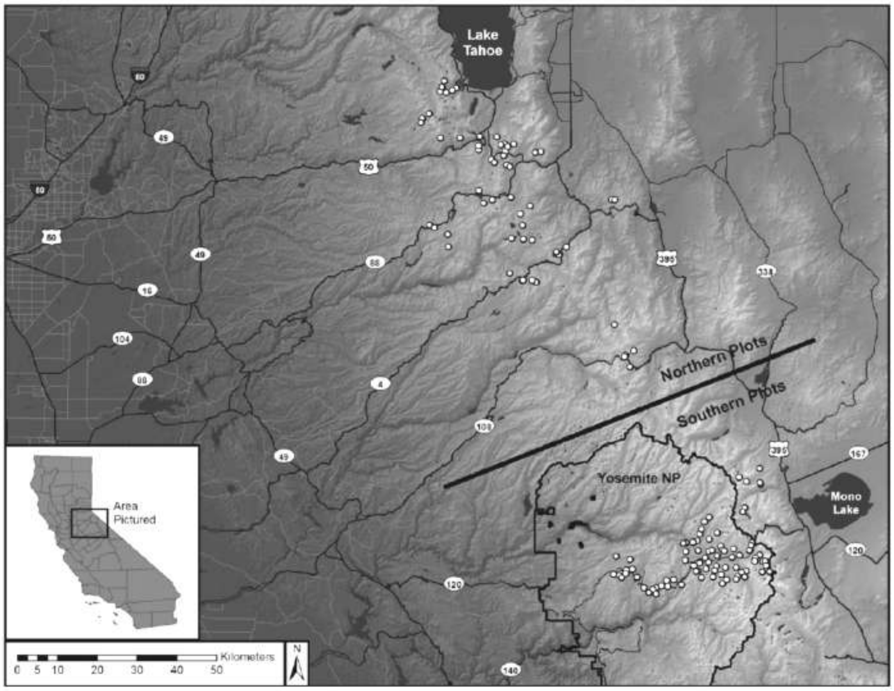
§*“Large trees” in this figure are classified as “SC3” and “SC4” in Figure 1.*

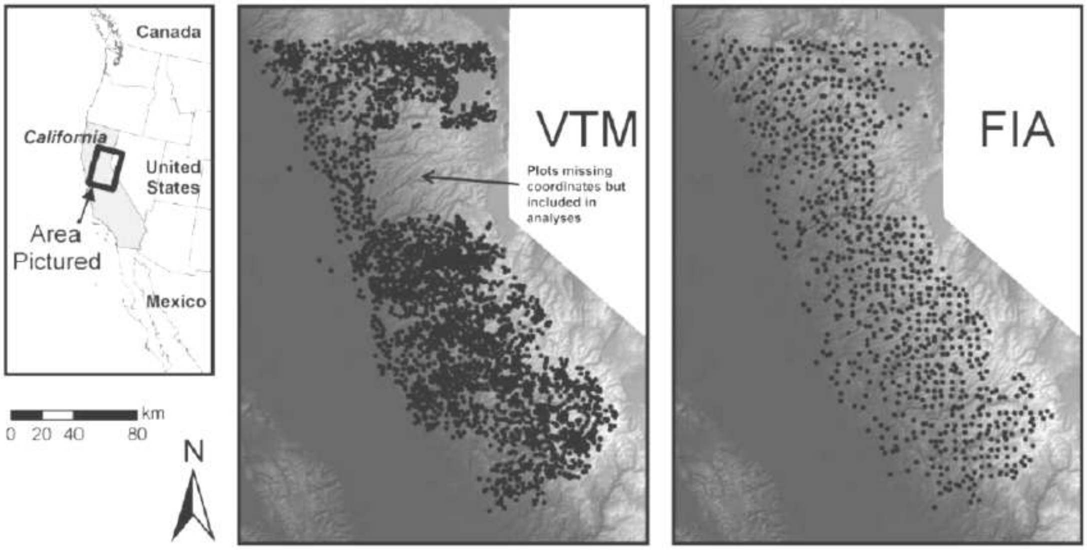
Figure 2 shows that declines in the density of large trees and increases in the density of small trees also occurred at lower elevations. These findings are from a more recent study by Dolanc et al. (2014a), which compared contemporary Forest Inventory Analysis (FIA) forest survey plots to the historical VTM data across a larger area that spans a broader range of elevations in the north and central Sierra Nevada. At subalpine elevations (>2500 m), the increases in small trees and the decrease in large trees recorded in this study are similar to those found in the first study (Figure 1; Dolanc et al., 2013). The similarity between the two studies provides further evidence of widespread and prevalent changes in the Sierra Nevada forest structure.

Figure 3. Maps showing Sierra Nevada study areas

A. Central Sierra Nevada study area for Figure 1 (circles show survey plots)



B. Northern and Central Sierra Nevada study area for Figure 2 (dots show study plots; arrow points to VTM plots with missing coordinates but for which elevation and tree data are available; these are included in analyses)



Sources: (A) Dolanc et al, 2013;
(B) Dolanc et al., 2014a

Why is this indicator important?

Shifts in forest structure could have detrimental effects on the ecology of the Sierra Nevada. Compared to small trees, large trees store considerable amounts of carbon, provide soil nutrients, provide nests and shelters, and play critical roles in hydrological regimes. Younger and smaller trees cannot provide these functions to the same extent as large trees, if at all (Lindenmayer et al., 2012).

In addition, increased tree density from small trees provides more fuel for larger and more frequent fires. Though much of California’s vegetation is adapted to frequent fire, fire in the subalpine zone has historically been infrequent and isolated (van Wagtendonk and Fites-Kaufman, 2006). Recently, however, wildfires have been documented to be increasing in elevation in the Sierra Nevada (Schwartz et al., 2015). Subalpine forests have historically been sparse, with insufficient accumulation of dead, woody residue on the forest floor to act as fuel to carry a fire very far. However, an increasing number of smaller trees will naturally lead to increased fuel and could ultimately lead to larger and more frequent fires. Since most species native to subalpine regions are not adapted to fire, this has the potential to shift dominance at these elevations toward lower-elevation, fire-adapted species, effectively accelerating an upward shift of ecological zones.

Densification of forests and warming temperatures could also make conditions more favorable for insect outbreaks and disease. Beetle infestations have caused widespread mortality in high-elevation forests in the Pacific Northwest and Rocky Mountain regions, including two species present in Sierran subalpine, lodgepole and whitebark pine. These infestations were linked to changing climate and forest conditions that are conducive to the beetle’s life cycle (Kurz et al., 2008). Increased density of Sierran subalpine forests and warming temperatures are expected to lead to increased tree mortality and conditions ripe for outbreaks in the Sierra Nevada. Such outbreaks have occurred during the recent drought (Meyer et al., 2016; Sierra Nevada Conservancy, 2017). A similar situation exists for white-pine blister rust, which affects 5-needle pines throughout the western mountains, including western white pine and whitebark pine, two species found in Sierran subalpine (Tomback and Achuff, 2010). Continued large-scale beetle outbreaks and/or disease could lead to a compositional shift in favor of species more resistant to these pathogens. In addition to these potential negative effects, major shifts in composition and structure to an ecosystem are likely to lead to numerous other, unforeseen biological changes in the ecosystem.

Tracking trends and patterns in how the high elevation forests in this region are changing helps advance the understanding of the factors driving these changes, and improves the ability to anticipate future changes.

What factors influence this indicator?

In the subalpine zone of the Sierra Nevada, deep spring snowpack and low summer moisture limit the germination and establishment of seedlings (known as “recruitment”), and the growth and survival of young trees. The Sierra Nevada is experiencing warmer temperatures, a greater proportion of rain to snow, and earlier snowmelt dates

(Dettinger and Cayan, 1995; Coats, 2010; Millar et al., 2012; Knowles et al., 2006), as well as overall decreases in snowpack during the recent drought (Berg and Hall, 2017). These climate-related changes could be making growing seasons longer, creating favorable conditions for tree recruitment and enhancing the survival of small trees (Dolanc et al., 2014a). At the same time large trees, which have a higher water demand, may be dying off due to insufficient moisture (McIntyre et al., 2015). Thus, the changes in tree densities are likely influenced by regional climatic changes since the 1930s. Interestingly, no apparent change in the relative abundance of tree species were observed (Dolanc et al., 2013).

Certain factors that help explain the increased tree densities at low to mid-elevations may not explain the changes observed at subalpine elevations. Fire suppression appears to be a primary factor for increased tree density at low to mid-elevations. However, fire suppression activities have been minimal at sub-alpine elevations due to the low occurrence of wildfire, implicating changing climatic conditions as the factor associated with increased small tree densities at these elevations. (Dolanc et al., 2014a; Dolanc et al., 2014b). Timber harvest and logging may explain some of the declines in large trees over time at lower elevations as well. However, logging has been minimal in Yosemite National Park, which has also experienced significant declines in large trees (Dolanc et al., 2014a; Lutz et al., 2010).

Increasing concentration of nitrogen may also contribute to densification of small trees. Increased deposition of nitrogen from pollution sources upwind has been documented in the Lake Tahoe Basin. However, because nitrogen deposition is highly contingent upon the location of pollution sources, its effects are highly variable across the landscape (Fenn et al., 2003) and therefore not likely to account for the rather consistent and widespread shift in subalpine structure. It has also been suggested that higher concentrations of carbon dioxide could cause major structural shifts, but research has shown that this is unlikely to happen in high-elevation forests (Grace et al., 2002). Similarly, although ozone pollution from upwind areas may increase mortality of ponderosa and Jeffrey pine in the Sierra Nevada, its effects on densification are likely minimal. The greatest tree mortality impacts from ozone have been observed south of the study area shown in Figure 3. In addition, declines in ponderosa and Jeffrey pine large tree densities were roughly in line with that of other species not affected by ozone (Dolanc et al., 2014a).

Technical considerations

Data characteristics

Data for Figure 1: Plots of approximately 809 m^2 (8712 ft^2) were originally sampled from 1929-1934 as part of the Wieslander Vegetation Type Mapping (VTM) project that represented the US Forest Service's original forest inventory in California (Wieslander et al., 1933; Thorne and Le, 2016). From 2007-2009, 139 historic vegetation plots were resampled throughout wilderness areas at 2300-3400 m elevation in the central Sierra Nevada. Care was taken to sample modern stand conditions with a protocol compatible with the original surveys, matching plot size, shape and orientation as closely as possible. Nearly half of the 139 plots were concentrated in the Tioga Pass area of Yosemite National Park, with the other half coming from passes located as far north as the Desolation Wilderness. The study area encompasses approximately 5500 km^2.

Analysis was centered on differences between numbers of stems in historic VTM versus modern stands, using the four size-class dbh (diameter at breast height) categories set by the VTM team (SC1, SC2, SC3, and SC4). Comparisons were made for all species combined as well as each of the eight most-common tree species.

To determine change in climate over the same time period, data from two weather stations at either end of the study area, Tahoe City in the north and Huntington Lake in the south, were accessed. Thirty-year means were calculated for 1916-1945 and 1976-2005, representing the historic and modern periods influencing each of the sample periods in the vegetation data. Differences in climate between the two time periods were calculated for annual minimum temperature, annual maximum temperature and annual precipitation. Differences in these variables during the July through September growing season were also calculated.

Data for Figure 2:

The US Department of Agriculture Forest Service (USFS) runs the Forest Inventory and Analysis (FIA) program, which collects, compiles and archives data on forest status across the United States. The FIA protocol divides plots into four 7.3-m radius circular subplots, with one central subplot and three outer subplots arranged at 120° angles from each other at distances of 36.5 m from plot center to plot center. Each subplot has a 2.1-m radius circular microplot nested within its boundaries. For all subplots, every tree >12.7 cm (5 in) is measured (DBH, height, etc.) and identified to species. Within microplots, every tree >2.5 cm is measured. The total area of all four subplots combined is 672.45 m^2.

This study used 4321 historical VTM plots and compared stand composition and structure to 1000 FIA plots occupying the central Sierra Nevada from Lake Tahoe to the southern end of Yosemite National Park. Tree sizes in the FIA plots were re-classed into three size classes used in the VTM study and tree densities were converted to per-area measures. Separate generalized linear model statistical tests were conducted for each elevation band and latitude category using a negative binomial distribution (Dolanc et al., 2014a).

<u>Strengths and limitations of the data</u>
The structural shifts observed from subalpine of the Sierra Nevada are the first empirical-based observations of changes in high elevation forests in the Sierra Nevada mountains.

Using VTM data as historic references has been criticized because VTM field crews did not permanently mark their plots, meaning precise relocation of plots is not possible.

However, it is possible to navigate to the same slope face and likely the same forest stand using their data on canopy composition, elevation, slope, aspect and several other environmental variables. As long as many locations are resampled, this approach should be sufficient and preferable to studies that use entirely different sets of modern data for comparison with VTM conditions. With resampling, differences between each pair of historic vs. modern plots have been minimized. Because of these considerations, the analysis for this study is focused on overall change (all 139 plots combined). The modern resampling effort covered a large region, with a large sample size. Numerous recent papers have used the VTM data set as a historic reference and it appears as though this trend will continue. A critique that the VTM plots may have been systematically biased to sampling larger trees has been suggested but never substantiated. Evidence from high elevation plots in the form of downed large trees suggests that the historical densities of large trees recorded are accurate (Dolanc et al., 2013) while the field manual for the VTM surveys instructs the surveyors to sample vegetation representative of the mapped vegetation (Thorne and Le, 2016).

VTM and FIA data differ in sampling protocol and plot selection. However, trends in comparisons of VTM and FIA data are similar in direction and magnitude to those reported in regional studies using a variety of methods, supporting the use of comparing these two data sets. In addition, scatterplot analyses suggest that the VTM crew sampled as wide a variety of stands as the current FIA program (Dolanc et al., 2014b).

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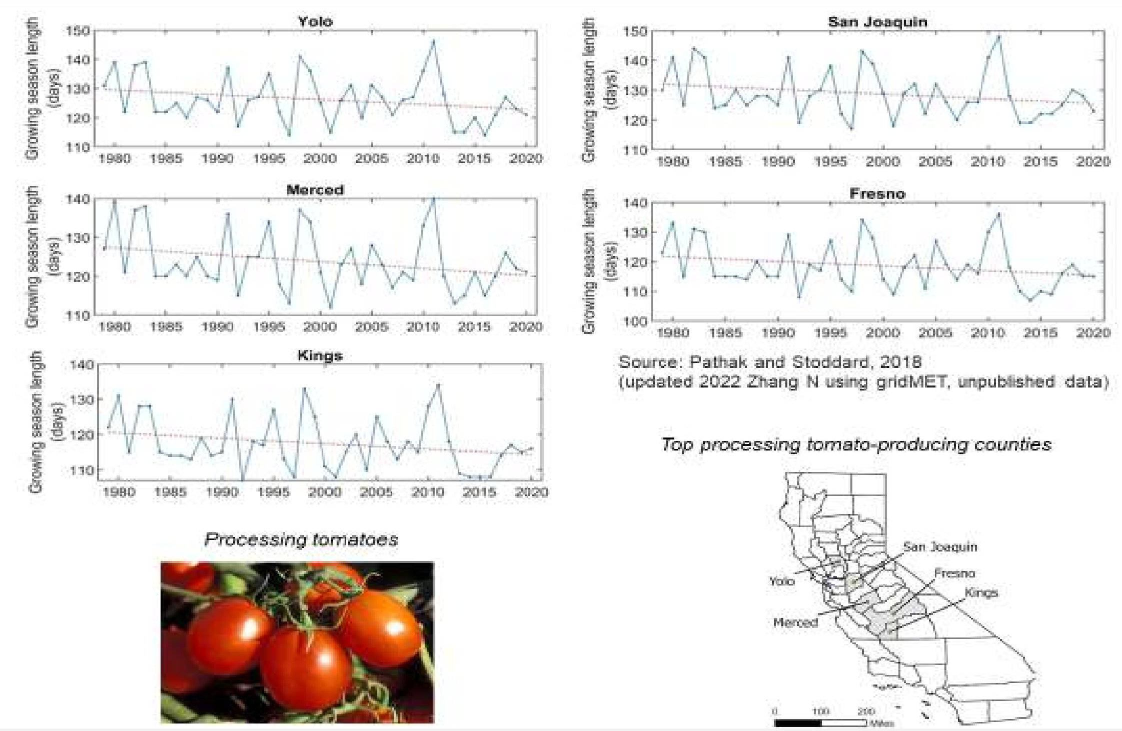
FRUIT AND NUT MATURATION TIME

With warming air temperatures, one walnut variety and several prune varieties in the Central Valley are maturing more rapidly, leading to earlier harvests. Temperature-based estimates indicate that processing tomatoes are also maturing faster.

Update to 2018 Report

Processing tomatoes are a type of tomato that eventually get canned, dehydrated, or turned into paste, puree, ketchup, tomato sauce, or tomato juice. California accounts for 95 percent of the nation’s and 30 percent of the world’s processed tomatoes. Fresno, Kings, Merced, San Joaquin, and Yolo counties in the Central Valley are the top five tomato-producing counties in the state. Processing tomatoes have been maturing faster over the past four decades in these counties (Pathak et al., 2018). The estimated length of the tomato growing season—the period between planting (March 15) and maturity (harvest)–in these five counties has been declining (see Figure A). These estimates were derived from temperature data using a “growing degree day” model to calculate the accumulation of “heat units”. When sufficient heat units are accumulated, tomatoes reach maturity. As temperatures increase, heat units accumulate faster and maturation occurs earlier. Consequently, estimates from 1979 to 2020 show that processing tomatoes in these counties are reaching maturity about 6 to 8 days earlier.

Figure A. Tomato growing season length at top processing tomato-producing counties, 1979-2020



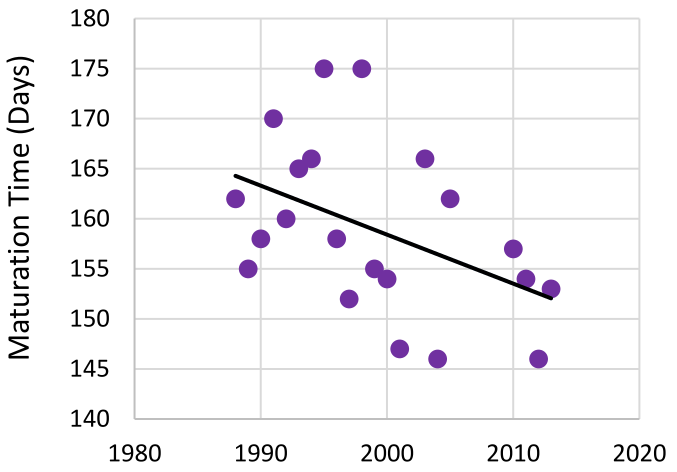
Source: Pathak and Stoddard, 2018
(updated 2022 Zhang N using gridMET, unpublished data)

Top processing tomato-producing counties

Processing tomatoes

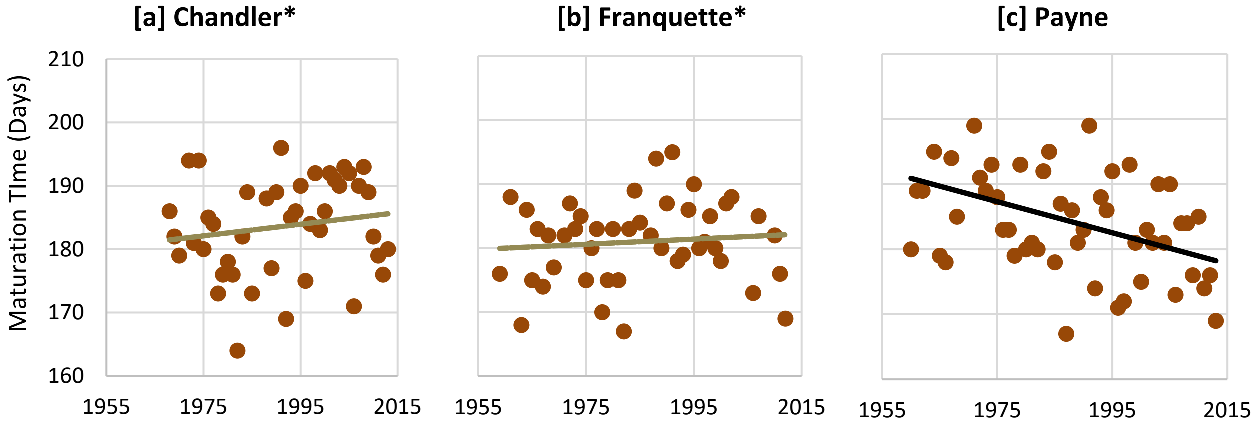
The sections below are unchanged from the 2018 report.

Figure 1. Prune maturation time in Parlier



Source: Jarvis-Shean et al., 2016

Figure 2. Walnut maturation time in Davis (3 cultivars)



**Trend not significant (dashed line)*

Source: Jarvis-Shean et al., 2016

What does the indicator show?

Figure 1 shows maturation times for California prunes and Figure 2 shows three cultivated walnut varieties ("cultivars"), grown respectively in two Central Valley locations: Parlier (Fresno County) and Davis (Yolo County). "Maturation time" refers to the period between bloom and harvest — specifically, flowering and fruit maturity for the prune, and leaf-out and first harvest for the walnut.

From 1988 to 2013, prune maturation (Figure 1) time decreased on average by about 12 days. The maturation time for one of the walnut cultivars, the Payne walnut (Figure 2[c]), similarly decreased by approximately 11 days since 1960. Maturation times for two other walnut cultivars, the Chandler and the Franquette (Figure 2[a] and [b]), have remained relatively constant since 1968 and 1959, respectively.

Why is this indicator important?

California accounts for an estimated 96 percent of the prunes grown in the US, with about half consumed domestically and half exported. The state currently supplies about 40 percent of the world's prunes (Lazicki et al., 2016). The prune industry in California is dependent on a single cultivar, the "Improved French Prune."

California growers produce 99 percent of the commercial US supply of walnuts with about a third of the crop exported (Geisseler and Horwath, 2016). The industry generates $1.4 billion in farm gate revenue annually (net value after subtracting marketing costs) and supports some 60,000 jobs directly and indirectly (California Walnut Board, 2017).

Climatic conditions following flowering and leaf-out for fruits and nuts are critical to the development of a robust crop. In general, shorter maturation times lead to smaller fruits and nuts. Because larger fruits command a premium price, this change can lead to a significant loss of revenue for growers and suppliers. For prunes, this can be somewhat offset by fruit thinning earlier in the year, which can promote larger fruits. This is not practical for walnuts, due to the size of the trees.

Shorter maturation times mean that crops are ripening more quickly. This results in a shorter timeframe for harvest and processing. During harvest season, farmers draw on a limited supply of workers and equipment. If the harvest timeframe shortens, hiring workers and renting equipment can present challenges. Thus, a compressed harvest schedule puts farmers at risk for significant loss of crop quality.

The trend toward earlier maturation for some cultivars of walnuts has some positive impact. Walnuts are often harvested in October — the beginning of the rainy season in the Central Valley. Rain immediately before or during the harvest can be catastrophic, making it difficult to properly dry the nuts, leaving them vulnerable to mold growth. The earlier in the season that walnuts mature, the less likely they are to encounter rain at harvest time.

Warming is expected on an annual, seasonal, and even daily basis in California, with impacts differing by region. The significant, overall outcome of warming is the likely reduction in yield of some of California's most valuable specialty crops, particularly perennial crops.

What factors influence this indicator?

Temperature influences how fast the fruits on a plant develop and mature. Following a period of dormancy in the winter (see *Winter chill* indicator), fruit and nut trees begin to bloom by opening flower or leaf buds. Prune trees have flower buds that produce flowers and vegetative buds that produce leaves. Flowering occurs before vegetative bud break. Walnuts have male buds that produce pollen and mixed buds that produce leaves and female flowers. Leaf emergence precedes the opening of the female flowers (Ramos, 1997).

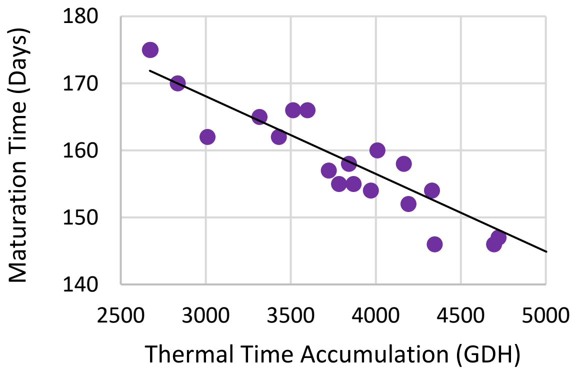
During the first 30 to 90 days after bloom, the amount and duration of warm weather experienced by the plant — referred to as heat accumulation — is the most significant factor that determines harvest timing. This period occurs during the months of April, May, June and July, depending on the variety of walnut. With warmer temperatures, the fruit or nut develops and matures more quickly, leading to an earlier harvest. However, temperatures that are too high (such as during hot days in the Central Valley) can slow development as trees divert energy from fruit development towards self-cooling and preventing or repairing heat damage (Jarvis-Shean et al., 2016)

Different crops have different heat requirements for fruit development; these requirements are typically expressed as ***thermal time accumulation***. In its simplest form, thermal time measures the difference between a given temperature and a certain threshold or base temperature, and the length of time this difference occurs in a day or other unit of time. Thermal time accumulation is calculated by summing hourly thermal time. A fruit or nut reaches maturity when it has accumulated sufficient thermal time. “Growing degree hours” (GDH) is a commonly used unit of thermal time accumulation.

Fruit or nut maturity represents the first possible harvest date. The timing of maturity is partially determined by the timing of flowering. Generally, a tree that blooms earlier will also be ready to harvest earlier. Consequently, changes in harvest readiness date can be due to changes in flowering dates as well as changes in temperature after flowering. Time to Maturity tracks the time between flowering and maturity, and thus the influence of temperature on changes occurring after flowering.

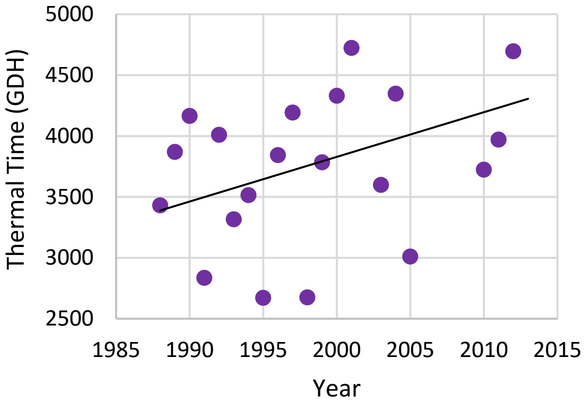
As shown in Figure 3, prune maturation time responded very strongly to thermal time accumulation: the greater the thermal time accumulation in a given season, the shorter the maturation time. In fact, thermal time accumulation for French prunes in Parlier has been increasing since 1988 (Figure 4) — a trend consistent with the decreasing season length. There is, however, too much variation in the data to make any strong conclusions at this time. If thermal time accumulation in Parlier continues to increase as the trend suggests, prune maturation times will most likely continue to shorten with increasing temperatures projected with climate change. Since 1931, minimum temperatures have been increasing for most months of the year in Parlier, while maximum temperatures have been decreasing.

Figure 3. Prune maturation time in response to thermal time accumulation in Parlier



Source: Jarvis-Shean et al., 2016

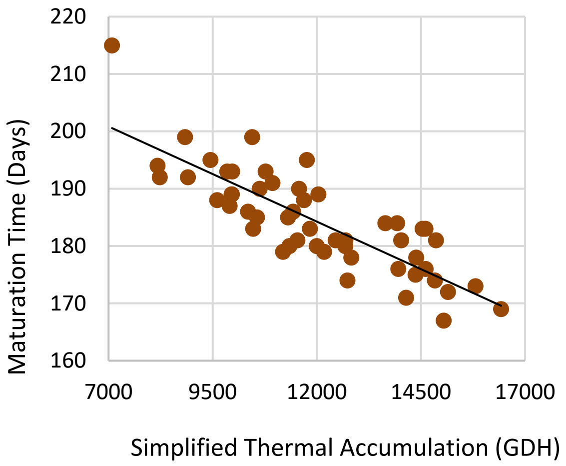
Figure 4. Thermal time accumulation for prunes in Parlier



Source: Jarvis-Shean et al., 2016

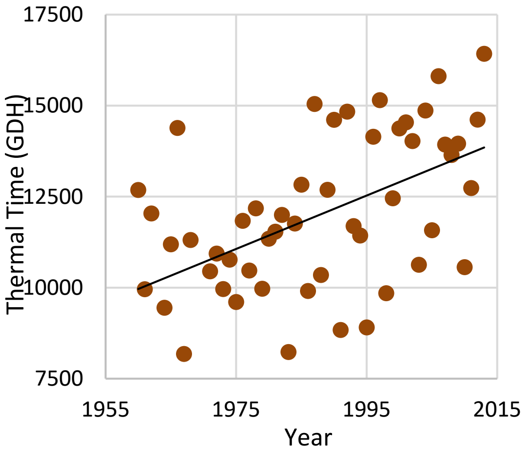
Of the three walnut varieties, only Payne showed a significant decreasing trend in maturation time length over the past 60 years. As with the prune, Payne maturation time responded strongly to thermal time accumulation, showing decreasing maturation times with increasing thermal time accumulation (Figure 5). Payne thermal time accumulation has been increasing since 1960 (Figure 6), indicating that maturation time for these walnuts will shorten with warming conditions associated with climate change. Although maturation times for both the Chandler and Franquette walnuts did not change appreciably over the past 46 and 54 years, respectively, thermal time accumulation for both cultivars increased over time, and showed a strong relationship with maturation time (not shown). Researchers anticipate that maturation times for these cultivars will likely shorten in the future with increasing thermal time accumulation.

Figure 5. Payne walnut maturation time in response to thermal time accumulation in Davis



Source: Jarvis-Shean et al., 2016

Figure 6. Thermal time accumulation for Payne walnut in Davis



Source: Jarvis-Shean et al., 2016

No definitive conclusions can be drawn regarding trends in the maturation times of three almond cultivars, given the short period for which observations are available (nine years).

Technical considerations

Data characteristics

Climate data:

Temperature data were obtained from the National Climatic Data Center of the National Oceanic and Atmospheric Administration (Menne et al*.,* 2015) and from the California Irrigation Management Information System (CIMIS). CIMIS, developed by the California Department of Water Resources and the University of California at Davis, is a repository of climatological data collected at more than 100 computerized weather stations throughout California.

Temperature data were retrieved from stations closest to the fruit and nut orchard locations. When data was missing from a primary station, temperature data from a nearby station were used to supplement the dataset. In Davis, for days when climatological data was absent from the primary station, temperatures from other surrounding locations were used in a model to estimate Davis temperatures.

Temperature time series going back to 1988 (prune) and 1960 (walnut) were analyzed to match up with the duration of maturation time.

Spring thermal time accumulation was calculated using the Growing Degree Hours (GDH) model of Anderson et al. (1986). This model counts the highest GDH accumulation at an optimal temperature of 25 degrees centigrade (°C); at temperatures above a minimum (4°C) and below a maximum (36°C), heat accumulates at fractions of the highest possible amount.

Prune bloom/leaf-out data and walnut maturity/harvest data:

Flowering onset and maturity data for prunes were provided by the University of California Dried Plum/Prune Cultivar Development Program. Full bloom is defined as when 50 percent of the flower buds on the tree have opened. The maturity date is defined as when the fruit can withstand 3 to 4 pounds of pressure (a penetrometer measures the pressure necessary to force a plunger of specified size into the pulp of a fruit).

The leaf-out and harvest data for walnuts were obtained from the University of California at Davis Walnut Breeding Program. Leaf-out is defined as the time at which 50 percent of the vegetative buds have started to open. The harvest date is the time at which the hull, the outer fleshy part, separates from the shell of the nut.

Strengths and limitations of the data

The prune and walnut orchards from which data were collected were at the same or nearby locations over the entire study periods. The walnut dataset is long by phenology data standards, with an average of 44 years of observation, a minimum of 35 years, and a maximum of 59 years, depending on cultivar. The prune dataset, although 25 years in length, provides sufficient information for evaluating phenology trends. In both cases, it would be advantageous to have records of walnut and prune phenology at multiple locations. Not only do crops responses change at different latitudes, but the climate effects may vary throughout California. Evaluating data at multiple sites would allow for a better understanding of how climate change may be affecting different agricultural regions within the state.

To measure prune maturity, the amount of pressure a fruit can withstand when punctured, is a very precise and consistent method. For walnuts, the measure of harvest readiness (hullsplit) is affected by humidity. Higher humidity accelerates nut maturity and can introduce uncertainty in timing of harvest readiness date.

For both the prune and the walnut data sets, a small number of researchers were collecting prune bloom/leaf-out data and walnut maturity/harvest data measurements. Researchers trained their successors to ensure consistency in data collection over time.

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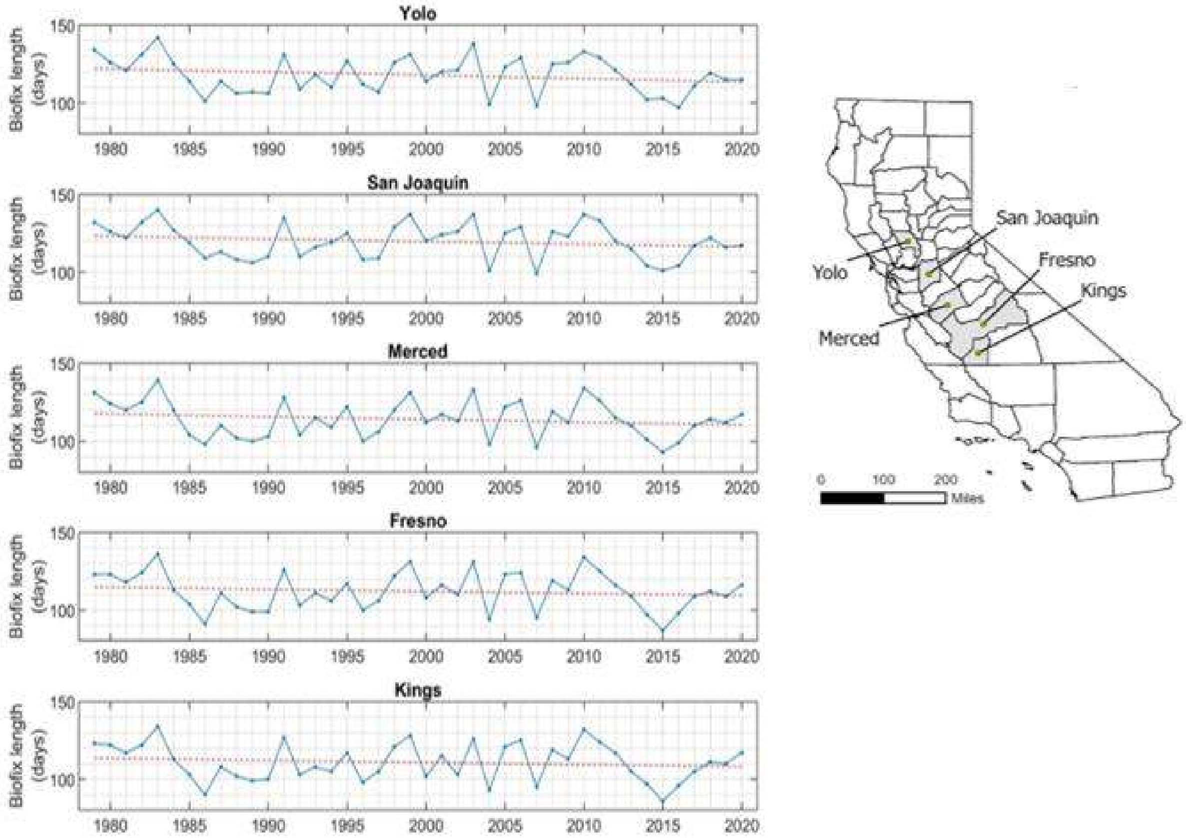
NAVEL ORANGEWORM ABUNDANCE

The navel orangeworm is a temperature-sensitive, highly damaging insect pest of nut crops (walnut, almond, and pistachio). In the Central Valley, temperature-based estimates indicate that the time required for a navel orangeworm to complete its life cycle has declined with warming from 1979 to 2020. The adults (moths) now appear earlier in the season and complete their lifecycles faster. With each successive generation of navel orangeworm, the population of these pests increases.

Figure 1. Estimated length of biofix* of navel orangeworm in almond for selected counties in the Central Valley, 1979-2020



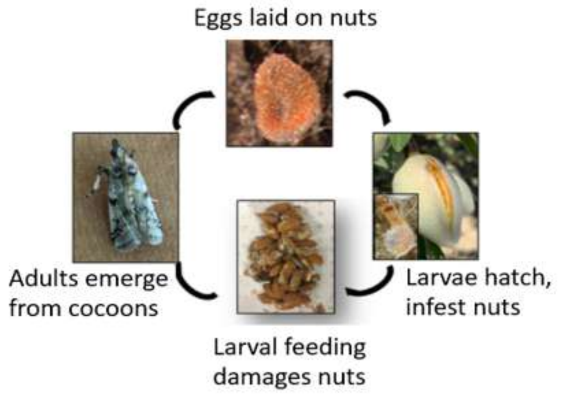
Source: Pathak et al., 2021 (updated)

**The “length of biofix” refers to the estimated number of days from emergence of larvae to the first appearance of the adult moth.*

What does the indicator show?

The navel orangeworm, *Amyelois transitella*, is a major pest of nut crops. Despite its name, the orangeworm is not a significant pest of citrus fruits -- its name comes from when it was first noticed by entomologists in the southwestern United States as it infested citrus fruits (Wilson et al., 2020). Figure 1 presents the estimated length of time (number of days) each year for the adult navel orangeworm to emerge from eggs (see life cycle diagram, Figure 2). This emergence is a biological event referred to as "biofix." A declining trend in the time it takes to reach biofix is evident for the Central Valley counties presented: since 1979, biofix is happening earlier, ranging from almost 9 days earlier in Yolo County to about 5 days in Fresno and Kings Counties (see Table 1). The estimates shown in Figure 1 were obtained using a "growing degree day" model. "Growing degree days" is a widely accepted unit of heat accumulation over time. As with crops (see *Fruit and nut maturation time* indicator), different insects have different heat requirements for development. A sufficient amount of heat – measured as growing degree days – must be accumulated to reach each life stage (such as biofix) and to eventually complete a full life cycle (from egg-laying to adult moth). As temperatures increase, the amount of time it takes for heat units to accumulate and reach these heat requirements decreases.

Figure 2. Lifecycle of the navel orangeworm



Source: Pathak et al., 2021

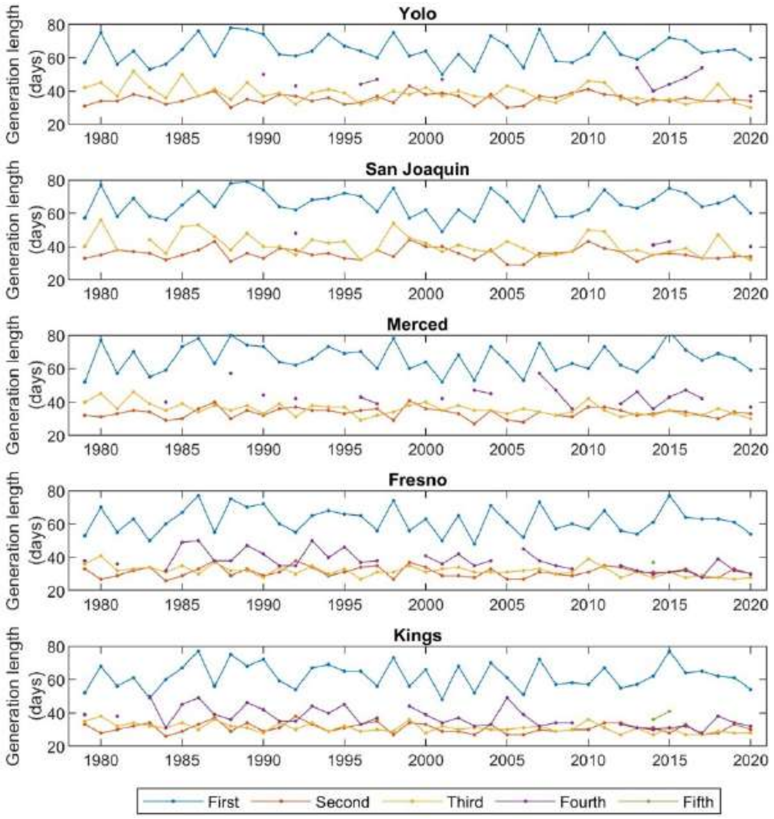
Table 1. Trends (number of days per year) in the duration of biofix and of the 1st through 5th generations of the navel orangeworm in Yolo, San Joaquin, Merced, Fresno, and Kings counties (1979-2020)

	Yolo	San Joaquin	Merced	Fresno	Kings
Biofix	-0.21	-0.18	-0.17	-0.13	-0.13
1st generation	-0.02	-0.01	-0.02	-0.05	-0.03
2nd generation	0.02	-0.03	-0.01	-0.02	-0.04
3rd generation	-0.17	-0.19	-0.16	-0.12	-0.13
4th generation	-0.04	-0.28	-0.12	-0.26	-0.27
5th generation	0	0	0	0.02	5.00

**Red text indicates statistically significant trends ($p < 0.05$).*

Similar to biofix trends, the estimated length of time for the navel orangeworm to complete each generation has also shown declining trends over the past 41 years (Figure 3 and Table 1). As expected with warming temperatures, the navel orangeworm has developed rapidly, resulting in reductions in the duration of the lifecycle for each generation. The duration of the third and fourth generation lifecycles – which occur later in the warm season when temperatures tend to be higher – declined the most.

Figure 3. Generation length of navel orangeworm in almond for selected counties in the Central Valley, 1979-2020



Source: Pathak et al., 2021 (updated)

Generation length refers to the estimated number of days it takes for navel orangeworm to complete one generation (from egg-laying to adult moth).

As a result of the reduced time for each lifecycle, the number of generations of navel orangeworm over the 41-year period has increased. For instance, in Yolo County the navel orangeworm accumulated a maximum of three generations until the late 1990s. However, in recent years, a fourth generation has become more common, suggestive of an upward trend in the number of generations. A fifth may also become more common under future climate conditions if trends toward shorter lifecycle durations and increasing generations continue. With each successive generation of navel orangeworm, the population of these pests increases.

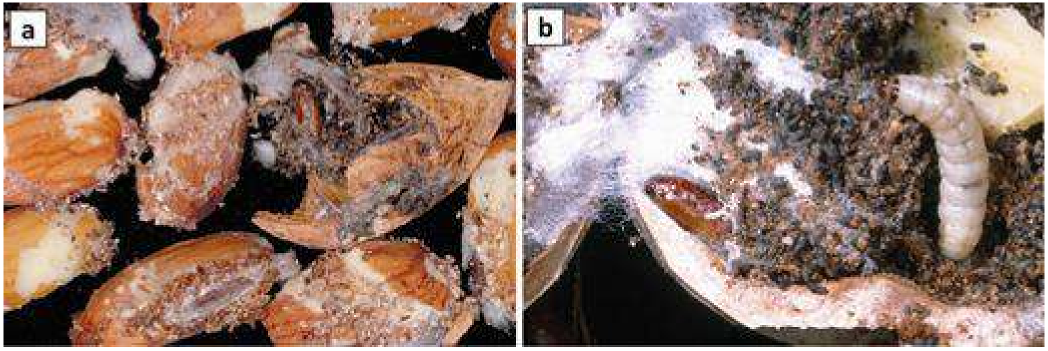
Why is this indicator important?

California is a leading producer of three major nut crops: walnut, almonds, and pistachios. The total cash value of these three crops exceeds $8 billion (CDFA, 2020). The navel orangeworm is considered the most damaging agricultural insect pest for these three important nut crops.

Navel orangeworm female moths lay eggs on a naturally split suture of the nuts. The freshly hatched larvae directly feed on the kernel, rendering it unmarketable (Figure 4).

The damaged kernels become a preferred target of the saprophytic fungi, *Aspergillus* spp., which produce carcinogenic toxins (aflatoxins) (Bentley et al., 2017; Grant et al., 2020; Haviland et al., 2019). Therefore, the economic impacts of navel orangeworm come from both the direct feeding damage and the indirect damage caused by contamination of marketable nuts with aflatoxins. Additionally, as damage to crops from navel orangeworms becomes more prevalent, greater use of pest control and pest management techniques will become necessary.

Figure 4. Damaged nuts due to feeding of navel orangeworm larva.



Source: Wilson et al., 2020

What factors influence this indicator?

The navel orangeworm is cold-blooded, so the temperature is the main factor in its growth and development. As temperatures continue to rise across California, tracking developmental rates and population dynamics of the orangeworm will become even more critical for strategic planning and minimizing risks associated with this pest. In addition, temporal trends observed with the navel orangeworm might reflect a broader pattern of increased generations and faster lifecycles of other pests in California as temperatures warm (Pathak et al., 2021).

Humidity, precipitation, and wind speed also affect their body temperature and thus their growth and development (Pathak et al., 2020). Factors other than climate that can potentially control the spread of this pest include biological controls, orchard sanitization in winter, timely pesticide applications, and early harvest to decrease risks to nut crops (Bentley et al., 2017; Grant et al., 2020; Haviland et al., 2019).

Technical considerations

Data characteristics

The metrics presented are based on Pathak et al., 2020. In this study, gridded temperature data from gridMET were used. GridMET was generated by blending spatially rich data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) with temporally rich data from the North American Land Data Assimilation System Phase 2 (NLDAS-2) using climatically aided interpolation (Abatzoglou, 2011). Daily updated minimum and maximum temperature data at 4-km spatial resolution from 1979 to 2020 were collected and used in this analysis.

A growing degree-days model was used to predict the timing of various life stages of navel orangeworm. In this model, growing degree days, which represent daily heat accumulations, were calculated from the minimum and maximum temperatures of 12.7 °C and 35 °C (based on the navel orangeworm's biological thresholds). 12.7 °C is the temperature at which orangeworm activity begins in the spring, and 35 °C indicates the temperature above which insect development begins to decrease or stop. The biofix for navel orangeworm occurs at around 148 °C degree days around the central portion of the Central Valley, so the biofix date was set when degree days reached 148 °C. The first generation completes its lifecycle in 565 °C degree-days (Siegel and Bas Kuenen, 2011; Zalom et al., 1997). It takes a fewer number of degree days to complete one generation for subsequent generations due to in-season nuts being nutritionally better in quality than the early season nuts available to the first generation, i.e., 444 °C for almond and walnut and 402 °C for pistachio (Siegel et al., 2010; Siegel and Bas Kuenen, 2011). October 31 was the last day for calculations, as nearly all nut crops are harvested by then, and there is a negligible activity of navel orangeworm due to the significant drop in daily temperatures.

Strengths and limitations of the data

Temperature-based degree-days models to estimate the lifecycle of agricultural pests have been widely used around the world. Zalom et al. (1997) have validated the navel orangeworm degree-days model in field conditions. Despite that, uncertainties associated with parameters and inherent model uncertainties can influence the model outputs. Additionally, pest models are simplified versions of complex systems, and many factors influence the growth and development of these pests. For instance, the degree days model does not account for pest mortalities related to extreme heat events, which may influence the expected pest pressure.

OEHHA acknowledges the expert contributions of the following to this report:

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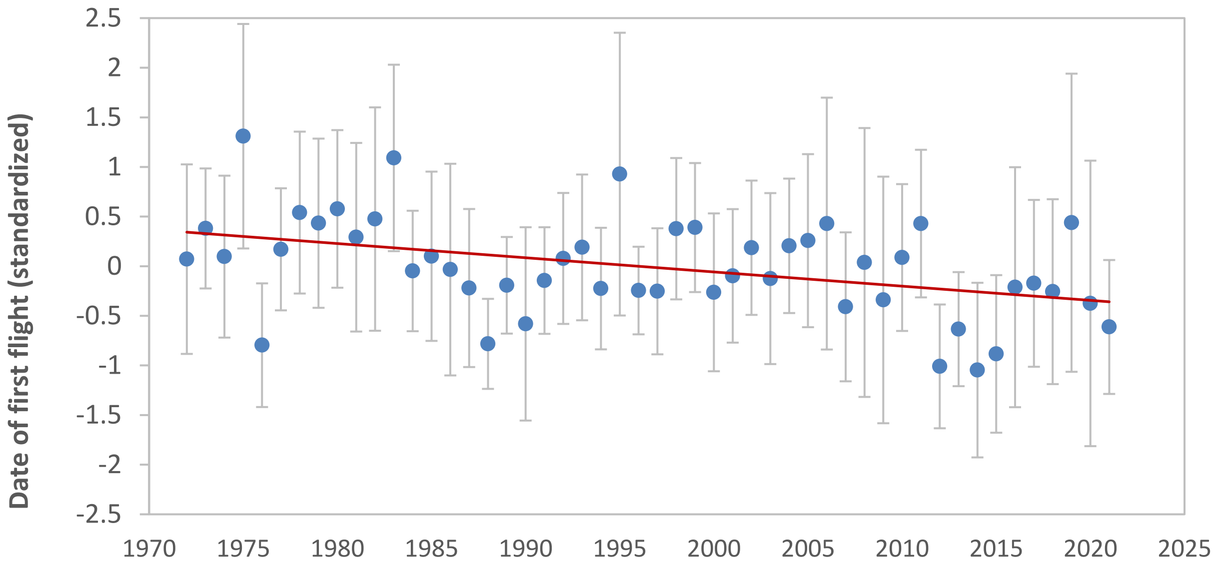
SPRING FLIGHT OF CENTRAL VALLEY BUTTERFLIES

Over the past 50 years, common butterfly species have been appearing in the Central Valley earlier in the spring.

Figure 1. Date of First Spring Flight of Central Valley Butterflies



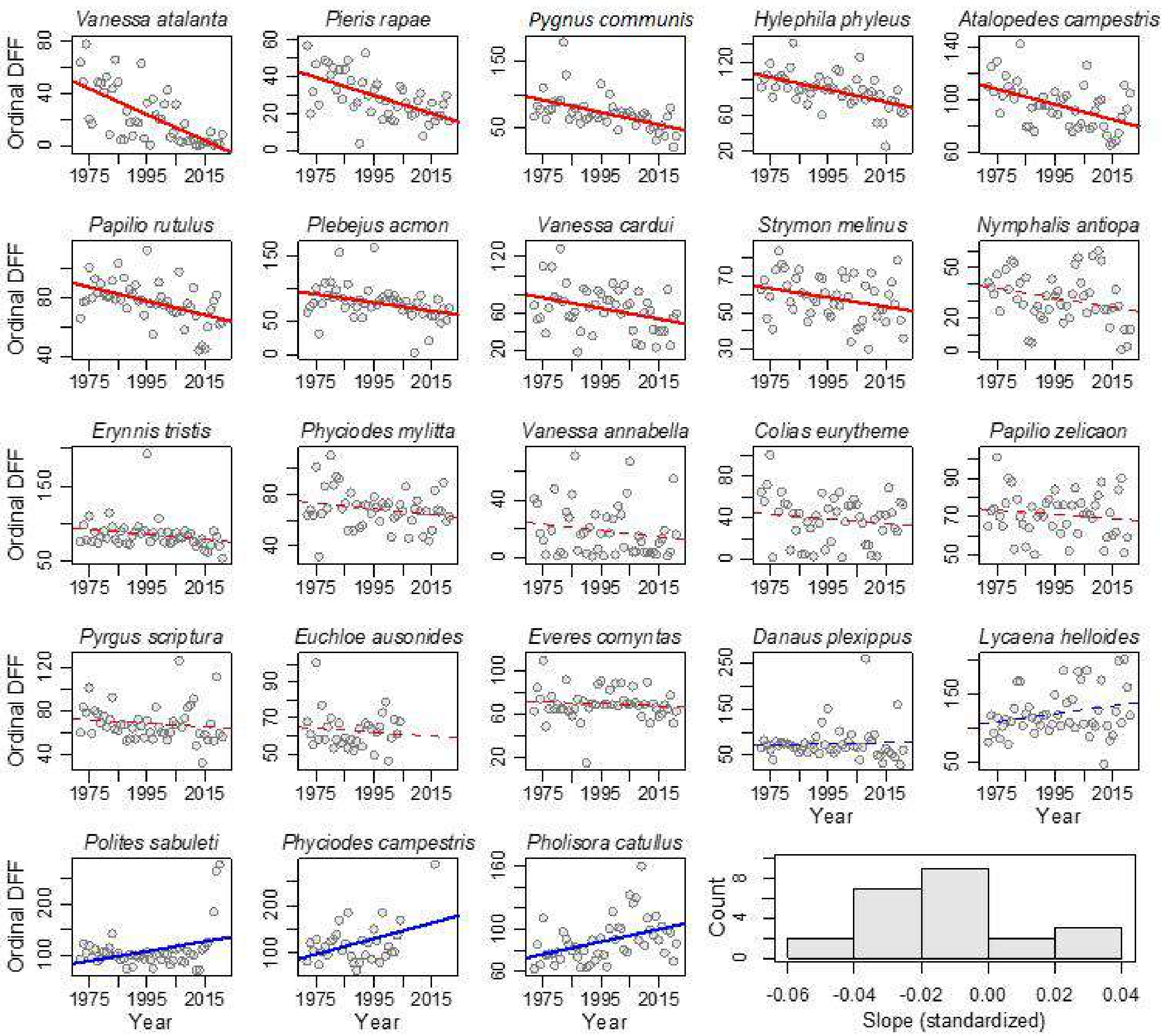
Source: Forister and Shapiro (2003), updated 2021 (see text for explanation)

What is the indicator showing?

Over the past 50 years, the average date of first flight (DFF) of a suite of 23 butterfly species in the Central Valley of California has been shifting towards an earlier date in the spring (Figure 1). The DFF refers to the date that the first adult of a species is observed in the field in a given calendar year. Change in DFF tracks shifts in the phenology (the timing of seasonal life cycle events) in the emergence of butterflies in the Central Valley. In Figure 1, the value shown for each year is the aggregate of DFFs across the 23 species, calculated as described in the *Technical Considerations* section below. The higher the value on the graph, the later the DFF. A negative value indicates a DFF that is earlier than the average; a positive value, later than the average. The red line in the graph indicates the overall trend towards earlier emergence (Forister and Shapiro, 2003, updated data available from UCD, 2021).

Photo: Jim Ellis
Painted lady (*Vanessa cardui*)

Figure 2. Date of first spring flight for 23 butterfly species*



Source: Forister and Shapiro 2003 (updated 2021)

**Ordinal DFF are days since the start of the calendar year*

Bold lines are drawn on plots if individual trends are significant in simple linear models with DFF predicted by year, at $P < 0.05$; dashed lines indicate $P > 0.05$. Red for species emerging earlier, and blue for species emerging later.

Figure 2 presents graphs showing DFF by year for each butterfly species, starting with species showing stronger trends towards earlier emergence, and ending with species showing trends towards later emergence. Across the nine species with individually significant responses for earlier emergence, the average slope is -0.62 days per year, which means that the spring phenology of these species is advancing by approximately 6 days per decade. As shown in the histogram in the lower right of the figure, the distribution of slope values across species (generated from analyses of z-scores) is significantly shifted towards the negative, indicating earlier emergence across species (one-sample t test = -2.70, $P = 0.013$), consistent with the pattern shown in Figure 1.

Why is this indicator important?

This indicator demonstrates the utility of common butterfly species for studying biological shifts consistent with the impacts of a changing climate. Plants and animals reproduce, grow and survive within specific ranges of climatic and environmental conditions. Species may respond when these conditions change beyond tolerances by moving to more favorable habitats (often poleward or to higher elevations), sometimes changing in morphology such as body size or wing color, or altering phenologicaly with respect to the timing of events such as migration, egg-laying or emergence (Hill et al., 2021; Root et al., 2003). Many studies have investigated the relationship between phenology and changes in climate conditions. These studies, however, have largely been from higher, temperate latitudes, where minor climatic changes can have large impacts on species that are often at the limits of their ranges (Chambers et al., 2013; Parmesan, 2006; Root et al., 2003; Walther et al., 2002).

The shifting phenology of these 23 butterfly species is correlated with the hotter and drier conditions in the region in recent decades (Forister et al., 2018; Forister and Shapiro, 2003; Halsch et al., 2021) (see *Annual air temperature*, *Precipitation* and *Drought* indicators). The data supporting this indicator suggest that Central Valley butterflies are not only responding to changing climate conditions, but also that their responses have been similar to butterflies from higher-latitude climates. This indicator complements similar studies from Austria, Switzerland, the United Kingdom and other European countries and demonstrates the apparently ubiquitous phenological response of spring butterflies to warming and drying conditions (e.g., Altermatt, 2012; Hill et al., 2021; Peñuelas et al., 2002; Roy and Sparks, 2000). It is also worth noting that the Central Valley has undergone intense land conversion, both to urban development and to agriculture (Forister et al., 2016). Thus, the data indicate that the phenological impacts of climate change are not restricted to northern latitudes or to pristine ecological conditions. Continued monitoring of phenological changes adds to the growing body of data that elucidate butterfly responses to changing temperature and precipitation linked to climate change, that are occurring alongside changing land use, increasing pesticide use, and other stressors (Chmura et al., 2019).

Changes in the seasonal timing among species that interact—for example, between butterflies and their plant food sources, or between prey and predators—could disrupt population dynamics and species abundance across trophic levels (Weiskopf et al., 2020). Declining populations of butterflies and other insects have been reported globally, underscoring the urgency to better understand how changes in climate, habitat degradation, pollution, and other stressors interact to affect insect populations (Halsch et al., 2021).

Dates of first flight are presented as an indicator of climate change, primarily because they have a history of being used in this context in global change research. However, the date of first flight is of course only one aspect of the biology of a butterfly population. Population densities in the northern Central Valley of California are declining in response to shifting land use, increased use of pesticides, and climate change (Casner et al., 2014; Forister et al., 2016). More recently, severe declines have been observed in areas not immediately adjacent to intense agricultural development and urbanization. During and after the mega-drought years of 2011 to 2015, butterfly populations in the Sierra Nevada Mountains reached historic lows that rival the declines previously seen in the Central Valley (Halsch et al., 2021).

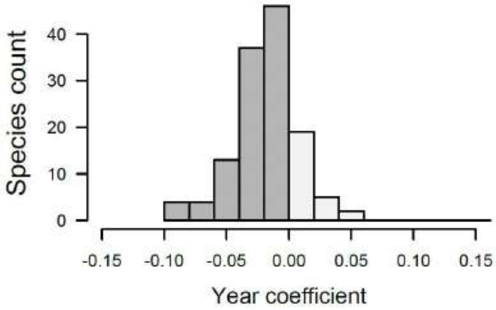
Widespread butterfly declines have been detected across the western US: specifically, Forister et al. (2021) estimated 1.6% fewer butterflies are being observed per year across all western states (95% Bayesian credible intervals around that value ranged from 3.4% decrease to 0.2% increase). That result is based on 72 sites (with 10 or more years of data) monitored by community scientists organized by the North American Butterfly Association (NABA). Changes in the total numbers of butterflies at those sites were modeled as a function of a range of climate and landscape factors, and the most powerful predictors were indices of climate change. In particular, locations where fall months had warmed the most (in maximum daily temperatures) were the locations where annual reductions in total butterfly densities were most pronounced (Forister et al. 2021).

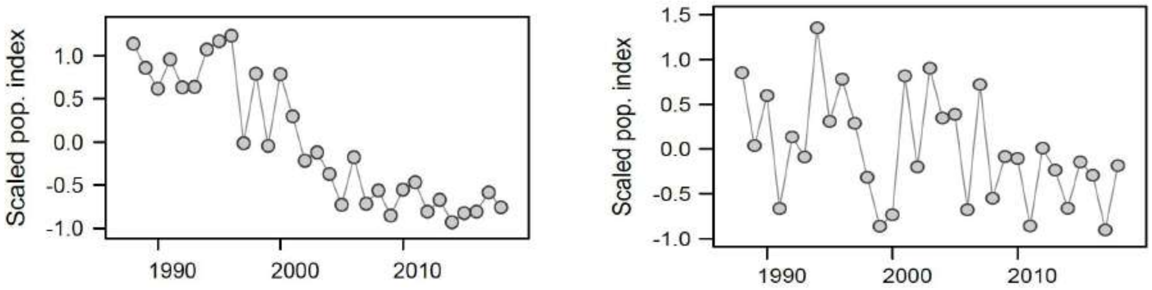
Consistent with the broader trend throughout the western United States, a majority of species in the Northern California data set that includes the butterfly species tracked by this indicator have been seen less frequently over time; the results are summarized in Figure 3A. This data set consists of observations from ten study sites that include large urban and agricultural areas from the Bay Area to the Sierra Nevada Mountains, and the population changes reflect both the effects of habitat loss or degradation and climate change. Annual changes in the probability of being observed (which is used as an index of population density) for two species are shown in Figure 3B and C.

The biological mechanisms linking fall warming to butterfly declines have yet to be thoroughly explored, but likely involve physiological stress on host and nectar plants as well as interference with overwintering stages of the butterflies. Although much has yet to be learned, it is worth nothing that the NABA community scientist program is based on a single day of observations during the middle of summer (in some cases sites are visited more than once, but most are visited once, typically in July). The efficiency of this program highlights the power of crowdsourced biological data for tracking climate effects, especially when used as a complement to the expert-derived data as described in this indicator report.

Figure 3. Declining Northern California butterfly populations

A. Summary of magnitude of change across species*




B. *Euchloe ausonides*

C. *Atalopedes campestris*

Source: Forister et al., 2021

**Based on data for ten sites across northern California monitored every other week during the butterfly flight season for between 33 and 49 years, depending on the site. See Forister et al. (2011) and Forister et al. (2021) for additional details on data and methods.*

A. Values summarized are year coefficients (from binomial regression models) that reflect upward or downward population trends; negative values, shown in dark gray, correspond to the majority of species with negative annual coefficients (one species with a large positive value is excluded for ease of visualization). **B and C**. Annual values for two exemplar species: *Euchloe ausonides* (B) and *Atalopedes campestris* (C); y axis values are z-standardized probabilities of being observed in each year (1988-2018).

What factors influence this indicator?

Climatic conditions have a significant impact on the phenology of butterflies. Butterflies in the temperate latitudes enter a dormant state during the winter months; in the spring, temperature cues cause them to hatch, to resume activity, or to emerge from pupae as adults (Dennis, 1993; Shapiro, 2007). As climatic conditions during key times of the year have changed, the timing of butterfly life-history events has undergone a corresponding change. The butterfly species monitored overwinter in different life history stages: as eggs (1 species), larvae (8 species), pupae (9 species) and adults (3 species); two of the species emigrate in the spring from distant over-wintering sites. Statistical analyses to determine the association between DFF and twelve different weather variables show winter conditions—specifically winter precipitation, average winter daily maximum temperature, and average winter daily minimum temperature—have the strongest associations with DFF (Forister and Shapiro, 2003). Between 2011 and 2015 (during the drought years), DFFs advanced at the low-elevation locations in the Central Valley, as well as at higher-elevation sites in the Sierra Nevada (Forister et al., 2018). However, dates of last flights remained close to the long-term average at low elevation sites, while advancing at higher elevations, thereby compressing the length of the flight window.

Other factors may impact the phenological observations described here, such as nectar and host plant availability. Plant resources may in turn be affected by habitat conversion, though it is not obvious how these factors could lead to the earlier emergence of a fauna. Finally, the impacts that a shifting insect phenology may have on other species at higher and lower trophic levels, including larval hosts and predators, are also unknown.

Technical considerations

Data characteristics

The data described here consist of the date of first spring adult flight (DFF) for 23 butterfly species. These were first reported by Forister and Shapiro (2003). The primary result remains unchanged by the updated data: an overall shift towards earlier emergence, with more dramatic shifts in a subset of species. Information about ongoing monitoring of study sites can be found at Monitoring Western Butterflies and Art Shapiro's butterfly site; data are available upon request.

The study area is located in the Central Valley portions (below 65 meter elevation) of three Northern California counties: Yolo, Sacramento, and Solano. Three permanent field sites in these counties are visited by an investigator at two-week intervals during "good butterfly weather." Most of the observations (> 90%) of DFF come from those permanent sites; however, if a butterfly was observed in a given year to be flying first at a location within the three counties but outside of the permanent sites, that observation was included as well.

The values for Figure 1 were derived as follows:

- Calendar dates were first converted into days since the start of the year, also known as "ordinal" dates.
- The ordinal dates of first flight (DFF values) were transformed into z-scores separately for each species. To do this, the mean and standard deviation of DFF values across years were calculated. The difference between each DFF value and the mean was then found, and that result divided by the standard deviation to produce a z-score corresponding to the number of standard deviations a value is from the long-term average DFF for that species. For example, a z-score of -1 indicates a DFF that is one standard deviation earlier than the average for that species, and a value of 1 indicates a DFF that is one standard deviation later than average.

- The mean of the z-scores across the 23 species for each year is shown in Figure 1, along with the standard deviation of the z-score values.

- The red line in Figure 1 is fit to the mean z-score values across years. It shows that the mean values have decreased over time, and corresponds to an overall trend towards earlier emergence that is significant.

Strengths and limitations of the data

Since the data are collected and compiled entirely by one observer (Arthur Shapiro), any biases in data collection should be consistent across years. This would not be true in studies which involve multiple workers—with variable levels of training—across years.

The primary limitation of the data stems from the fact that DFF is only one aspect of a potentially multi-faceted suite of population-level dynamics. For example, if the spring phenology of a species shifts, does this affect the total flight window? Does it affect peak or total abundance throughout the season? The picture becomes even more complex considering general declines in low-elevation butterfly populations in the region that have been reported by Forister et al. (2010). If populations are in overall decline, with lower densities of individuals throughout the year, this could lower detection probabilities. This is true particularly early in the season for multivoltine species (i.e., species that produce more than one generation in a season, where the first generation tends to be smaller). Lower detection probabilities could appear as later phenological emergence (i.e., a "backwards" shift in time as is shown for *P. catullus* in the bottom right of the second figure). These issues are addressed in more detail in Forister et al. (2011); and for further discussion of relevant biological complexities, see Shapiro et al. (2003) and Thorne et al. (2006).

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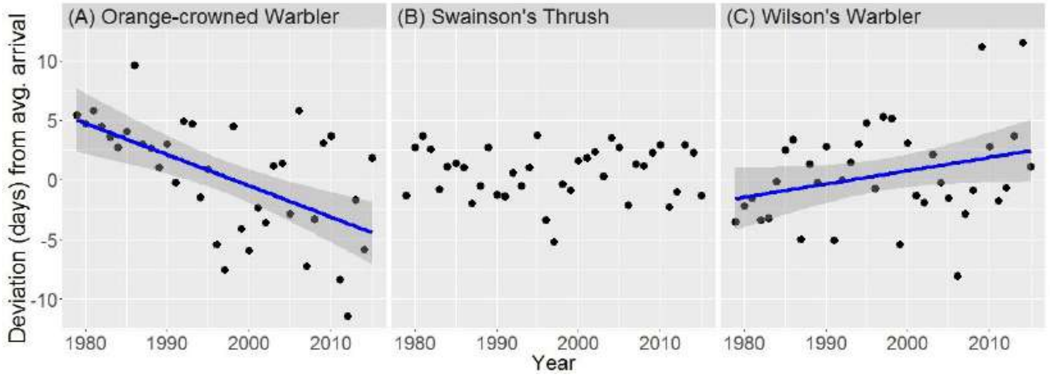
MIGRATORY BIRD ARRIVALS (NO UPDATE)

Migratory songbird species are showing a diversity of changes in arrival dates. Of the three species studied that arrive at a coastal California site in the spring, two are showing opposite trends in timing (one shows no significant change). Of the four species that arrive in the fall, two have been arriving earlier over the past 35 years, while one has been showing a trend toward earlier arrival since 1995. The fourth species shows no significant change.

Figure 1. Annual arrival dates, 3 spring migrant species at Palomarin Field Station, 1979-2015



Deviation (in days) from the overall mean spring arrival date for that species is shown for each year.

Significant linear trend shown for (A) and (C); shading shows confidence interval. No significant trend in (B).

Orange-crowned warbler

Swainson's thrush

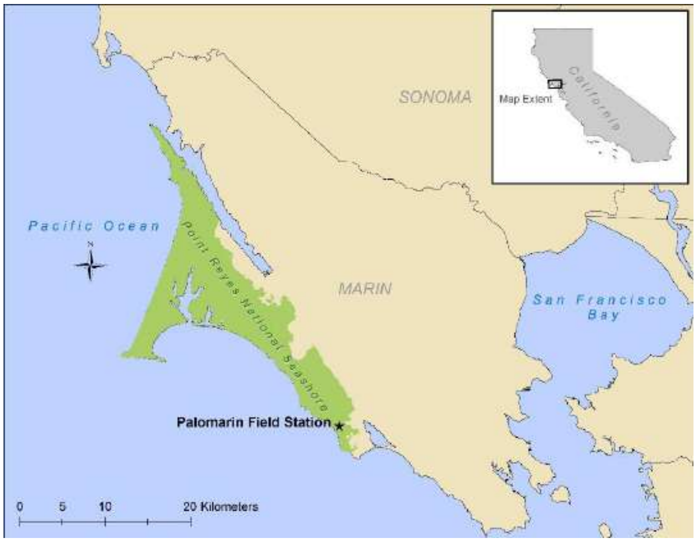
Wilson's warbler

Photo credits (left to right): Rich Stallcup, Point Blue; Ian Tait, Point Blue; Rich Stallcup

What does the indicator show?

Trends in spring and fall arrival dates of birds migrating to their breeding grounds in the spring (Figure 1) and their wintering grounds in the fall (Figure 3) differ among seven species of songbirds that spend part of the year at the Point Blue Conservation Science's Palomarin Field Station in Point Reyes National Seashore, Marin County, California (see Figure 2). Arrival dates are based on a 36-year record of observations at this location, where the habitat is

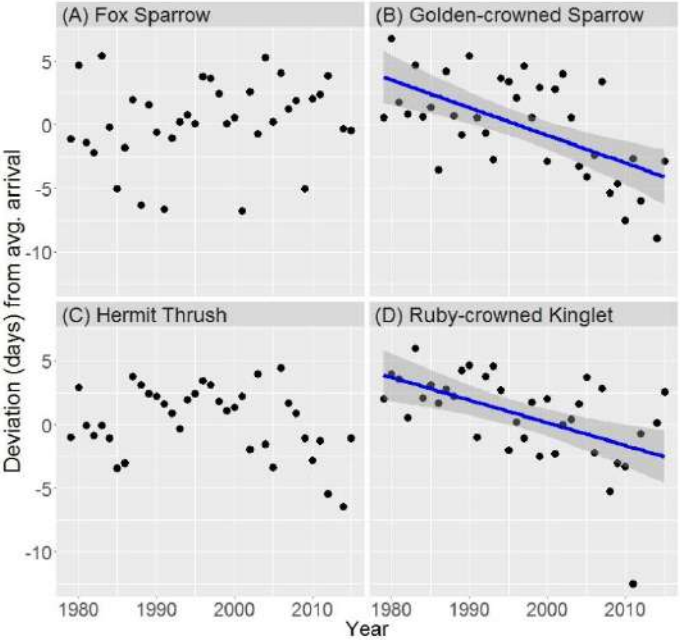
Figure 2. Map showing location of Palomarin Field Station



Source: Point Blue Conservation Science, 2017 a mix of coastal scrub and mixed-evergreen hardwood forest with encroaching Douglas-fir forest.

As shown in Figure 1, of the spring species migrating to their breeding grounds, the Wilson’s Warbler (*Wilsonia pusilla*) has been arriving later (1.1 days later per decade), while the Orange-crowned Warbler (*Oreothlypis celata*) has been trending towards earlier arrivals (2.6 days earlier per decade) over the past 36 years. No significant trend was observed for the Swainson’s Thrush (*Catharus ustulatus*).

Figure 3. Annual arrival dates, 4 fall migrant species at Palomarin Field Station, 1979-2015



Deviation (in days) from the overall mean fall arrival date for that species is shown for each year.

Significant linear trend shown for (B) and (D); shading shows confidence interval. No significant linear trend in (A) and (C).


Fox sparrow


Golden-crowned sparrow


Hermit thrush


Ruby-crowned kinglet

Photo credits (left to right): Tom Munson; Kim Savides, Rick Clark; Rick Lewis, Point Blue.

Figure 3 shows that, among species migrating to their wintering grounds in the fall, the Ruby-crowned Kinglet (*Regulus calendula*) and the Golden-crowned Sparrow (*Zonotrichia atricapilla*) have been arriving earlier (1.8 and 2.1 days per decade, respectively) since 1980. The overall linear trend over the 36-year period is not significant for the Hermit Thrush (*Catharus guttatus*); however, the data show a trend toward earlier arrival beginning in 1995. This response is similar to that of the Golden-crowned Sparrow, which has been arriving at increasingly earlier dates (the data show a significant acceleration in the past two decades). The Fox Sparrow (*Passerella iliaca*) shows no significant linear trend.

Globally, a general trend of earlier arrival of birds migrating in the spring has been reported, associated with warming temperatures and the earlier onset of spring and with it, the emergence of the plant and insect resources the birds rely on (Usui et al., 2017; Herbert and Liang, 2012; Parmesan, 2006). However, there is considerable variation, with different species (or even populations of the same species) exhibiting both earlier and later timing of spring migration. While there are less data on fall migration, some studies have indicated shifts to later arrivals (Jarjour et al., 2017).

Why is this indicator important?

Tracking changes in migratory bird arrivals adds to the body of evidence of how terrestrial species have responded to regional changes in climate. A growing number of studies have examined changes in the timing of migration in recent decades across the Northern Hemisphere. Changes in the timing of spring migration (Marra et al., 2005; MacMynowski et al., 2007; van Buskirk et al., 2009; Ward et al., 2015) and, to a lesser extent fall migration, have been documented (Cotton, 2003; Jenni and Kéry, 2003; Mills, 2005).

The timing of bird arrivals on breeding territories and wintering grounds is a key determinant of reproductive success and survival (Cotton, 2003). To the extent that migrating birds species are adapted to arrive at the optimum stage in the growth season — thus maximizing the availability of resources — shifts in migration timing can be expected to be disadvantageous (Travers et al., 2015). An analysis of changes in spring arrival dates among 48 bird species and the emergence of vegetation (spring "green-up" dates) across North America from 2001-2012 found that both have changed over time, usually in the same direction; however arrival of eastern species increasingly lagged behind greenup, while in the west, where green-up typically shifted later, birds arrived increasingly earlier (Mayor et al., 2017). These findings highlight mismatches in timing that may potentially lead to adverse consequences on bird populations.

Knowledge of how migratory birds are responding to changing climatic conditions is critical in assessing and projecting the impacts of those changes on bird populations. Of particular concern are species or populations that are unable to modify their arrival times; reduced genetic variability due to a decline in their population size could limit their ability to adapt to climate change, potentially hastening further population declines (Hurlbert and Liang, 2012) . A study of changes in spring migration timing among 100 European bird species found that population declines occurred in species that did not advance their spring migration in the period 1990-2000; those with stable or increasing populations advanced their migration considerably (Møller et al., 2008).

This indicator illustrates the value of long-term data, gathered in a systematic way, in revealing trends in spring and fall arrival dates of migratory songbirds. It adds California and western North American observations to the growing body of data describing temporal patterns in bird migration patterns (Seavy et al., in press). Such regional information helps improve the scientific understanding of factors that may be influencing the timing of migration and how these factors may be reflected in global trends. The data presented can serve as a baseline with which to compare future observations and to develop long-term projections under future climate change scenarios. While there is no definitive explanation for why the responses of the seven species differ, this information can also help inform studies that seek to elucidate the mechanisms and consequences of these phenological changes — particularly studies that examine whether shifts in timing are synchronous with changes in the timing of optimal conditions in breeding or wintering grounds.

What factors influence this indicator?

Bird migrations are seasonal movements between wintering and breeding grounds that allow individuals to take advantage of abundant resources, or to avoid predators or exposure to harsh conditions. As environmental conditions change over time, birds can potentially adjust the timing of migration — a response that reflects the interactions among several intrinsic and extrinsic factors. Migratory birds exhibit seasonal physiological changes in preparation for migration, triggered by environmental cues such as photoperiod (the length of day or night) and temperature (Hurlbert and Liang, 2012).

Researchers have investigated the association between changes in migration timing and a number of factors. Species that migrate more slowly and over short distances, and that occupied broader climatic niches (that is, habitats with a wider range of physical and biological resources) were found to have advanced arrival dates the earliest in a study of 18 common bird species in eastern North America (Hurlbert and Liang, 2012). An analysis of over 70 published studies on the timing of spring migration of 413 species across five continents found that, correlated with warmer spring conditions on arrival grounds, short distance migrants advanced their arrival dates by more than long distance migrants; no relationship was found between species' habitat or diet and arrival time (Usui et al., 2017). In contrast, a study of 19 songbird species in Quebec, Canada from 2005 to 2015 found a significant association between changes in migration timing and feeding habits: 10 of 14 insectivores, and only one of five granivores showed evidence of a shift in migration (Jarjour et al., 2017); overall spring arrival dates shifted earlier, while fall departure dates varied considerably.

As fall temperatures increase, insects and plants may be available as food for longer, delaying fall departure as individuals improve their condition to increase survival during migration (Jarjour et al., 2017) Similarly, some species may be shifting their spring arrival timing in response to climatic conditions at their wintering grounds, which has been shown to affect the physiological condition of migrants and thus their departure dates (Marra et al., 2015).

Environmental conditions in the wintering or breeding grounds, stopover locations along the migration route, or in the final settling location — all of which affect arrival times — may, in turn be affected by factors operating on multiple spatial scales. The variety of factors and the multiplicity of temporal and spatial scales at which birds operate during migration undoubtedly contribute to the considerable inter-annual variation in arrival dates.

The earlier arrival of the Orange-crowned Warbler at Palomarin is not surprising. Earlier onset of spring conditions has been documented over much of the Northern

Hemisphere (Root et al., 2005; Parmesan, 2006). This can influence the timing of migration and breeding (Gordo, 2007; Møller et al., 2010; Seavy et al., in press). However, Both and Visser (2001) found that changes in conditions on the breeding grounds influenced laying date but did not lead to changes in spring arrival dates for a long-distance migrant. The contrasting arrival patterns of the two warbler species — both small, insectivorous songbirds in the same taxonomic family — presents a paradox, however, and indicates the need for further research.

In contrast, less research has investigated fall arrival patterns of birds to their wintering grounds (Gallinat et al., 2015). Trends in fall arrival dates likely relate, in part, to spring breeding ground conditions elsewhere: If breeding conditions persist later in the season, fall arrivals could be delayed; if breeding conditions support earlier breeding or if drier conditions result in earlier cessation of breeding, fall arrivals could advance.

The species described here migrate to the Point Reyes area from different wintering or breeding locations. Among the spring arrivals to the Point Reyes area, Swainson's Thrushes (which show no trend in arrival dates) winter predominantly in western Mexico (Cormier et al., 2013); Wilson's Warblers, which have been arriving later, winter in a larger area covering Baja California as well as western Mexico (Ruegg et al., 2014). Baja California and western Mexico are characterized by different wintering habitats that may influence departure timing from the wintering grounds. The migratory pathways of Orange-crowned Warblers have not been documented; while their wintering range includes areas farther north than the other species (Gilbert et al., 2010), the wintering location of the population migrating to Palomarin is unknown.

The four species that arrive in the fall migrate from temperate regions. The Golden-crowned Sparrow (arriving earlier) and Fox Sparrow (no change in arrivals) both breed predominantly in the Gulf of Alaska (Seavy et al., 2012, Cormier et al., 2016; Point Blue unpublished data). The difference in these species' arrival patterns suggests that either conditions on the breeding grounds are not having a direct effect on timing of arrival or that the species are responding differently. Hermit Thrush, whose pattern is similar to Golden-crowned Sparrows (tendency to earlier arrival), breed in the Pacific Northwest, in particular, coastal British Columbia and the Olympic Peninsula of Washington (Nelson et al., 2016). It is not known where the population of Ruby-crowned Kinglets breed, although subspecies-related plumage patterns at Palomarin (Point Blue unpublished data) suggest that the majority are likely from either or both of the above two regions (Pacific Northwest and Gulf of Alaska), with some originating from interior Alaska or Canada (Swanson et al., 2008). Thus it is possible that either finer-scale differences in conditions at breeding grounds or along migratory stopover sites, or differential responses to shared conditions, may be influencing their arrival timing on their wintering grounds.

Technical considerations

Data characteristics

The data for this analysis consist of banding records of individual birds captured and marked as part of a constant-effort mist-netting program at the Palomarin Field Station (Ralph et al., 1993; Point Blue, 2016). Although mist-netting was initiated in 1966, the period of analyses was restricted to 1979, when constant-effort mist netting became fully standardized, through fall 2015. Fall 2013 was excluded due to a 15-day October hiatus in banding operations resulting from the federal government shutdown. This provides a 37-year dataset for spring arrivals and 36 years for fall arrivals.

The dataset was restricted to the first capture of each individual in each season. In spring, newly fledged birds were excluded from the analysis, thus all individuals analyzed were approximately 1 year or older; in the fall, all age classes were included, including immature birds that fledged earlier in the year (during the breeding season immediately preceding fall arrival).

The species selected for this analysis were chosen for their migratory status and high capture rates. These species differed somewhat from the previous iteration of this report (OEHHA, 2009), by including analyses of three species not previously reported, namely Hermit Thrush, Golden-crowned Sparrow and Orange-crowned Warbler, and the removal of three species due to modest sample sizes: Black-headed Grosbeak, Warbling Vireo, and Yellow Warbler.

The distribution of first capture dates for each species was assessed to determine species-specific “arrival windows.” The beginning of the arrival window was determined by the first captures; the end of the arrival period was determined by the date at which first captures had declined to relatively low “baseline” levels (see Nur et al., 2017 for details). Any further captures after the arrival window’s end-date were determined to be individuals that likely had been present in the study area but had avoided capture until then. Thus, the arrival window encompassed the first wave of captures during the season in its entirety.

Arrival window dates are as follows:

- Swainson’s Thrush: 6 April – 8 June
- Wilson’s Warbler: 12 March – 29 May
- Orange-crowned Warbler: 20 February – 19 May
- Ruby-crowned Kinglet: 8 September – 15 November
- Hermit Thrush: 13 September – 15 December
- Fox Sparrow: 29 August – 5 November
- Golden-crowned Sparrow: 6 September – 30 November

Of these species, two occur in the region in small numbers year-round. In addition to the overwintering population in this study, a small number of Hermit Thrushes also breed in the region and migrate south in the fall (Phillips, 1991); however, the small number of post-breeding individuals from this population that were captured in early fall did not overlap in time with the window for arrivals from the north. Similarly, in addition to the breeding population of Orange-crowned Warblers studied here, a relatively small number of individuals winter in the region; again, the capture window allowed those few breeding individuals to be excluded from this study.

None of the species in this study are passage migrants at the Palomarin Field Station; rather, Palomarin is the final stopping location (either for breeding or wintering) for all

7 species. In addition, the arrival window was set to exclude individuals that may have been present at the location for some period of time in order to better identify the timing of the wave of migrants as they first arrive on their wintering or breeding grounds.

The 25th percentile of capture dates during the arrival window was used to track the initial wave of arrival of migrants. Linear models were then fit to the capture dates for each species to analyzing a linear-only trend (reported in Figures 1 and 3). To better analyze changes in trend, quadratic models were also fit to the same data (depicted as blue lines in Figures 1 and 3). Details on data processing and analysis are provided in the companion Technical Report (Nur et al., 2017).

One concern was that a change in population size could result in fewer captures which could affect measures of arrival date. Reduced sample size will bias the metric of the very earliest arrival date (Miller-Rushing et al., 2008). In order to provide a more robust metric, not biased by sample size, the 25th percentile value was used, though other quantiles could have been used, e.g., the median.

Strengths and limitations of the data

These data provide a long-term record of bird migration phenology. There were sufficient data to analyze these seven migrant songbirds, including both fall and spring migrants; species included came from four taxonomic families, thus providing taxonomic breadth. The time series is extensive for biological monitoring: 37 years as of 2015.

Monitoring efforts have been strictly standardized since 1979. In general, sampling efforts and net hours per season (where each “net hour” equals a single net open for one hour) have remained relatively stable during the period included in these analyses. Frequency of mist netting was generally three days per week (April through Thanksgiving) or 6 days per week (May through Thanksgiving), weather permitting; one significant change in effort was a switch from banding 6 days/week to 3 days/week in the month of April starting in 1989. This change, as well as the generally small variation in effort in other months due to weather and other variables, was addressed by standardizing the analysis with regard to bird captures per 1000 net hours (a full banding day at Palomarin results in 120 net hours) and pooling captures into 5-day periods.

The 2013 *Indicators of Climate Change in California* Report provided results for four of the seven species analyzed here, using the long-term mist-netting data from the Palomarin Field Station. For one of the species, Swainson’s Thrush, previous results are very similar to what is presented here. However, for the other three species (Wilson’s Warbler, Ruby-crowned Kinglet, and Fox Sparrow) there were noticeable differences in trend. The principal reason for the differences was that the earlier analysis used 1971-1978 (which, as noted earlier, were excluded here because mist-netting was not fully standardized until 1979), while the current analysis included the years 2006-2015. These more recent years made a substantial difference in characterizing the trend. The bottom line is that most species analyzed demonstrate both year-to-year variability and a trend over time that is not constant over the entire time series and, therefore, two different time intervals can produce two different trend values.

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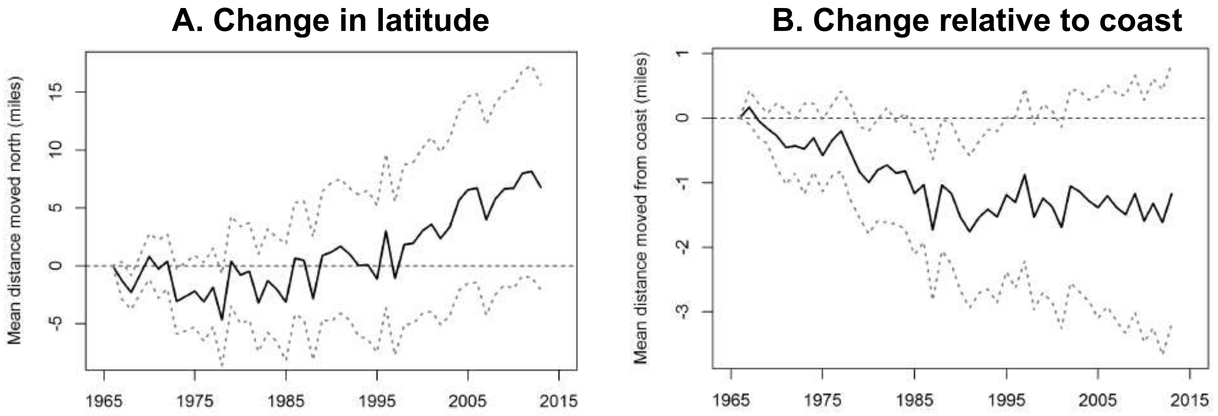
BIRD WINTERING RANGES (NO UPDATE)

Over the past 48 years, wintering bird species have collectively shifted their range northward and closer to the coast in California.

Figure 1. Changes in wintering bird center of abundance in California (1966-2013)



Source: Michel et al., 2017

Note: The dashed lines show the likely range of each year's values based on the number of observations and the precision of the methods used.

What does the indicator show?

This indicator examines changes in the ranges of 234 migratory and resident wintering California bird species between 1966 and 2013 and shows, in aggregate, a shift northward. Data for this indicator are the California subset of observations from the Christmas Bird Count (CBC), managed by the National Audubon Society. The CBC consists of observations recorded from December 14 to January 5 each year by over 50,000 volunteers across the Western Hemisphere, following a specified methodology. It is the longest-running census of birds that relies on public participation and collaboration (often referred to as "citizen science").

The graphs show the position of the center of abundance (the center of the population distribution) for each year relative to the winter of 1965-1966, averaged across the species for latitude (Figure 1A) and for distance from the coast (Figure 1B). An overall northward movement of about seven miles was observed between 1966 and 2013, as birds moved a farther distance north than south (Figure 1A). Over the same time period, a shift of approximately 1 mile toward the coast occurred (Figure 1B).

The center of abundance is a common way to characterize the general location of a population. In terms of latitude, half of the individuals in the population live north of the center of abundance and the other half live to the south. Similarly, in terms of distance to coast, half of the individuals live closer to the coast than the center of abundance, and the other half live further from the coast.

Why is this indicator important?

Monitoring changes in the geographic distribution of birds provides scientists with a way to track which birds may be responding to a changing climate — one of many factors that are threatening bird populations. A better understanding of these responses will help inform conservation strategies. As the climate continues to change, its pace may exceed many bird species' capacities to migrate to more favorable habitats (La Sorte and Jetz, 2012). The predicted increase in extreme weather events, such as severe storms, might also impact the ability of birds to make these range shifts. Birds that cannot adapt to changing conditions could experience a population decline as a result.

Birds are a particularly good indicator of environmental change for several reasons:

- Each species of bird has adapted or evolved to favor certain habitat types, food sources, and temperature ranges. In addition, the timing of certain events in their life cycles — such as migration and reproduction — is driven by cues from the environment. For example, many North American breeding birds follow a regular seasonal migration pattern; moving north to feed and breed in the summer, then moving south to spend the winter in warmer areas. Changing conditions can influence the distribution of both migratory and non-migratory birds as well as the timing of important life cycle events (La Sorte and Thompson, 2007).
  Birds are relatively easy to identify and count, and thus there is a wealth of scientific knowledge about their distribution and abundance. People have kept detailed records of bird observations for more than a century.

- There are many different species of birds living in a variety of habitats, including water birds, coastal birds, and land birds. If a change in behavior or range occurs across a range of bird types, it suggests that a common external factor might be the cause.

When bird wintering ranges shift, human and ecological communities lose not just the birds themselves, but also the valuable functions and services they provide. For example, western bluebirds eat insects that damage crops, nectar-eating birds like hummingbirds pollinate flowers, and birds like woodpeckers build roosting cavities in trees that other bird and mammal species use (Kearns et al., 1998; Sekercioglu, 2006; Jedlicka et al., 2011). The movement of a species to places where it was not previously present, or where it was present in lower numbers, may also disrupt complex ecosystem interactions. For example, a newcomer species may compete for food or other resources with species that already inhabit the area (Kearns and Inouye, 1997).

What factors influence this indicator?

In the Northern Hemisphere, a changing climate has been associated with shifts in the habitat ranges of certain animals toward more northern latitudes and higher elevations (Field et al., 2014; Ralston et al., 2016; Moritz et al., 2008). Warming temperatures may cause species to expand their wintering ranges further north into regions that were, until recently, too cold to support populations, and away from regions that are now too hot.

A continental-scale analysis of 305 bird species found that their wintering ranges moved approximately 40 miles north between 1966 and 2013, and that this change was related to warming winter temperatures (National Audubon Society, 2009; USEPA, 2013). The movement of species toward the coast in California is the opposite of both what was expected and what was observed in the continental-scale study. The latter analysis found that bird wintering ranges moved about 13 miles away from the coast — a shift associated with a warming climate and a decrease of extreme cold inland. In California, in contrast, birds moved closer to the coast as temperatures increased. The California trend may be the result of the combined influence of climate and topography. Inland areas of the state, already drier compared to the coast, are further drying due to warming temperatures, causing birds to move towards the coast to seek wetter conditions.

Both the continental and the California analysis found no significant longitudinal movement. This is not surprising given that there are no clear longitudinal gradients in temperature or precipitation, which instead vary in response to topographical features (e.g., elevation or location relative to mountain ranges).

Latitudinal range movement varied among the California species: 87 species (37 percent) moved northward, 74 species (32 percent) moved southward, and 73 (31 percent) showed no significant change. Some bird species moved farther than others. Snow goose showed the greatest northward shift of 326 miles, while Ross' goose showed the greatest southward shift of 242 miles. Similarly, distance shifted relative to the coast ranged from 84 miles towards the coast by Canada goose to 60 miles inland by Barrow's goldeneye. Eighty-six species (37 percent) moved towards the coast, while 86 other species moved inland and 62 (26 percent) showed no significant change. While equal numbers of species moved inland and towards the coast, the range shifts towards the coast involved greater distances than inland, resulting in an overall shift toward the coast. These differences in range shifts are not surprising. Species have been found to respond to environmental change in a highly variable and idiosyncratic fashion, reflecting the complex interplay between land cover, climate, species interactions, and other factors.

Many factors can influence bird ranges, including food availability, habitat alteration, and interactions with other species, and these factors may also be influenced by climate change. Some of the birds covered in this indicator might have moved northward or inland for reasons other than changing temperatures. Responses to climate change may also vary among different types of birds. However, within California, there were no differences in average movements north or towards the coast between birds differing in habitat use, diet, body size, life expectancy, clutch size, age at sexual maturity, or urban affiliation. Though moderate- and short-distance migrants moved slightly further north than year-round residents, migratory status did not influence movement towards the coast.

Technical considerations

Data characteristics

This indicator is based on data collected by the annual Christmas Bird Count (CBC), managed by the National Audubon Society. Data are collected in a citizen science activity by volunteer birdwatchers who systematically survey certain areas and identify and count all bird species they encounter within a specified area. Bird surveys take place each year in approximately 2,000 different locations throughout the contiguous 48 states and the southern portions of Alaska and Canada. This indicator used only data from CBC circles within the state of California. All local counts take place between December 14 and January 5 of each winter. Each local count takes place over a 24-hour period in a defined “count circle” that is 15 miles in diameter. A variable number of volunteer observers separate into field parties which survey different areas of the count circle and tally the total number of individuals of each species observed (National Audubon Society, 2009).

CBC data starting in 1966 are used, as data prior to 1966 lack sufficient quality and quantity for a North American-scaled analysis. At the end of the 24-hour observation period, each count circle tallies the total number of individuals of each species seen in the count circle. Audubon scientists then run the data through several levels of analysis and quality control to determine final count numbers from each circle and each region. Data processing steps include corrections for different levels of sampling effort — for example, if some count circles had more observers and more person-hours of effort than others. Population trends over the 48-year period of this indicator and annual indices of abundance were estimated for the entire survey area with hierarchical models in a Bayesian analysis using Markov chain Monte Carlo techniques (Soykan et al., 2016).

This indicator covers 234 bird species, listed in Table 1 (Appendix). These species were included because they are widespread, occur within California, and meet specific criteria for data availability. Information on study methods is available on the National Audubon Society website at: http://web4.audubon.org/bird/bacc/techreport.html and in Soykan et al. (2016). Methods are largely based on those used for an earlier analysis, which is documented in the National Audubon Society (2009) report: *Northward Shifts in the Abundance of North American Birds in Early Winter: A Response to Warmer Winter Temperatures?.* For additional information on CBC survey design and methods, see Soykan et al. (2016) and the reports classified as “Methods” in the list at: http://www.audubon.org/conservation/christmas-bird-count-bibliography.

Strengths and limitations of the data

Although the indicator relies on human observation rather than precise measuring instruments, the people who collect the data are skilled observers who follow strict protocols that are consistent across time and space. These data have supported many peer-reviewed studies, a list of which can be found on the National Audubon Society’s website at http://www.audubon.org/christmas-bird-count-bibliography.

Uneven effort between count circles, such as inconsistent level of effort by volunteer observers, could lead to data variations. However, these differences are carefully corrected in Audubon’s statistical analysis (Soykan et al., 2016). Rare or difficult-toobserve bird species could lead to increased variability. Gregarious species (i.e., species that tend to gather in large groups) can also be difficult to count, and they could be either overcounted or undercounted, depending on group size and the visibility of their roosts. These species tend to congregate in known and expected locations along CBC routes, however, so observers virtually always know to check these spots. Locations with large roosts are often assigned to observers with specific experience in estimating large numbers of birds. For this analysis, the National Audubon Society included only 234 widespread bird species that met criteria for abundance and the availability of data to enable the detection of meaningful trends.

The tendency for saltwater-dependent species to stay near coastlines could impact the change in distance to coast calculation for species living near the Pacific Ocean. By integrating these species into the distance to coast calculation, Figure 2 may understate the total extent of coastward or inland movement of species.

This indicator is based solely on shifts in the center of abundance of birds observed within the state of California. As a result, it represents only a small portion of the wintering range of many species, and may either overestimate or underestimate distances moved across the species' entire wintering ranges.

Figures 1 and 2 show average distances moved north and towards the coast, based on an unweighted average of all species. Thus, no adjustments are made for population differences across species. No attempt was made to estimate trends prior to 1966 (i.e., prior to the availability of complete spatial coverage and standardized methods), and no attempt was made to project trends into the future. The entire study description, including analyses performed, can be found in National Audubon Society (2009), Soykan et al. (2016), and references therein. Information on this study is also available on the National Audubon Society website at: http://web4.audubon.org/bird/bacc/techreport.html.

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APPENDIX

Table 1. Bird species included in the California wintering bird range shift climate change indicator analysis.

Common name	Scientific name
Acorn Woodpecker	*Melanerpes formicivorus*
American Avocet	*Recurvirostra americana*
American Bittern	*Botaurus lentiginosus*
American Coot	*Fulica americana*
American Crow	*Corvus brachyrhynchos*
American Dipper	*Cinclus mexicanus*
American Goldfinch	*Spinus tristis*
American Kestrel	*Falco sparverius*
American Pipit	*Anthus rubescens*
American Robin	*Turdus migratorius*
American Wigeon	*Anas americana*
Anna's Hummingbird	*Calypte anna*
Arctic and Pacific Loon[¶]	*Gavia arctica and G. pacifica*
American Tree Sparrow	*Spizelloides arborea*
American White Pelican	*Pelecanus erythrorhynchos*
Bald Eagle	*Haliaeetus leucocephalus*
Baltimore Oriole	*Icterus galbula*
Band-tailed Pigeon	*Patagioenas fasciata*
Barrow's Goldeneye	*Bucephala islandica*
Barn Owl	*Tyto alba*
Bell's and Sagebrush Sparrow[††]	*Amphispiza belli and A. nevadensis*
Belted Kingfisher	*Megaceryle alcyon*
Bewick's Wren	*Thryomanes bewickii*
Black-and-white Warbler	*Mniotilta varia*
Black-bellied Plover	*Pluvialis squatarola*
Black-billed Magpie	*Pica hudsonia*
Black-capped Chickadee	*Poecile atricapillus*
Black-crowned Night-Heron	*Nycticorax*
Blue-gray Gnatcatcher	*Polioptila caerulea*
Blue-headed, Cassin's, and Plumbeous Vireo[‡‡‡]	*Vireo solitarius, V. cassini, and V. plumbeus*
Blue-winged Teal	*Anas discors*
Brown-headed Cowbird	*Molothrus ater*
Black Brant	*Branta b. nigricans*
Black Phoebe	*Sayornis nigricans*
Black Rail	*Laterallus jamaicensis*
Black Scoter	*Melanitta americana*
Black Turnstone	*Arenaria melanocephala*
Black-necked Stilt	*Himantopus mexicanus*
Bonaparte's Gull	*Chroicocephalus philadelphia*
Brewer's Blackbird	*Euphagus cyanocephalus*

Common name	Scientific name
Brown Creeper	*Certhia americana*
Bufflehead	*Bucephala albeola*
Burrowing Owl	*Athene cunicularia*
Bushtit	*Psaltriparus minimus*
Cackling and Canada Goose	*Branta hutchinsii and B. canadensis*
Cactus Wren	*Campylorhynchus brunneicapillus*
California and Canyon/Brown Towhee[#]	*Melozone crissalis and M. fuscus*
California Gull	*Larus californicus*
California Quail	*Callipepla californica*
Canvasback	*Aythya valisineria*
Canyon Wren	*Catherpes mexicanus*
Caspian Tern	*Hydroprogne caspia*
Cassin's Finch	*Haemorhous cassinii*
Cattle Egret	*Bubulcus ibis*
Cedar Waxwing	*Bombycilla cedrorum*
Chestnut-backed Chickadee	*Poecile rufescens*
Chipping Sparrow	*Spizella passerina*
Chukar	*Alectoris chukar*
Cinnamon Teal	*Anas cyanoptera*
Clapper Rail	*Rallus crepitans*
Clark's Nutcracker	*Nucifraga columbiana*
Clark's and Western Grebe[§§§]	*Aechmophorus clarkii and A. occidentalis*
Common Goldeneye	*Bucephala clangula*
Common Ground-Dove	*Columbina passerina*
Common Loon	*Gavia immer*
Common Merganser	*Mergus merganser*
Common Moorhen	*Gallinula galeata*
Common Murre	*Uria aalge*
Common Raven	*Corvus corax*
Common Yellowthroat	*Geothlypis trichas*
Cooper's Hawk	*Accipiter cooperii*
Dark-eyed Junco	*Junco h. hyemalis*
Double-crested Cormorant	*Phalacrocorax auritus*
Downy Woodpecker	*Picoides pubescens*
Dunlin	*Calidris alpina*
Eared Grebe	*Podiceps nigricollis*
Eastern and Spotted Towhee[‡‡]	*Pipilo erythrophthalmus and P. maculatus*
Eastern and Western Screech-Owl[¶¶¶]	*Megascops asio and M. kennicottii*
European Starling	*Sturnus vulgaris*
Evening Grosbeak	*Coccothraustes vespertinus*
Ferruginous Hawk	*Buteo regalis*
Forster's Tern	*Sterna forsteri*
Fox Sparrow	*Passerella iliaca*
Gadwall	*Anas strepera*
Gambel's Quail	*Callipepla gambelii*

Common name	Scientific name
Glaucous Gull	*Larus hyperboreus*
Glaucous-winged Gull	*Larus glaucescens*
Golden Eagle	*Aquila chrysaetos*
Golden-crowned Kinglet	*Regulus satrapa*
Golden-crowned Sparrow	*Zonotrichia atricapilla*
Gray Jay	*Perisoreus canadensis*
Great Blue Heron	*Ardea herodias*
Great Egret	*Ardea alba*
Great Horned Owl	*Bubo virginianus*
Greater Roadrunner	*Geococcyx californianus*
Greater Scaup	*Aythya marila*
Greater White-fronted Goose	*Anser albifrons*
Greater Yellowlegs	*Tringa melanoleuca*
Green Heron	*Butorides virescens*
Green-tailed Towhee	*Pipilo chlorurus*
Green-winged Teal	*Anas crecca*
Hairy Woodpecker	*Picoides villosus*
Harlequin Duck	*Histrionicus histrionicus*
Harris's Sparrow	*Zonotrichia querula*
Hermit Thrush	*Catharus guttatus*
Herring Gull	*Larus argentatus*
Hooded Merganser	*Lophodytes cucullatus*
Horned Grebe	*Podiceps auritus*
Horned Lark	*Eremophila alpestris*
House Finch	*Haemorhous mexicanus*
House Sparrow	*Passer domesticus*
House Wren	*Troglodytes aedon*
Hutton's Vireo	*Vireo huttoni*
Iceland and Thayer's Gull §	*Larus glaucoides and L. thayeri*
Inca Dove	*Columbina inca*
Juniper and Oak Titmouse##	*Baeolophus ridgwayi and B. inornatus*
Killdeer	*Charadrius vociferus*
Ladder-backed Woodpecker	*Picoides scalaris*
Lapland Longspur	*Calcarius lapponicus*
Lark Sparrow	*Chondestes grammacus*
Least Bittern	*Ixobrychus exilis*
Least Sandpiper	*Calidris minutilla*
Lesser Goldfinch	*Spinus psaltria*
Lesser Scaup	*Aythya affinis*
Lesser Yellowlegs	*Tringa flavipes*
Lewis's Woodpecker	*Melanerpes lewis*
Lincoln's Sparrow	*Melospiza lincolnii*
Little Blue Heron	*Egretta caerulea*
Loggerhead Shrike	*Lanius ludovicianus*
Long-billed Dowitcher	*Limnodromus scolopaceus*

Common name	Scientific name
Long-eared Owl	*Asio otus*
Long-tailed Duck	*Clangula hyemalis*
Marbled Godwit	*Limosa fedoa*
Marbled Murrelet	*Brachyramphus marmoratus*
Marsh Wren	*Cistothorus palustris*
Merlin	*Falco columbarius*
Mew Gull	*Larus canus*
Mountain Bluebird	*Sialia currucoides*
Mountain Chickadee	*Poecile gambeli*
Mourning Dove	*Zenaida macroura*
Nashville Warbler	*Oreothlypis ruficapilla*
Northern Cardinal	*Cardinalis cardinalis*
Northern Goshawk	*Accipiter gentilis*
Northern Harrier	*Circus cyaneus*
Northern Flicker	*Colaptes a. cafer*
Northern Mockingbird	*Mimus polyglottos*
Northern Pintail	*Anas acuta*
Northern Pygmy-Owl	*Glaucidium gnoma*
Northern Saw-whet Owl	*Aegolius acadicus*
Northern Shoveler	*Anas clypeata*
Northern Shrike	*Lanius excubitor*
Orange-crowned Warbler	*Oreothlypis celata*
Osprey	*Pandion haliaetus*
Palm Warbler	*Setophaga palmarum*
Pelagic Cormorant	*Phalacrocorax pelagicus*
Peregrine Falcon	*Falco peregrinus*
Pied-billed Grebe	*Podilymbus podiceps*
Pileated Woodpecker	*Dryocopus pileatus*
Pine Siskin	*Spinus pinus*
Pinyon Jay	*Gymnorhinus cyanocephalus*
Prairie Falcon	*Falco mexicanus*
Purple Finch	*Haemorhous purpureus*
Pygmy Nuthatch	*Sitta pygmaea*
Red Crossbill	*Loxia curvirostra*
Redhead	*Aythya americana*
Red Knot	*Calidris canutus*
Red-breasted Merganser	*Mergus serrator*
Red-breasted Nuthatch	*Sitta canadensis*
Red-necked Grebe	*Podiceps grisegena*
Red-shouldered Hawk	*Buteo lineatus*
Red-winged Blackbird	*Agelaius phoeniceus*
Ring-billed Gull	*Larus delawarensis*
Ring-necked Duck	*Aythya collaris*
Ring-necked Pheasant	*Phasianus colchicus*
Rock Sandpiper	*Calidris ptilocnemis*

Common name	Scientific name
Rock Wren	*Salpinctes obsoletus*
Ross's Goose	*Chen rossii*
Rough-legged Hawk	*Buteo lagopus*
Royal Tern	*Thalasseus maximus*
Ruby-crowned Kinglet	*Regulus calendula*
Ruddy Turnstone	*Arenaria interpres*
Rufous-crowned Sparrow	*Aimophila ruficeps*
Sanderling	*Calidris alba*
Sandhill Crane	*Antigone canadensis*
Savannah Sparrow	*Passerculus sandwichensis*
Say's Phoebe	*Sayornis saya*
Semipalmated Plover	*Charadrius semipalmatus*
Sharp-shinned Hawk	*Accipiter striatus*
Short-billed Dowitcher	*Limnodromus griseus*
Short-eared Owl	*Asio flammeus*
Snow Goose	*Chen caerulescens*
Snowy Egret	*Egretta thula*
Snowy Plover	*Charadrius nivosus*
Song Sparrow	*Melospiza melodia*
Sora	*Porzana carolina*
Spotted Sandpiper	*Actitis macularius*
Steller's Jay	*Cyanocitta stelleri*
Surfbird	*Calidris virgata*
Surf Scoter	*Melanitta perspicillata*
Swamp Sparrow	*Melospiza georgiana*
Townsend's Solitaire	*Myadestes townsendi*
Townsend's Warbler	*Setophaga townsendi*
Tree Swallow	*Tachycineta bicolor*
Tricolored Heron	*Egretta tricolor*
Tundra Swan	*Cygnus columbianus*
Turkey Vulture	*Cathartes aura*
Varied Thrush	*Ixoreus naevius*
Verdin	*Auriparus flaviceps*
Vermilion Flycatcher	*Pyrocephalus rubinus*
Vesper Sparrow	*Pooecetes gramineus*
Virginia Rail	*Rallus limicola*
Western Bluebird	*Sialia mexicana*
Western Meadowlark	*Sturnella neglecta*
Western Scrub-Jay	*Aphelocoma californica*
Whimbrel	*Numenius phaeopus*
White-breasted Nuthatch	*Sitta carolinensis*
White-crowned Sparrow	*Zonotrichia leucophrys*
White-tailed Kite	*Elanus leucurus*
White-throated Sparrow	*Zonotrichia albicollis*
White-winged Dove	*Zenaida asiatica*

Common name	Scientific name
White-winged Scoter	*Melanitta fusca*
Wild Turkey	*Meleagris gallopavo*
Willet	*Tringa semipalmata*
Williamson's Sapsucker	*Sphyrapicus thyroideus*
Wilson's Snipe	*Gallinago delicata*
Wilson's Warbler	*Cardellina pusilla*
Winter Wren	*Troglodytes hiemalis*
Wood Duck	*Aix sponsa*
Yellow-bellied Sapsucker	*Sphyrapicus varius*
Yellow-headed Blackbird	*Xanthocephalus xanthocephalus*
Yellow-rumped Warbler	*Setophaga coronata*

Notes:

Since the Cackling and Canada Goose (*Branta hutchinsii* and *B. canadensis*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

§ Since the Iceland and Thayer's Gull (*Larus glaucoides and L. thayeri*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

¶ Since the Arctic and Pacific Loon (*Gavia arctica* and *G. pacifica*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

Since the California and Canyon/Brown Towhee (*Melozone crissalis* and *M. fuscus*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

‡‡ Since the Eastern and Spotted Towhee (*Pipilo erythrophthalmus* and *P. maculatus*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

†† Since the Bell’s and Sagebrush Sparrow (*Amphispiza belli* and *A. nevadensis*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

Since the Juniper and Oak Titmouse (*Baeolophus ridgwayi* and *B. inornatus*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

‡‡‡ Since the Blue-headed, Cassin's, and Plumbeous Vireo (*Vireo solitarius*, *V. cassini*, and *V. plumbeus*) were not distinguished in CBC counts until after 1966, the three species were lumped for trend analyses.

§§§ Since the Clark's and Western Grebe (*Aechmophorus clarkii* and *A. occidentalis*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

¶¶¶ Since the Eastern and Western Screech-Owl (*Megascops asio* and *M. kennicottii*) were not distinguished in CBC counts until after 1966, the two species were lumped for trend analyses.

SMALL MAMMAL AND AVIAN RANGE SHIFTS

Certain birds and mammals are found at different elevations in the Sierra Nevada Mountains today compared to a century earlier. Almost 75 percent of the small mammal species and over 80 percent of the bird species surveyed in this region have shifted ranges. While high-elevation mammals tended to shift their range upslope, birds and low-elevation mammals shifted downslope as frequently as upslope. Range responses of both taxa differed across montane portions of California. In the Mojave Desert, which has become warmer and drier over the past century, widespread collapse of bird communities has occurred, while populations of small mammals remained stable.

Update to 2018 Report

Modern resurveys of sites originally visited in the early 20th century by Joseph Grinnell and colleagues examined changes in bird and mammal communities in California's deserts. Desert conditions, already defined by extremes in temperature and precipitation, test the physiological limits of many species. Warming and drying associated with climate change threaten desert species through the direct impacts of heat and water stress, as well as through indirect impacts on their habitat and food sources (Iknayan and Beissinger, 2018).

At resurvey sites which have become warmer and drier over the past century in the Mojave Desert, birds and mammals have shown divergent responses (Riddell et al., 2021; Iknayan and Beissinger, 2018). Small mammal communities have remained stable while bird communities have collapsed. The ability of small mammals to seek cooler microhabitats (such as underground burrows) reduced their exposures to high temperatures, allowing them to persist. Reduced precipitation drove community collapse in birds (such as prairie falcons, turkey vultures, northern mockingbirds, chipping sparrow and mourning dove), particularly at sites that both warmed and dried (Iknayan and Beissinger, 2018). The increased water required for cooling body temperature in hotter, drier conditions was an important underlying mechanism in the decline in bird populations (Riddell et al., 2019). Larger species and those with animal based diets that obtain water primarily from their food were especially vulnerable; examples are the large carnivores prairie falcon and turkey vulture, and the smaller insectivores canyon wren and hermit thrush.

The warm, dry Mojave Desert lies south of the cooler and wetter Great Basin Desert, where 45 historic sites visited by Grinnell were also resurveyed. The deserts share a winding east-west boundary stretching about 450 kilometers (280 miles) from southern California across Nevada to Utah. A transition area separates the distinct bird communities within each desert. Both deserts have warmed substantially over the past century; however, the Mojave has become drier while the Great Basin has become wetter. As with the Mojave Desert, reduced occupancy was observed in the resurveyed Great Basin sites. Bird species that tolerate warmer, drier conditions became more dominant in both deserts over the past century; however, community composition remained significantly different between deserts. Significant range shifts occurred in 60 percent of the species studied in both deserts, however only contractions of southern limits or no change were observed among Mojave species. The transition area served as a barrier to range expansion of species from the Mojave into the Great Basin (Iknayan and Beisinger, 2019)

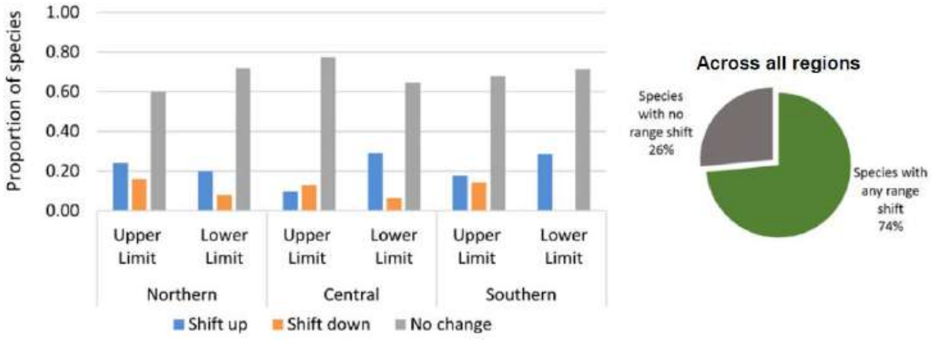
Observations from the Grinnell survey also provided the basis for comparing contemporary and early 20th century bird distributions in California's Central Valley (MacLean et al., 2018). While metrics tracking community-level changes – that is, mean occupancy, species richness, and similarity in species composition between sites – remained stable over the past century, species-level changes in occupancy varied. Of the 122 bird species studied, 60 showed no significant change, 27 significantly decreased, and 35 significantly increased. Declines were more common among species with specialized habitat preferences, while increases occurred among habitat generalists and those that utilized human-modified habitats. Bird distributions were found to be most strongly affected by water availability, thus indicating both climate (precipitation) and land use (percent water cover) as drivers.

The sections below are unchanged from the 2018 report.

Figure 1. Shifts in elevational range limits over the past century for three regions in the Sierra Nevada: Northern (Lassen), Central (Yosemite) and Southern (Sequoia/Kings Canyon)

Bars show the proportion of species that have shifted their upper or lower elevational limits to higher ("shift up") or lower ("shift down") elevations, or that have shown no elevational change ("no change") over the past century. Pie charts show the percentages of species that shifted in any direction in any region (green) and that did not shift at all (gray). See Figure 3 for map showing the study regions, and appendix for graphs showing species-specific elevational changes.

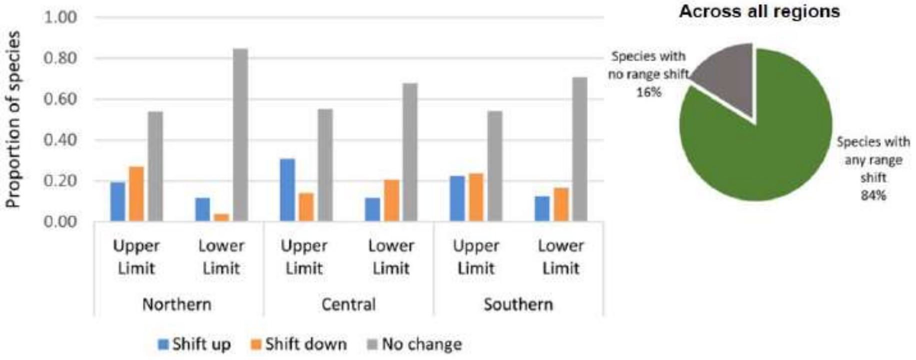
A. Small mammal range shifts



Based on data from: Rowe et al., 2015 (mammals);
Tingley et al., 2012 (birds)

Figure 1, continued.

B. Bird range shifts



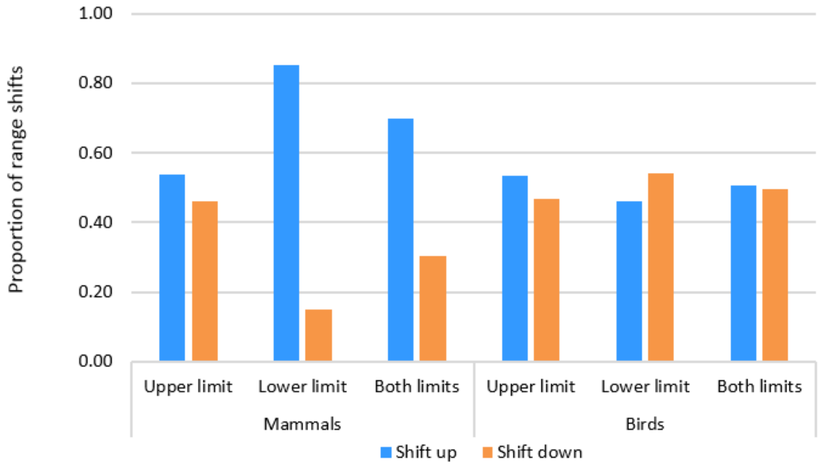
Based on data from: Rowe et al., 2015 (mammals); Tingley et al., 2012 (birds)

What does the indicator show?

Significant changes have occurred in the elevational range of small mammals (Figure 1A) and birds (Figure 1B) in three study regions in the Sierra Nevada: the northern (Lassen), central (Yosemite) and southern (Sequoia and King's Canyon) regions (see map, Figure 2). The shifts reflect changes that have occurred since a survey conducted by Joseph Grinnell and a team of scientists in the early 20th century. Current ranges are based on resurveys of the same field sites conducted between 2003 and 2010. (See *Technical Considerations* for more information.)

Of the 34 mammalian species surveyed, 25 were found to have shifted their elevational ranges in at least one region (Figure 1A). A shift involves a contraction or expansion of the upper and/or lower limits of a species' elevational range. About two-thirds of the species ranges across the three regions remained unchanged at either or both the upper and lower elevational limits. Of the 22 species found in the three regions, none shifted both their upper and lower limits consistently in the same direction in all the regions (see Appendix, Figure A1). Across the three regions, elevational limits were more than twice as likely to have moved upslope as downslope (Figure 2). High-elevation

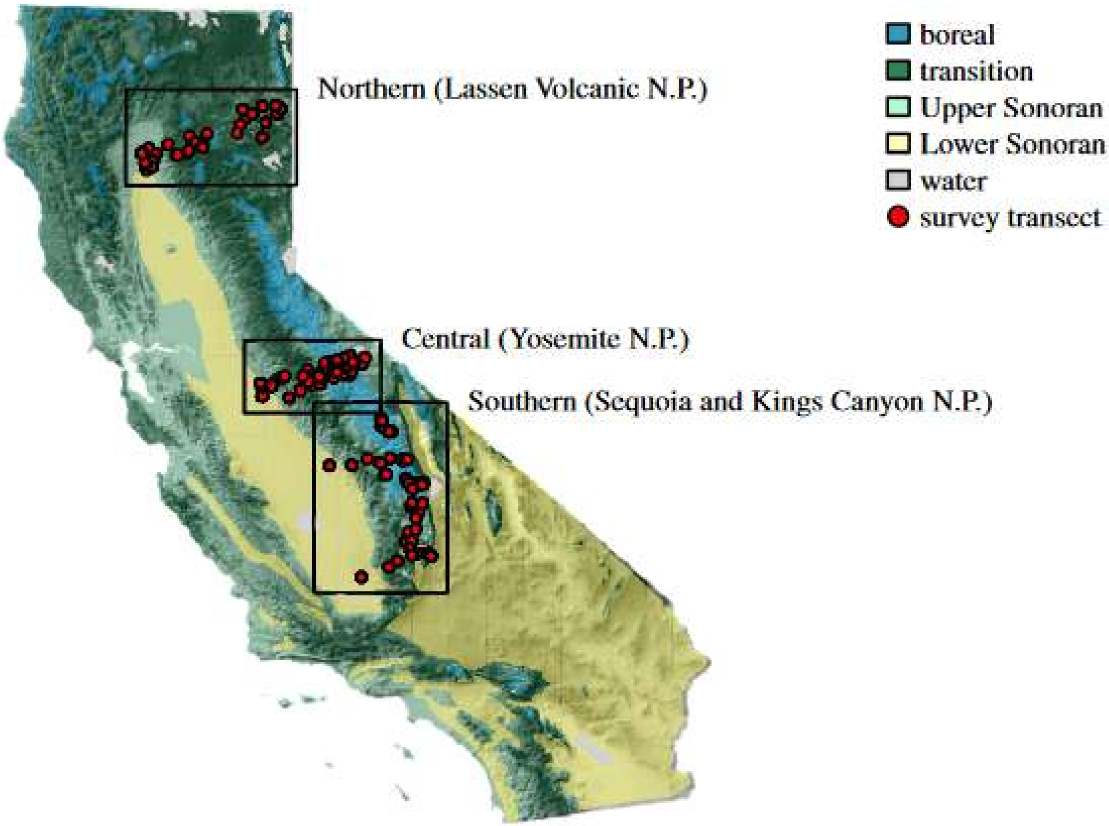
Figure 2. Proportion of range shifts across regions



Based on data from: Rowe et al., 2015 (mammals); Tingley et al, 2012 (birds) species were more likely to contract their ranges (typically as a result of an upslope shift of their lower limits) than to expand them, whereas low-elevation species were just as likely to have contracted their limits as expanded them (Rowe et al., 2015).

Shifts in elevation among birds were more frequent than among mammals; 84 percent of bird species shifted their elevational distribution (Figure 1B). Upslope shifts occurred in 46 percent of lower elevation limits (resulting in range contraction), and 53 percent of upper limits (resulting in range expansion) (Figure 2). Downward shifts were as common as upward shifts (Tingley et al., 2012).

Figure 3. Location of Sierra Nevada survey transects



Source: Rowe et al., 2015

Why is this indicator important?

Animals reproduce, grow and survive within specific ranges of climatic and environmental conditions. Species may respond to changes in these conditions by, among other things, a shift in range boundaries. Globally, broad patterns of species shifts in response to warming temperatures have occurred over historical time scales ranging from years to millennia. Models project with high confidence that species movement will be a common phenomenon with continued warming (Settele et al., 2014).

Species respond uniquely to climatic and other environmental changes. This indicator shows both upslope and downslope shifts in elevation for small mammals and birds, demonstrating the idiosyncratic nature of species' responses to climate change. Range shifts can change community composition as the abundance of some species decreases or increases (Settele et al., 2014). Changes in species occurrence can lead to competitive displacement, intensification of predation or new predator-prey interactions and ultimately a decline in biodiversity (Blios et al., 2013). In general, climate change should favor species that are better able to tolerate warmer and more variable climatic conditions.

Certain species may not be able to shift their ranges fast enough to migrate to suitable environments, particularly where has been loss or fragmentation of habitat or barriers to species movement (see *What factors influence this indicator?* below). Declines in population abundance can result. In extreme cases, extirpation (eradication) or extinction of species may occur (Settele et al., 2014). For example, the American pika, a small mammal adapted to high altitudes and cold temperatures, has disappeared from a 64-square-mile span of habitat from Mount Shasta to the southern Sierra Nevada (Stewart et al., 2015). Resurveys of historical pika locations over six years found they no longer occurred at 10 of 67 (15 percent) historical sites. The authors suggested that pikas have experienced climate-mediated range contraction over the past century tied to increasing summer temperatures.

The indicator presented here tracks changes in the elevation at which species are found today, compared to earlier in the century. This information will help in understanding and anticipating the long-term dynamics of the distribution of small mammals and birds in California, and examining the factors that influence them. This knowledge is crucial in efforts to identify which species are resilient or sensitive to climate change and, thus, to guide efforts to maintain species diversity in the face of regional warming. Models project with high confidence that species movement will be a common phenomenon with continued warming. The data from this indicator are useful in research to test the performance of model-based predictions of species' responses to changes in climate and land cover. Such research will improve predictions of future species' responses.

Changes in the composition of ecological communities, such as the loss of species, can change the ways in which ecosystems function (Hooper et al., 2005). Altered biodiversity has led to widespread concern for both economic (e.g., food sources) and non-economic (e.g., ethical, aesthetic) reasons. Wildlife and habitat conservation programs, government agencies and international scientific programs are taking steps to understand and minimize biodiversity loss and species invasions in an effort towards preserving ecosystems. This is important for our national parks, where scientists predict future warming will cause substantial turnover of species (Moritz et al., 2008).

What factors influence this indicator?

Range shifts are in part a response to the stresses of climate change (temperature and precipitation). Both the magnitude and the rate of climate change can impact a species' ability to adapt and survive. Recent research suggests that the picture is complex: temperature, precipitation and habitat may force range shifts in multiple directions and affect upper and lower range limits differently, with the relative contribution of different factors varying by elevation (Santos et al., 2017). The mixed or heterogeneous responses described here may reflect a species' intrinsic sensitivity to temperature, precipitation or other physical factors, as well as altered interactions with biological elements of the community (such as food sources, vegetation, and competitors) — all of which are changing in different ways in the three regions.

Changes in climate over the past century differed among the three study regions (Tingley et al., 2012; Rowe et al., 2015). The Central region reported the greatest and the Northern region the least increase in mean annual temperature. Across all three regions, the maximum temperature of the warmest month was relatively constant, while the minimum temperature of the coldest month increased. The Yosemite Valley record indicates a substantial increase in monthly minimum temperatures of greater than 3 degrees centigrade (°C). This temperature increase is also evident from tree ring data and analyses of vegetation change (Millar et al., 2004), snowmelt data, and retraction of the Mt. Lyell glacier. Precipitation increased most in the Northern region, which also cooled, and also in the Central region, but not in the Southern region. These kinds of spatially variable changes in climate over the past century in California can be seen in other ecosystem indicators, such as actual evapotranspiration and climatic water deficit (Rapacciuolo et al., 2014).

Small mammals may respond differently to changes in minimum and maximum temperatures based on differences in species traits, such as lifespan, dietary breadth, and reproduction habitat (Moritz et al., 2008). Increased temperatures have been identified as a likely cause of the contractions of the high-elevation small mammal species and at least some of the upwards expansions of lower elevation species, although temperature effects on lower elevation species are less predictable. The effect of temperature is especially pronounced at higher elevations where changes in minimum temperature can affect thermoregulatory capacity, hibernation, behavior, and food-web structure (Santos et al., 2017). The average increase in elevation of about 500 meters for affected species in the Yosemite re-survey is consistent with what would be expected with the estimated temperature increase of 3°C, assuming that the species ranges are limited primarily by physiology (Moritz et al., 2008). The mechanisms explaining downslope shifts and the variable responses among related species are not well understood. Other factors also could be at play, including community structure and competitive interactions. The effects of changing precipitation on small mammals are not as clear but include challenges in finding water or cover (e.g., below the snow pack). Changes in moisture can also have metabolic impacts, such as difficulties in thermoregulation through transpiration when relative humidity is high (Santos et al., 2017). Moreover, some species may be able to persist in refugia (that is, areas in which individuals can survive through a period of unfavorable conditions) created by anthropogenic changes to the habitat, such as campgrounds where food and water are available (Morelli et al., 2012 and 2017).

Birds showed more heterogeneous elevational range shifts within species and among the three study regions over the past century (Tingley et al., 2012). In general, birds shifted upslope with increasing temperatures and shifted downslope with increased precipitation. Species-specific factors were also associated with the elevational changes: species were more likely to shift elevational ranges if they had small clutch sizes, defended all-purpose territories (i.e., where courtship, mating nesting, foraging all occur), and were non-migratory. The greatest changes to composition of montane bird communities occurred in the highest and lowest elevations (Tingley and Beissinger, 2013).

Birds have also been shown to respond to warming by breeding earlier to reduce the temperatures to which nests are exposed during breeding and to track shifting peaks in the availability of resources (Socolar et al., 2017). Using data from the Grinnell Resurvey Project, researchers found that breeding dates in the Sierra Nevada and the Coast Range (from the Oregon border to north of San Luis Obispo) shifted 5 to 12 days earlier over the last century. These findings suggest that earlier breeding might reduce both the need and the opportunity to shift geographically.

A group of researchers have studied biogeographic responses in birds, mammals and plants in California along with regional patterns of climate data during the 20th century to better understand species responses to a warming climate (Rapacciuolo et al., 2014). Although the expected response with warming is upward elevational shifts, they describe how downslope shifts are as common as upslope shifts. One common finding (noted above) was contractions of lower limits of high-elevation mammal species occurring primarily in response to warmer temperatures. They suggested that the substantial heterogeneity in response to warming with low elevation species may be due to influences such as interspecific competition and the spread of invasive species. In addition to temperature alone, species responses were also reportedly affected by the shifting seasonal balance of temperature and precipitation (water availability). They found that species-specific sensitivities to local-scale trophic interactions and habitat changes can also influence range shift dynamics, highlighting a need to adopt a more multifaceted and finer-scale understanding of climate change impacts.

The topography of a habitat can play a role in how an animal is impacted by climate change. Topographically complex areas provide potential climate change “refugia” whereas low-relief topography can exacerbate climate change impacts as organisms must travel further to remain in the same climate space (Maher et al., 2017). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (i.e., they can disperse relatively short distances upslope to track favorable environmental conditions). However, species that already occur near mountaintops are among the most threatened by climate change because they cannot move upwards. The consequences of losing favorable climate space are not yet well understood (Settele et al., 2014).

In addition to topographic influences, research suggests that climate change effects on animals during the 20th century in California may have been largely affected by changes in vegetation rather than, or in addition to, direct physiological effects (Rapacciuolo et al., 2014), although warming winter temperatures are sometimes clearly important (Morelli et al., 2012). Substantial vegetation changes within the Central region (Yosemite National Park) have occurred since the early 1900's due to a number of factors, including fires, fire suppression efforts, and temperature changes. Of the 23 small mammal species in Yosemite National Park, 11 shifted their elevational ranges in the same direction as shifts in vegetation, six species shifted in a different direction, and the rest showed no relationship (Santos et al., 2015). Species that shifted in the same direction as vegetation were mostly inhabitants of low to intermediate elevations, while species that shifted in different direction inhabited high elevations. Vegetation change appears to directly affect some of the changes in the range of small mammals. For example, the expansion of the upper limit of the ranges of the California pocket mouse and the Piñon mouse (on the west slope) can be attributed to stand-replacing fires in the lower areas of the park. The large downwards shift in the elevation of the Montane shrew is probably related to its preference for wet meadows and the recovery of wet meadow systems in Yosemite Valley, following cessation of grazing and intense restoration efforts (Moritz et al., 2008).

Technical considerations

Data characteristics

Resurveys of small mammals and birds were conducted between 2003 through 2010 along three elevational transects in the Sierra Nevada Mountains that spanned four National Parks (see map above) and numerous other state, federal and private land holdings. The surveys revisited sites that were originally studied between 1911-1920 by Joseph Grinnell and staff of the Museum of Vertebrate Zoology (MVZ), University of California at Berkeley (Grinnell, 1930). The resurveys provide updated information on habitat and community changes at each site over the past century, while documenting the presence as well as ranges (geographic and habitat) of species of special concern to the lay and scientific communities. Detailed information on the Grinnell Resurvey Project can be found at: http://mvz.berkeley.edu/Grinnell/index.html.

Small mammal surveys were conducted at 166 locations: 38 in the Northern, 81 in the Central and 47 in the Southern region. Species were categorized as low elevation, high elevation or widespread for purposes of observing how species at different elevations respond. Statistical analyses of range shifts were restricted to 34 species that were detected at more than 10 percent of sites for at least one region in both eras. Details can be found in Rowe et al. (2014).

The resurvey of bird species for the three regions was conducted during breeding season. Observers collected data with temporal sampling as follows: Lassen, 2006-07; Yosemite, 2003-04; Southern Sierra, 2008-09. A total of 251 modern surveys were conducted at 84 sites, with each site surveyed a maximum of 5 times. Over 87 percent of the survey sites were located on permanently protected lands. All sites contained "west slope Sierran" vegetation communities. Habitat descriptions were matched to historic field notes wherever possible. The data from this resurvey can be found at: http://arctos.database.museum. Details can be found in Tingley et al. (2012).

Strengths and limitations of the data

Detailed maps and field notes from the Grinnell investigators facilitated the relocation of actual sites, transects and trap lines. The position of all generalized sites, based on documentation of the actual campsite, has been reasonably well established.

Substantial differences in small mammal survey methodologies between the two survey periods may result in biases in trapability. The Grinnell team used shotguns and snap traps for all mammal surveys, while the recent survey used live traps. To assess the comparability of survey success for each species across the time periods, statistical ("Occupancy") analyses were conducted. For the 34 species of small mammals considered above, detectability probabilities were sufficiently high across the survey periods to yield robust results. The analysis of changes in elevational range of mammals incorporates differences in detectability between study periods.

Natural year-to-year fluctuations in species' abundances may affect the detection of particularly rare species, and hence the comparisons between the study periods.

For purposes of examining possible climate change impacts on species shifts, field surveys were conducted in protected areas where other human influences (e.g., land use changes) were limited.

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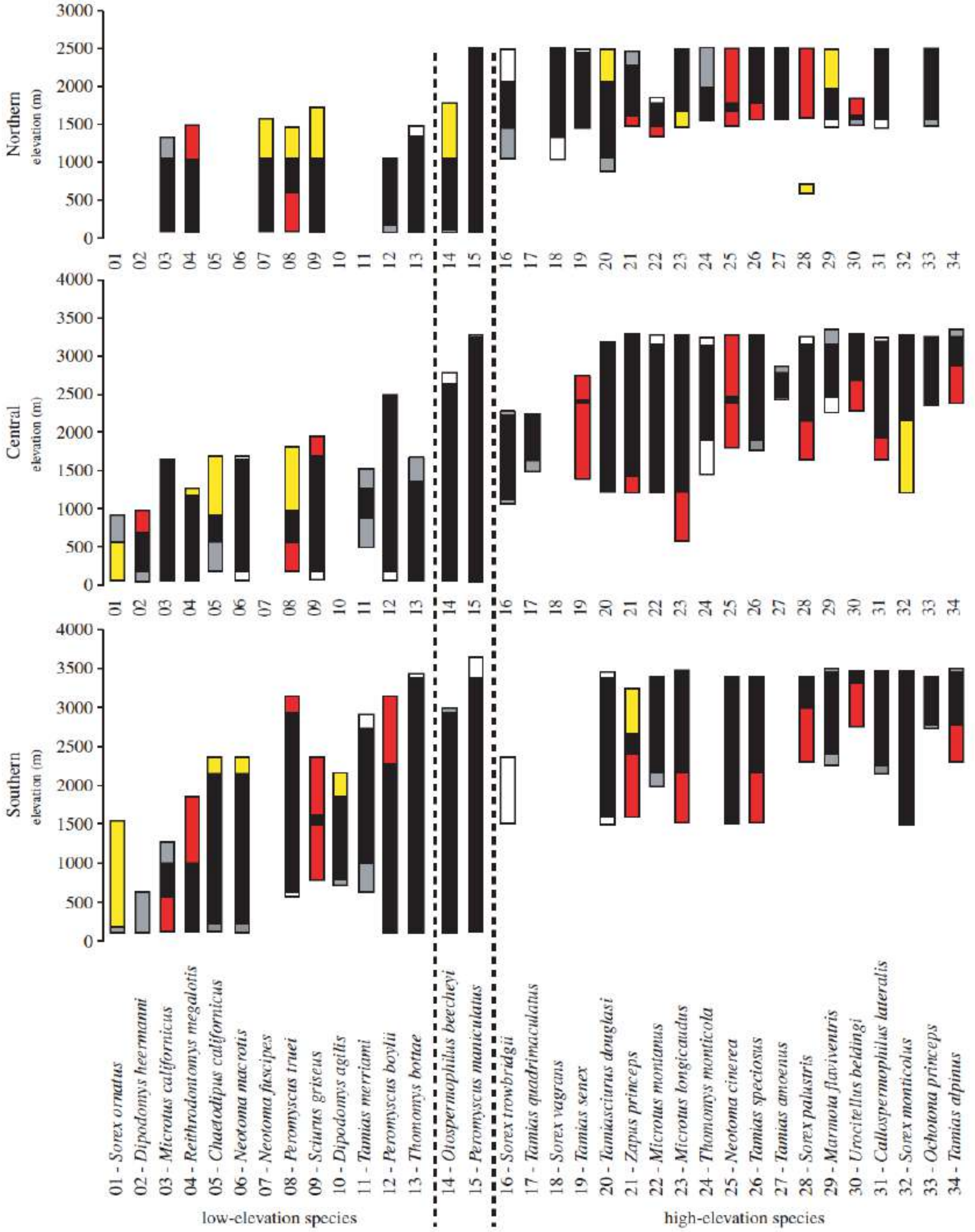
APPENDIX

Figure A1. Small mammal range limit shifts, by species*



Red bars — range contractions; yellow bars — range expansions: gray bars — non-significant contractions; white bars — non-significant expansions (white); black bars — historic range. (Lack of a bar indicates that species is not found in that region.)

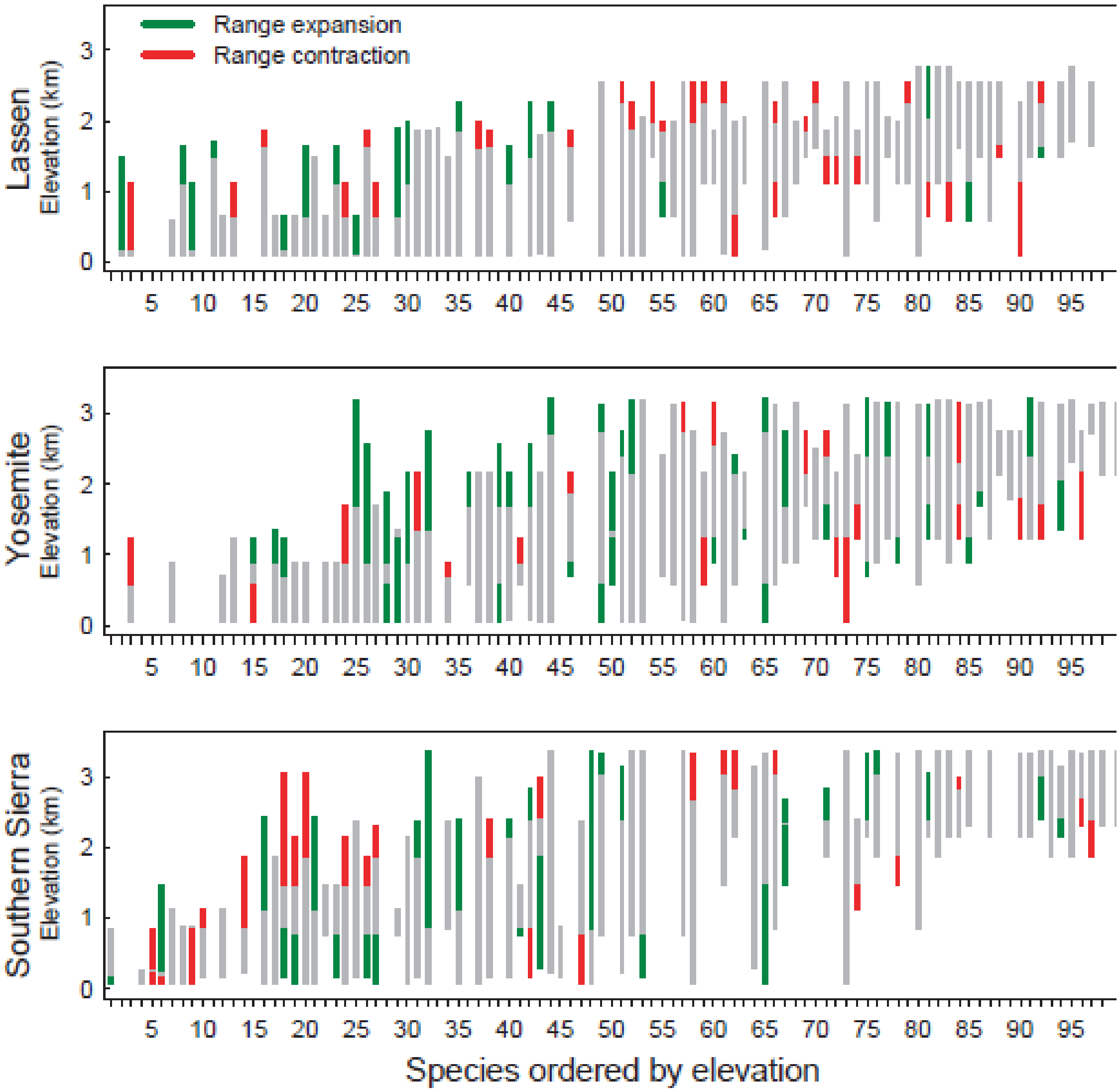
**List of common names follows.*

Source: Modified from Rowe et al., 2015

Common names for the species listed in Figure A-1 are as follows:

01 *Sorex ornatus* (Ornate shrew)
02 *Dipodomys heermanni* (Heermann's kangaroo rat)
03 *Microtus californicus* (Amargosa vole)
04 *Reithrodontomys megalotis* (Western harvest mouse)
05 *Chaetodipus californicus* (California pocket mouse)
06 *Neotoma macrotis* (Big-eared woodrat)
07 *Neotoma fuscipes* (Dusky-footed woodrat)
08 *Peromyscus truei* (Pinyon mouse)
09 *Sciurus griseus* (Western gray squirrel)
10 *Dipodomys agilis* (Agile kangaroo rat)
11 *Tamias merriami* (Merriam's chipmunk)
12 *Peromyscus boylii* (Brush mouse)
13 *Thomomys bottae* (Botta's pocket gopher)
14 *Otospermophilus beecheyi* (California ground squirrel)
15 *Peromyscus maniculatus* (Deer mouse)
16 *Sorex trowbridgii* (Trowbridge's shrew)
17 *Tamias quadrimaculatus* (Long-eared chipmunk)
18 *Sorex vagrans* (Vagrant shrew)
19 *Tamias senex* (Allen's chipmunk)
20 *Tamiasciurus douglasii* (Douglas' squirrel)
21 *Zapus princeps* (Western jumping mouse)
22 *Microtus montanus* (Montane vole)
23 *Microtus longicaudus* (Long-tailed vole)
24 *Thomomys monticola* (Mountain pocket gopher)
25 *Neotoma cinerea* (Bushy-tailed woodrat)
26 *Tamias speciosus* (Lodgepole chipmunk)
27 *Tamias amoenus* (Yellow-pine chipmunk)
28 *Sorex palustris* (American water shrew)
29 *Marmota flaviventris* (Yellow-bellied marmot)
30 *Urocitellus beldingi* (Belding's ground squirrel)
31 *Callospermophilus lateralis* (Golden-mantled ground squirrel)
32 *Sorex monticolus* (Dusky shrew)
33 *Ochotona princeps* (American pika)
34 *Tamias alpinus* (Alpine chipmunk)

Figure A2. Bird range limit shifts, by species*



Source: Tingley et al., 2012

Red bars — range contractions; green bars — range expansions; gray bars — historical range. (Lack of a bar indicates that species is not found in that region.)

**Numbers along the x-axis correspond to the species list that follows.*

Species are presented in Figure A-2 in the following order:

01 *Corvus brachyrhynchos* (American Crow)
02 *Spinus tristis* (American Goldfinch)
03 *Icteria virens* (Yellow-breasted chat)
04 *Passer domesticus* (House Sparrow)
05 *Eremophila alpestris* (Horned Lark)
06 *Mimus polyglottos* (Northern Mockingbird)
07 *Tyrannus verticalis* (Western Kingbird)

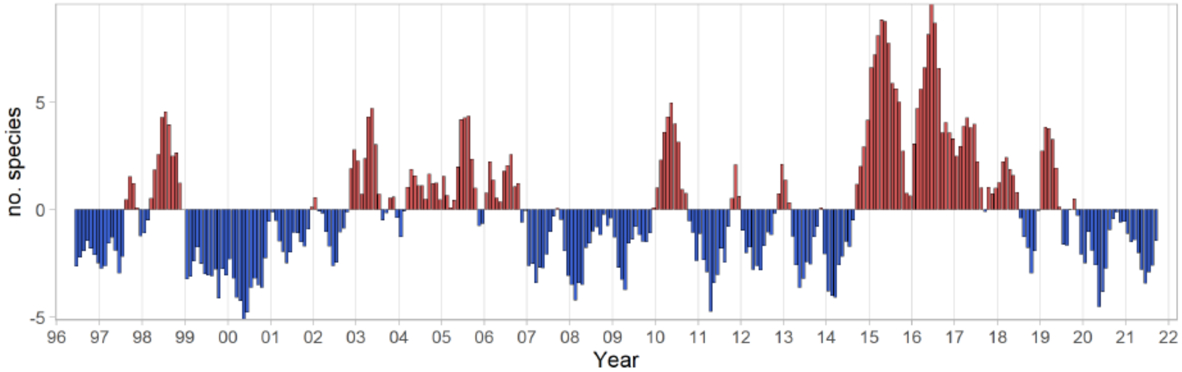
08 *Pterochelidon pyrrhonota* (Cliff Swallow)
09 *Geothlypis trichas* (Common Yellowthroat)
10 *Passerina caerulea* (Blue Grosbeak)
11 *Empidonax traillii* (Willow Flycatcher)
12 *Picoides nuttallii* (Nuttall's Woodpecker)
13 *Picus formicivora* (Acorn Woodpecker)
14 *Archilochus alexandri* (Black-chinned Hummingbird)
15 *Polioptila caerulea* (Blue-gray Gnatcatcher)
16 *Sturna neglectus* (Western Meadowlark)
17 *Icterus bullockii* (Bullock's Oriole)
18 *Thryomanes bewickii* (Bewick's Wren)
19 *Melozone crissalis* (California Towhee)
20 *Haemorhous mexicanus* (House Finch)
21 *Chondestes grammacus* (Lark Sparrow)
22 *Baeolophus inornatus* (Oak Titmouse)
23 *Callipepla californica* (California Quail)
24 *Myiarchus cinerascens* (Ash-throated Flycatcher)
25 *Sayornis nigricans* (Black Phoebe)
26 *Psaltiparus minimus* (Bushtit)
27 *Aphelocoma californica*, *Aphelocoma insularis* and *Aphelocoma woodhouseii* (Western Scrub-Jay, now split into three)
28 *Calypte anna* (Anna's Hummingbird)
29 *Picoides pubescens* (Downy Woodpecker)
30 *Zenaida macroura* (Mourning Dove)
31 *Setophaga petechial*, formerly *Dendroica petechial* (Yellow Warbler)
32 *Agelaius phoeniceus* (Red-winged Blackbird)
33 *Tachycineta bicolor* (Tree Swallow)
34 *Sialia mexicana* (Western Bluebird)
35 *Melospiza melodia* (Song Sparrow)
36 *Empidonax difficilis* (Pacific-slope Flycatcher)
37 *Spinus psaltria* (Lesser Goldfinch)
38 *Pheucticus melanocephalus* (Black-headed Grosbeak)
39 *Catherpes mexicanus* (Canyon Wren)
40 *Piplio maculatus* (Spotted Towhee)
41 *Chamaea fasciata* (Wrentit)
42 *Passerina amoena* (Lazuli Bunting)
43 *Tachycineta thalassina* (Violet-green Swallow)
44 *Euphagus cyanocephalus* (Brewer's Blackbird)
45 *Molothrus ater* (Brown-headed Cowbird)
46 *Setophaga nigrescens* (Black-throated Gray Warbler)
47 *Spinus lawrenci* (Lawrence's Goldfinch)
48 *Passerculus sandwichensis* (Savannah Sparrow)
49 *Troglodytes aedon* (House Wren)
50 *Patagioenas fasciata* (Band-tailed Pigeon)
51 *Vireo gilvus* (Warbling Vireo)
52 *Sitta carolinensis* (White-breasted Nuthatch)
53 *Colaptes auratus* (Northern Flicker)
54 *Loxia curvirostra* (Red Crossbill)
55 *Oreortyx pictus* (Mountain Quail)
56 *Oreothlypis celata* (Orange-crowned Warbler)
57 *Contopus sordidulus* (Western Wood-Pewee)
58 *Cardellina pusilla* (Wilson's Warbler)

59 *Geothlypis tolmiei* (MacGillivray's Warbler)
60 *Setophaga occidentalis* (Hermit Warbler)
61 *Piranga ludoviciana* (Western Tanager)
62 *Vireo cassinii* (Cassin's Vireo)
63 *Dryocopus pileatus* (Pileated Woodpecker)
64 *Corvus corax* (Common Raven)
65 *Turdus migratorius* (American Robin)
66 *Picoides villosus* (Hairy Woodpecker)
67 *Haemorhous purpureus* (Purple Finch)
68 *Oreothlypis ruficapilla* (Nashville Warbler)
69 *Empidonax hammondii* (Hammond's Flycatcher)
70 *Regulus satrapa* (Golden-crowned Kinglet)
71 *Picoides albolarvatus* (White-headed Woodpecker)
72 *Coccothraustes vespertinus* (Evening Grosbeak)
73 *Spizella passerina* (Chipping Sparrow)
74 *Sphyrapicus ruber* (Red-breasted Sapsucker)
75 *Contopus cooperi* (Olive-sided Flycatcher)
76 *Cyanocitta stelleri* (Steller's Jay)
77 *Selasphorus calliope* (Calliope Hummingbird)
78 *Certhia americana* (Brown Creeper)
79 *Cinclus mexicanus* (American Dipper)
80 *Salpinctes obsoletus* (Rock Wren)
81 *Passerella iliaca* (Fox Sparrow)
82 *Poecile gambeli* (Mountain Chickadee)
83 *Junco hyemalis* (Dark-Eyed Junco)
84 *Pipilo chlorurus* (Green-tailed Towhee)
85 *Sitta canadensis* (Red-breasted Nuthatch)
86 *Myadestes townsendi* (Townsend's Solitaire)
87 *Setophaga coronata* (Yellow-rumped Warbler)
88 *Melospiza lincolnii* (Lincoln's Sparrow)
89 *Dedragapus fuliginosus* (Sooty Grouse)
90 *Spinus pinus* (Pine Siskin)
91 *Empidonax oberholseri* (Dusky Flycatcher)
92 *Catharus guttatus* (Hermit Thrush)
93 *Sitta pygmaea* (Pygmy Nuthatch)
94 *Haemorhous cassinii* (Cassin's Finch)
95 *Nucifraga columbiana* (Clark's Nutcracker)
96 *Regulus calendula* (Ruby-crowned Kinglet)
97 *Sialia currucoides* (Mountain Bluebird)
98 *Sphyrapicus thyroideus* (Williamson's Sapsucker)
99 *Zonotrichia leucophrys* (White-crowned Sparrow)

COPEPOD POPULATIONS

Variations in copepod populations in the northern California Current Ecosystem reflect large-scale and regional changes in ocean temperatures and circulation patterns.

Figure 1. Monthly anomalies of copepod species richness in the northern California Current System*



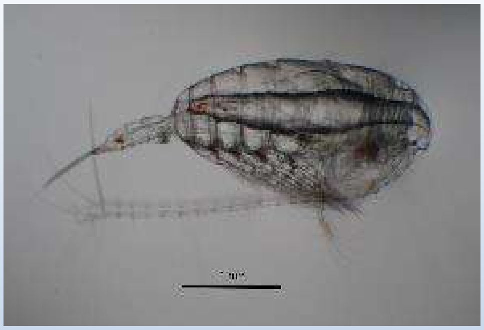
Source: NOAA/NWFSC, 2021

**Copepod species richness is the number of copepod species in a plankton sample. The monthly anomaly is the difference between the monthly average and the long-term monthly average of copepod species richness values. Samples are collected from the northern California Current, which flows along the west coast of North America, from southern British Columbia to Baja California*.

Note: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

What does the indicator show?

As shown in Figure 1, copepod species richness has fluctuated since the late 1990s with no clear trend. The data are from a monitoring site off the coast of Newport, Oregon, which is about 300 kilometers north of Crescent City, California, in the northern portion of the California Current System (see Figure 2). Low anomalies occurred from 1999 until 2002, generally high anomalies from 2003 until 2007, followed by a mixed pattern until a very high jump in species richness in much of 2015 through mid-2018, before returning to negative anomalies in 2020 and 2021. The copepod *species richness* index represents the average number of copepod species collected in monthly plankton samples (see *Data Characteristics* for more details). Figure 1 presents monthly anomalies — that is, the departure from the long-term monthly

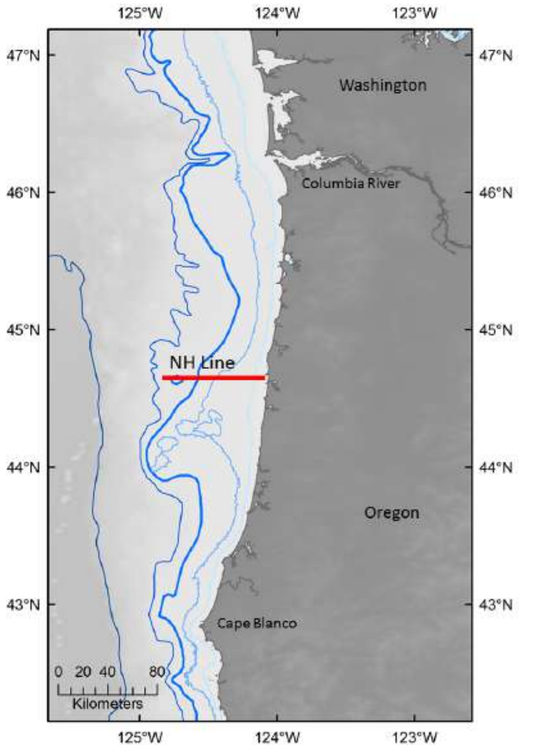


Calanus marshallae

Copepods are a large and diverse group of small marine crustaceans and a key component of the food chain. They link primary producers (such as algae and other phytoplankton) and higher trophic levels such as fish, whales, and seabirds.

average — in copepod species richness values. Values are negative when the observed number of copepod species is less than the long-term monthly average, and positive when the observed number is greater. While copepod population metrics such as species richness (Figure 1) and biomass (Figure 3) predominantly describe interannual to decadal climate variability, they likely indicate long-term climate change, since changes in ocean transport and water mass source are responsive to variations in global climate.

Figure 2. Location of monitoring site ("NH Line")



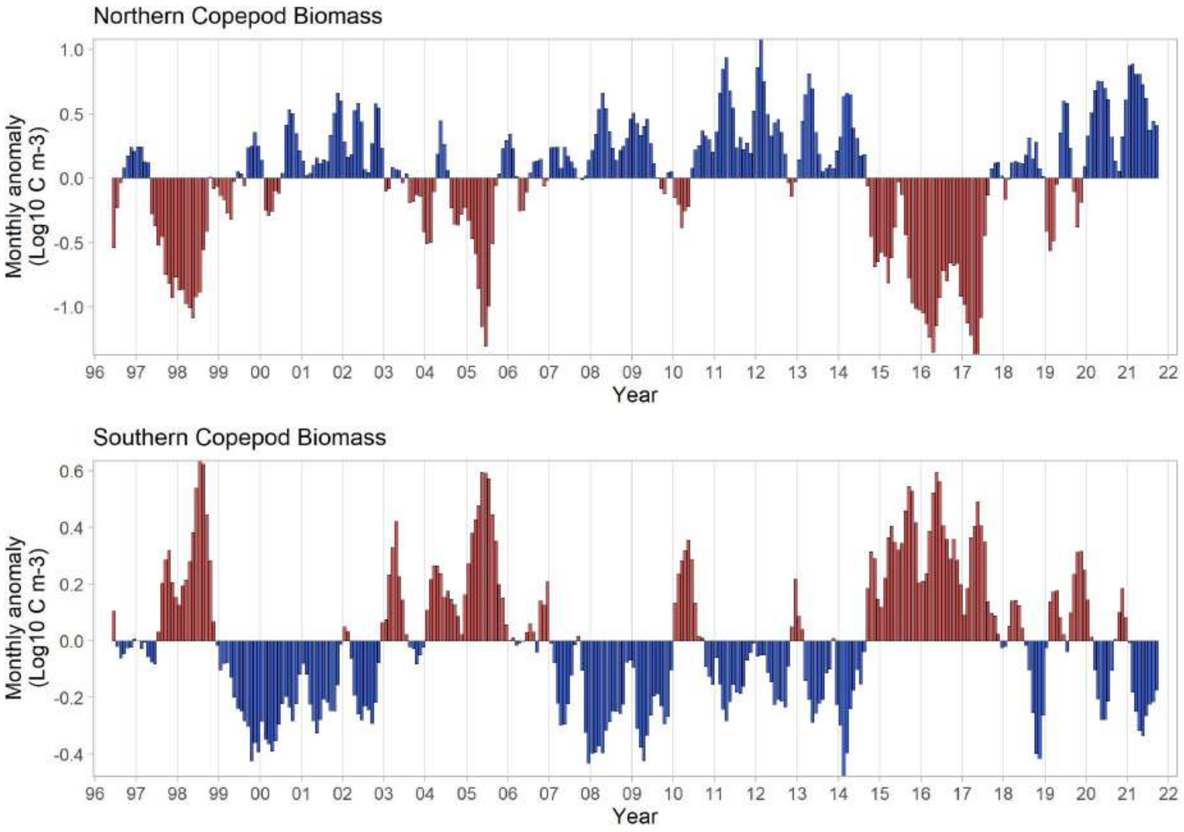
Source: NOAA/NWFSC, 2021

Because copepods drift with ocean currents, they are good indicators of the type and sources of waters transported into the northern California Current. Thus, changes in copepod populations off Oregon are also indicative of changes occurring off the California coast. These changes impact all levels of the food chain in California's marine ecosystems.

Negative values in species richness anomalies generally indicate that the copepods are being transported to the monitoring location chiefly from the north, out of the coastal subarctic Pacific which is a region of low species diversity. While positive values in species richness anomalies generally indicate that the waters originate either from the south or from offshore, which are warmer, subtropical, low-salinity waters containing a more species-rich planktonic fauna.

Figure 3 shows the abundance, in milligrams of organic carbon biomass per cubic meter of water, of two copepod groups based on the affinities of copepods for different water masses (i.e., temperature and salinity; Hooff and Peterson, 2006). The main species occurring at the monitoring site are classified into two groups: those with cold-water affinities (northern copepods) and those with warm-water affinities (southern copepods). Two of the northern species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich, containing wax esters and fatty acids that appear to be essential for many pelagic fishes to grow and survive through the winter (Miller et al., 2017). Therefore, positive biomass anomalies of northern copepods generally translate to the base of the food web composed of lipid rich copepods. On the contrary, the southern copepod species are generally smaller than the northern species, and have low lipid reserves and nutritional quality. Therefore, positive biomass anomalies of southern copepods generally translate to the base of the food web composed of lipid poor copepods. The cold-water species usually dominate the coastal zooplankton community during the summer, while the warm-water species are usually dominant during the winter. Zooplankton anomalies are on a log10 scale and represent a multiplicative (not additive) scaling relative to the average seasonal cycle: for example, an anomaly of +1 means that observations average 10 times the 1996–2021 monthly average.

Figure 3. Monthly anomalies of copepod biomass in the northern California Current System *



Source: NOAA/NWFSC, 2021

**Copepod biomass is abundance in milligrams of organic carbon biomass per cubic meter of water. The anomaly is the difference between the monthly average and the long-term monthly average of copepod biomass values.*

Note: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

Figures 1 and 3 show how the cycle of copepod richness and copepod biomass are related. Over the 25-year time series, during periods when the copepods are dominated by cold water northern species (positive biomass anomalies of northern copepods; Figure 3, top graph), there were usually negative anomalies of southern copepod species (Figure 3, bottom graph) and lower than average species richness (Figure 1). These low frequency changes are independent of the seasonal pattern of low species richness in the summer and high richness in the winter. Throughout much of 2015 and into the summer of 2017, large populations of southern copepod species dominated the coastal waters, and species richness was the highest observed in the 25-year time series as a result of anomalously warm ocean temperatures (described below).

Why is this indicator important?

Copepods are the base of the food chain, eaten by many fish (especially anchovies, sardines, herring, smelt and sand lance), which in turn are consumed by larger fish, marine mammals and seabirds. Because they are planktonic, copepods drift with the ocean currents and therefore are good indicators of the type of water being transported into the northern California Current. Tracking copepods provides information about changes occurring in the food chain that fuels upper trophic-level marine fishes, birds, and mammals. As noted above, “northern species” are larger and bioenergetically richer than the “southern species.” When copepods largely consist of northern species, the pelagic (water column) ecosystem is far more productive than when southern species dominate.

Year-to-year variations in the species composition and abundance of copepods has been correlated to the abundance of small fishes, as well as species that feed on these fish (Peterson et al., 2014). For example, following four years of positive anomalies of northern copepod species from 1999-2002, extraordinarily high returns of Coho and Chinook salmon occurred in the rivers of California and Oregon. Conversely, during the years 2003-2007 and 2014-2016, when salmon returns began to decline dramatically, positive anomalies of southern copepod species were occurring. These observations reflect a rich food chain from 1999-2002 and an impoverished food chain from 2003-2007 and 2014-2016.

Like other zooplankton, copepods are useful indicators of the ecosystem response to climate variability. Due to their short life cycles (on the order of weeks), their populations respond to and reflect short-term and seasonal changes in environmental conditions and are sensitive to the magnitude of environmental change (Fisher et al., 2015). Moreover, many zooplankton taxa are indicator species whose presence or absence may represent the relative influence of ocean transport processes and perturbations in the northern California Current on ecosystem structure. For example, during the marine heat wave in 2015 and 2016 (see *Coastal ocean temperature* indicator), the seasonal springtime shift from a warm southern copepod community to a cold summer northern community did not occur. The lowest biomass of lipid-rich northern copepods and the highest biomass of small tropical and sub-tropical southern copepods in the 25-year time series occurred during this time period. This time period was also marked by novel ecosystem states and unprecedented changes in the distribution, timing and abundance of species ranging from phytoplankton, zooplankton, and fish to whales (Cavole et al. 2016, Peterson et al., 2017, Morgan et al. 2019).

Finally, copepod populations may give an advance warning of major changes in the ocean ecosystem. Copepod indices have proven useful for the prediction of the returns of Chinook and Coho salmon (Peterson and Schwing, 2003; Peterson et al., 2014), and forecasts of salmon survival have been developed for the Coho and Chinook salmon runs along the Washington/Oregon coasts based on copepod indices (NOAA/NWFSC, 2021 and also see *Chinook salmon abundance* indicator). These same copepod indices have been correlated with the recruitment of the invasive green crab along the west coast of the US (Yamada et al., 2015, 2021); and the recruitment of sablefish, rockfish, and sardine in the northern, central and southern California Current respectively (Peterson et al., 2014). They have also been correlated with seabird nesting success in Central California (Jahncke et al., 2008; Wolf et al., 2009; Manugian et al., 2015; also see *Cassin's Auklet breeding success* indicator), seabird mortality off northern Washington (Parrish, personal communication), and nest occupancy rates of the iconic and threatened seabird the marbled murrelet (Betts et al., 2020).

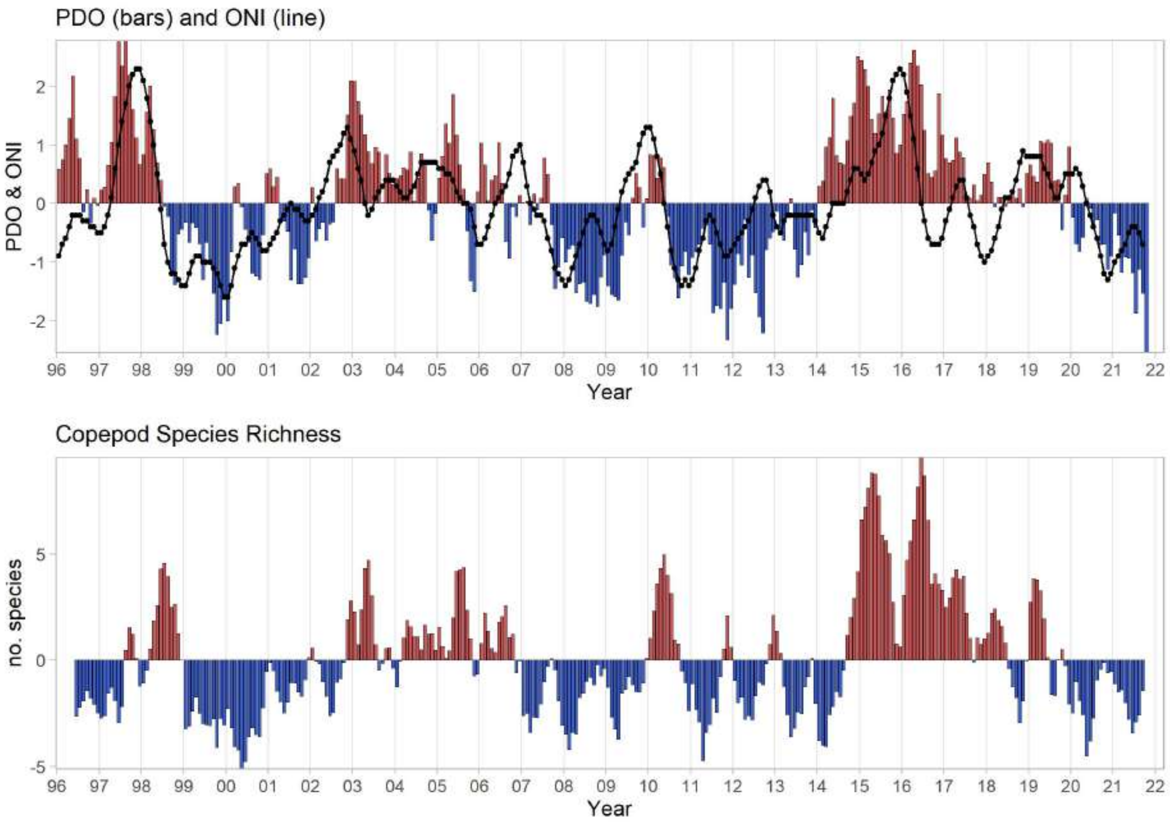
What factors influence this indicator?

Copepod dynamics in this region of the California Current display strong seasonal patterns, influenced by circulation patterns of local winds and coastal currents. The copepod community tends to be dominated by cold-water species during the upwelling season, typically from May through September, as winds blow toward the equator and subarctic waters are transported southward from the Gulf of Alaska. As noted above, the cold-water copepod species are characterized by low species diversity. During winter, offshore warmer waters from the south carry more zooplankton species-rich water to the Oregon continental shelf. During the spring, there is a shift back to the upwelling season with increased northern copepod species and decreased species richness (Hooff and Peterson, 2006).

The interannual patterns of species richness and biomass anomalies of copepods with different water-type affinities are found to track measures of ocean climate variability (Keister et al. 2011, Fisher et al., 2015). The Pacific Decadal Oscillation (PDO) is a climate index based on sea surface temperatures across the entire North Pacific Ocean. When the ocean is cold in the California Current, the PDO has a negative value; when the ocean is warm in the California Current, the PDO has a positive value. Coastal waters off the Pacific Northwest are also influenced by equatorial Pacific conditions, especially during El Niño events. The Oceanic Niño Index (ONI) tracks sea surface temperature anomalies at the equator, where positive ONI values indicate warming (El Niño) conditions, while negative values indicate cooling conditions.

Figure 4 shows the relationship between the PDO and ONI ocean indices and copepod species richness. The upper panel shows two time series: monthly values of the PDO (red and blue bars) and the ONI (black dotted line). The lower panel is the same graph as Figure 1 (monthly anomalies in copepod species richness). There are clear relationships between the interannual variability in the physical climate indicators (PDO and ONI) and copepod species richness anomalies. The switch to a positive PDO in 2014 corresponded with high species richness in 2014 through the summer of 2017. When the PDO turned negative again in 2020, species richness also declined. The biomass anomalies of the southern and northern copepod species also track ocean climate variability. When the PDO is negative, the biomass of northern copepods is high (positive) and the biomass of southern copepods is low (negative), and vice versa (not shown).

Figure 4. Relationship between the Pacific Decadal Oscillation and Oceanic Niño Indices (upper) and copepod species richness (lower) anomalies



Source: NOAA/NWFSC, 2021

Top graph: Blue bars indicate colder waters; red bars warmer waters.

Lower graph: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

The shift to high richness anomalies observed in 2014 and persisting through summer 2017 originated from an intrusion of warm water (dubbed the “warm blob”) into the Oregon shelf due to the North Pacific marine heat wave that originated in late 2013 (Bond et al., 2015). Subsequently, the North Pacific heat wave interacted with an El Niño developing in the equatorial Pacific in 2015 resulting in an unusually long period of strong warm anomalies (Peterson et al., 2017). Because of the anomalously warm ocean conditions throughout much of 2015 and 2016, the copepod community was dominated by warm-water species while the biomass of northern species was lower than usual. These conditions lead to poor feeding conditions for small fish, which in turn are prey for juvenile salmon, affecting the local hydrography and pelagic communities. As previously stated, the seasonal shift from a winter warm copepod community to a cold summer community did not occur in 2015 or 2016. However, in July 2017, the copepod community did shift to a community dominated by cold water species and the species richness also dropped to average levels.

Technical considerations

Data characteristics

The copepod data are based on biweekly to monthly sampling off Newport, Oregon, and are usually available by the end of each month. The sampling station is a coastal shelf station located 9 kilometers offshore, at a water depth of 62 meters. Samples are generally collected during daylight hours, using nets hauled from 5 meters off the bottom to the surface. One milliliter subsamples containing 300-500 copepods were used to enumerate copepods by species, developmental stage, and taxa-specific biomass estimated from literature values or the investigators' unpublished data of carbon weights.

Northern and southern biomass anomalies are derived by converting counts to biomass using length-to-mass regressions and standardized to units of mg Carbon m^{-3}. The copepod biomass data (mg C m^{-3}) are averaged monthly and transformed by taking the base 10 logarithm, specifically log10 (x + 0.01). Monthly biomass anomalies are calculated for each species using 1996–present as the base period. Species are grouped based on their water mass affinities (southern or northern), and the individual biomass anomalies are averaged within each group (southern and northern) (Fisher et al., 2015).

Values are updated annually and posted on two websites (https://www.fisheries.noaa.gov/west-coast/science-data/local-biological-indicators and https://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/indicators/climate-and-ocean-drivers.html). Monthly values are available here https://www.fisheries.noaa.gov/content/newportal-blog-northwest-fisheries-science-center. Details of the sampling program and data analysis can be found in Peterson and Schwing, 2003; Peterson and Keister, 2003; and Fisher et al., 2015.

Strengths and limitations of the data

This 25-year time series represents the longest biological monitoring of lower trophic levels in the northern California Current. While longer time series of physical variables (e.g., PDO) provide important context for understanding variability over decadal scales, these monitoring efforts provide the foundation for examining relationships between copepod populations and fish, birds, and mammals.

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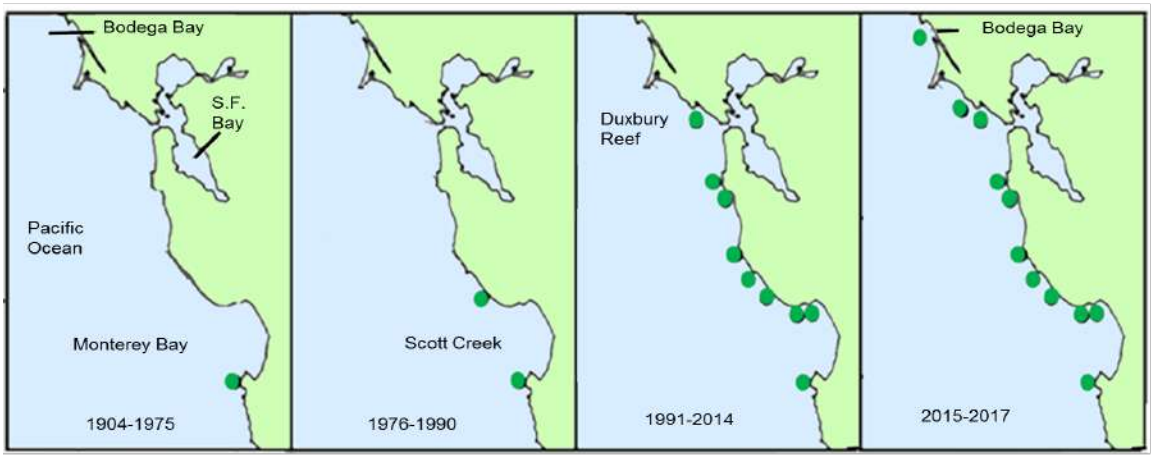
NUDIBRANCH RANGE SHIFTS (NO UPDATE)

A species of nudibranch sea slug is expanding its range northward along the California coast in response to warming ocean conditions.

Figure 1. Northernmost locations of *Phidiana hiltoni* along the California coast (1904-2017)



Source: Adapted from Goddard et al., 2011, updated 2017

What does the indicator show?

Historical surveys of nudibranch populations along the California coast show a 210 kilometer (km) northward shift in the range for *Phidiana hiltoni* (*P. hiltoni*) since the mid-1970s (Goddard et al., 2011; 2016). Figure 1 shows locations where *P. hiltoni* had been observed (green dots) during four different periods, starting in 1904. Until 1975, *P. hiltoni's* most northern location was on the Monterey Peninsula. Beginning in the late 1970s, its range expanded north across Monterey Bay to Santa Cruz County. By 1992, it had spread another 110 km up the coast into the San Francisco Bay area as far north as Duxbury Reef. By 2015, it had reached Bodega Bay. Following its initial spread, *P. hiltoni* has persisted at each of these sites to the present day.

Warm water conditions occur periodically in California's coastal waters, usually as part of the El Niño-Southern Oscillation. From late 2013 to 2016, the West Coast experienced unusually warm sea surface temperatures (Bond et al., 2015; Di Lorenzo and Mantua, 2016). Fish and other marine organisms, including many nudibranchs, shifted their distributions farther north during this unprecedented marine heat wave (Cavole et al., 2016). All told, 26 sea slug species were found at new northernmost locations (Goddard et al., 2016; Goddard, 2017). Among these was *P. hiltoni*, which after inhabiting Duxbury Reef for 13 years, was found for the first time in Bodega Bay in 2015. Warm ocean conditions ended in 2016, yet as of late 2017, *P. hiltoni* has persisted at this new northernmost location.

Why is this indicator important?

The habitats of nudibranchs overlap with commercially important organisms, including abalone, crab, and lingcod. Although changes in the ranges of small, short-lived marine organisms such as nudibranchs may seem inconsequential, the nudibranch's response to ocean warming may foretell larger ecological changes that may already have been set in motion by climate change.

Species live in habitats defined by certain physical conditions, such as temperature and salinity. These conditions often show gradual change through space, creating an environmental gradient across latitudes, elevations, or depths. As conditions change, such as with warming ocean temperatures, species' distributions along an environmental gradient can provide important insights into how they will respond to climate change. For example, many species that can only survive within defined temperature ranges moved to higher elevations with long-term climate warming (IPCC, 2014). *P. hiltoni* has remained in its expanded range even after cooler temperatures have temporarily returned to coastal waters. With climate change driving a longer-term increase in global ocean temperature, scientists expect some of the other northward range shifts observed during the past few years in California to become permanent. Northern populations of these nudibranchs are being closely monitored.

Credit: Jeffrey Goddard

The nudibranch sea slug Phidiana hiltoni is a soft-bodied marine organism found on the California coast. Nudibranchs are recognized for their intricate shapes and striking colors. They are bottom-dwelling, specialized predators of aquatic invertebrates such as sponges, jellyfish, and in a few cases, other nudibranchs. Lifespans vary from weeks to about a year depending on species. Nudibranchs are not harvested by humans and many are conspicuous and easy to count in the marine environment (Schultz et al., 2011).

The expansion of marine organisms into new territories can have negative biological impacts on resident organisms, similar to those of invasive species. Population declines in other nudibranch species have occurred at Duxbury Reef, where particularly high densities of *P. hiltoni* have been observed (Goddard et al., 2011). These declines appear to have resulted from *P. hiltoni* preying on other nudibranchs and competing for common prey species. Scientists suggest the range shift of this predatory species may therefore be disrupting food webs and altering community composition at sites along the California coast where its populations are dense.

What factors influence this indicator?

Nudibranchs inhabit the California Current System (CCS), which includes the span of coastline from Oregon to Baja California Sur. In this system, the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) influence sea surface temperatures (SSTs), coastal upwelling and strength of southerly currents. During certain phases of these oscillations, including El Niño events in which coastal waters shift from relatively cool to warm temperatures and poleward movement of ocean currents increases, researchers have found episodic northward range expansions of nudibranch species.

Local and basin-scale fluctuations in ocean climate can affect larval development, mortality, and transport, and these in turn can affect adult population dynamics. The transport of larval-stage nudibranchs, called *larval advection*, is hypothesized to explain the relationship between ocean climate conditions and changes in adult population abundance. For example, El Niño conditions appear to increase larval advection of nudibranchs from southern source populations, extending their ranges northward and increasing population sizes in shallow water (Schultz et al., 2011; Goddard et al., 2016).

The strong El Niños of 1982-83 and 1997-98 drove transient shifts of many nudibranchs from southern and central California to their northernmost sites (Engle and Richards, 2001; Goddard et al., 2016). In 1976-77 a shift from a cool to warm phase of the PDO and increased sea surface temperatures also corresponded with northward expansion of nudibranchs. When this warm phase ended in 2007 and cooler sea surface temperatures returned in 2008, *P. hiltoni* was the only nudibranch to remain in its expanded range. Interestingly, additional evidence presented by Goddard et al. (2011) suggests that *P. hiltoni* did not occur north of Monterey during the previous warm phase of the PDO, which lasted from 1925 to 1946 (Mantua and Hare, 2002).

Phidiana hiltoni and other nudibranchs are responding in a manner similar to other marine fishes and invertebrates, which have shifted their distributions to higher latitudes and/or into deeper depths in response to warmer conditions (Lluch-Belda et al., 2005; Cavole et al., 2016). A very strong El Niño contributed to an unprecedented multiyear marine heat wave along the Pacific Coast from late 2013 to 2016 and caused extensive biological impacts, including range shifts, at all trophic levels. Investigators documented range shifts for 48 species of sea slugs from 2014 through late 2017 along the California and Oregon coastline associated with the unusually warm ocean conditions (Goddard et al., 2016; Goddard, personal communication). Twenty-six species were found at new northernmost localities, while the remainder were located at or near northern range limits established during previous El Niños. It remains to be seen how many of these species will persist in their northern locations — as *P. hiltoni* has — when ocean conditions shift back to cooler temperatures.

Technical considerations

Data characteristics

Historical data (before 1969):

Qualitative searches for sea slugs, especially nudibranchs, were conducted from Monterey to Sonoma Counties by taxonomic specialists. Results are scattered in published papers and monographs, as well as the online database of the Invertebrate Collection at the California Academy of Sciences (http://researcharchive.calacademy.org/research/izg/iz_coll_db/index.asp). The counts of sea slugs in San Mateo County reported by Bertsch, et al. (1972) were conducted intermittently from 1966 to 1970 and were semi-quantitative in nature. The taxonomic results in Marcus (1961) were based largely on collections made in Marin and Sonoma Counties in 1958–9, and those in Steinberg (1963) on collections from Monterey to Sonoma Counties from 1948 to 1963.

Duxbury reef data:
Nudibranch population abundances prior to the arrival of *P. hiltoni* at Duxbury Reef were estimated based on five timed counts conducted in June and July 1969, January and June 1970, and June 1972; and three more in December 1974 and May and December 1975. Since December 2007, 11 more timed counts of nudibranchs in the same area as the original counts were conducted. Data from all counts were standardized to number of individuals per hour per observer or number of species per hour per observer (Goddard, 2011).

<u>Strengths and limitations of the data:</u>
Historical data (before 1969):
Since the 1940s, coastal nudibranch counts by taxonomic specialists have had good geographic representation from Monterey to Sonoma County. Geographic coverage was more limited for the first half of the 20th century, when the only marine laboratory in the region was at Pacific Grove. However, collections of nudibranchs were made in the greater San Francisco Bay region in the early 20th century, and deposited in the Invertebrate Collection at the California Academy of Sciences (CAS), with the associated data now available via the CAS online database (Goddard et al., 2011).

Data since 1969:
The timed counts at Duxbury Reef in the 1960s-70s and again starting in 2007 were conducted by the same two taxonomic specialists in nudibranchs, assisted at times by experienced observers familiar with intertidal nudibranchs from California. This continuity ensures minimal effect of observer on those counts. Since 2011, additional timed counts, as well as qualitative surveys, have been conducted in Marin and Sonoma Counties, supplemented by observations of Bodega Marine Laboratory personnel and citizen scientists. Currently, three sites in Sonoma County, plus two in Mendocino County are being surveyed at least once a year for the presence of *P. hiltoni*.

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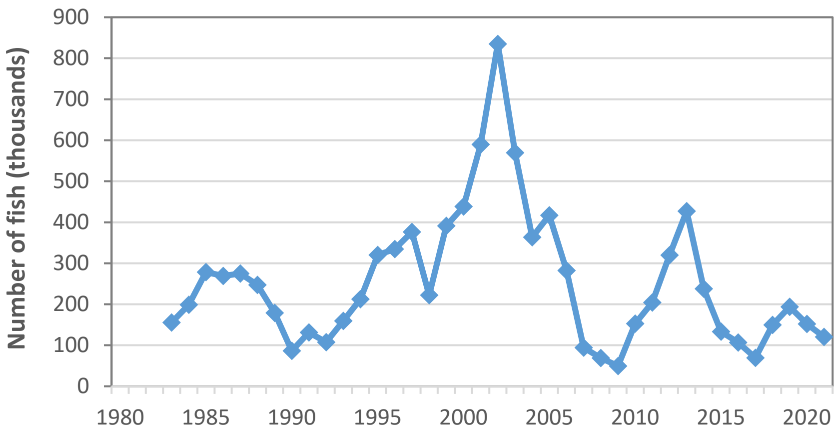
CHINOOK SALMON ABUNDANCE

California Chinook salmon (Oncorhynchus tshawytscha) populations are threatened by warming temperatures and changing conditions in freshwater, estuarine, and ocean habitats. While Sacramento River Chinook salmon abundance has been variable, winter-run abundance has seen low numbers over most of the past four decades. Salmon River spring-run Chinook salmon abundance, while also variable, dramatically declined after 2011, and has remained extremely low over the past five years.

Figure 1. Sacramento River Chinook Salmon Abundance: Fall-Run (Number of adult Salmon*)



Source: Azat (CDFW), 2022

** These counts reflect adult Chinook salmon returning to their spawning grounds in the fall after having spent 3 to 4 years maturing in the ocean. This number is also known as annual escapement, since it estimates the number of salmon that have escaped harvesting by fisheries.*

Source: US Fish and Wildlife Service

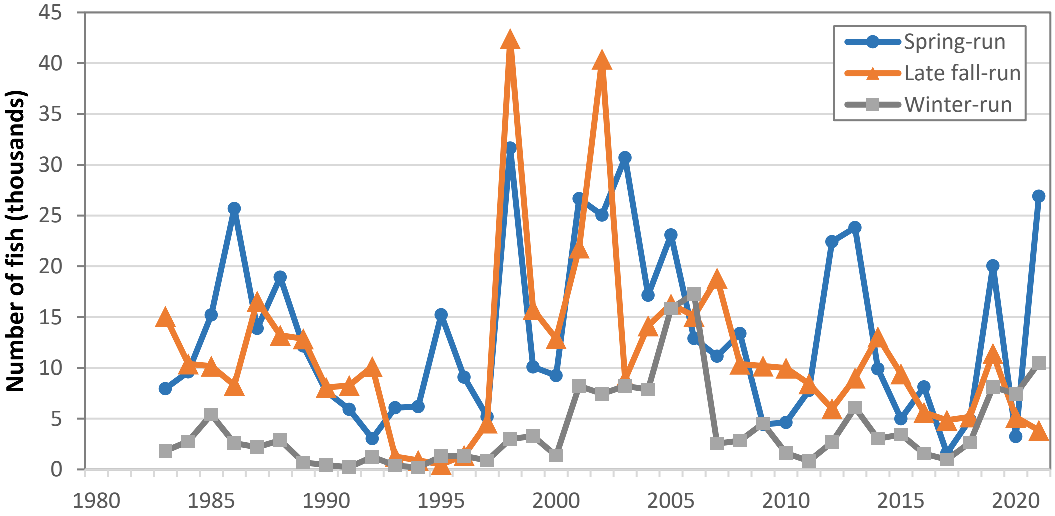
Source: USGS, 2019

Central Valley Chinook salmon rear in the fresh waters of interior California, migrate as juveniles to feeding grounds in the Pacific Ocean, and return to fresh water from July to December to spawn. Four distinct runs ("ecotypes") spawn in the Sacramento-San Joaquin River system (map on the right), named for the season when the majority of the run enters freshwater as adults. Spawning adult Chinook salmon change color from blue-green with silvery sides to olive brown, red or purple (image, left).

What does the indicator show?

Figure 1 shows the number of adult Sacramento River fall-run Chinook salmon returning from the ocean to their freshwater spawning habitat. This number is also known as annual *escapement*, since it estimates the number of salmon that have escaped harvesting by fisheries. The most abundant of the four Sacramento River runs, fall-run Chinook salmon abundance fluctuated from 1983 to 2021. Relatively constant prior to 1995, the numbers peaked in 2002 followed by seven years of mostly declining numbers. The drop in 2007 was followed by two years of record lows. Salmon numbers increased in 2012 and 2013 to levels above the 39-year average (about 260,000 fish) before declining again in 2014 through 2017. Escapement numbers started to recover in 2018 and 2019 but began declining again in 2020 and 2021.

Figure 2. Sacramento River Chinook Salmon Abundance: Winter-, Spring-, Late-fall- Runs (Number of adult fish*)



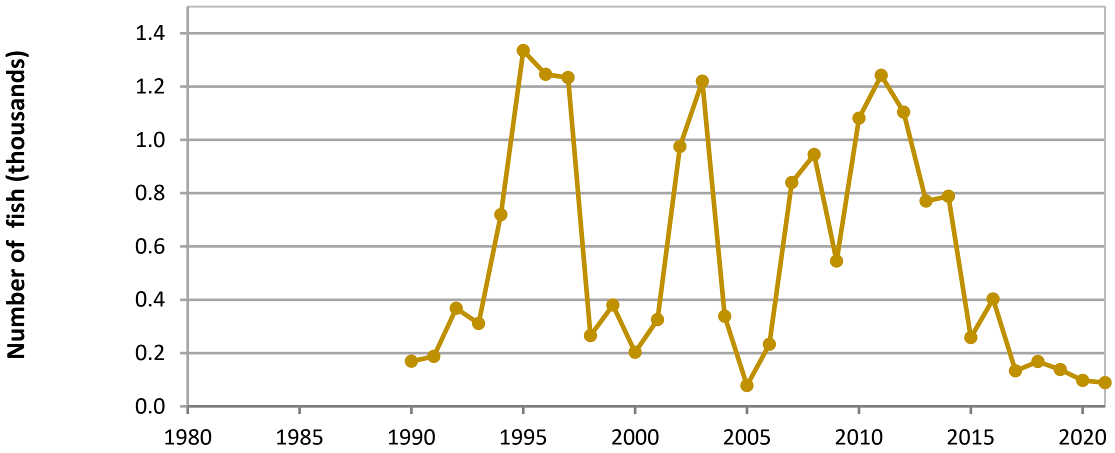
Source: Azat (CDFW), 2022

** Counts reflect adult salmon returning to their spawning grounds after spending 1 to 3 years (winter-run), 3 to 5 years (spring-run), and 3 to 4 years (late-fall) maturing in the ocean.*

Figure 2 shows Sacramento River Chinook salmon abundance for the spring, late-fall, and winter runs, which are much smaller than the fall-run population. These runs represent three distinct populations of fish with different migration patterns (described below). The staggered runs have historically allowed Chinook populations to spread risk across seasons and changing habitats. For all three runs, salmon abundance fluctuated considerably over the approximately four-decade period shown.

Spring-run abundance shows steep highs and lows but peak abundance numbers over the last decade are not reaching those seen between 1998 and 2003. The late-fall run was precipitously low from 1993 to 1996, but rebounded and reached two of its highest numbers in 1998 and 2002. Winter-run abundance is low (under 5,000 fish) in most years, dipping to extremely low numbers from 1989 to 1997, but showing an overall increase until 2006. In the late 2000s, abundance numbers again dipped for the late-fall and winter runs, and have generally remained below average since. Average fish counts over the past four decades are 11,000, 4,000 and 13,000 for the late-fall, winter- and spring-runs, respectively. Abundance numbers for all runs have been below their respective long-term averages in at least 10 of the last 15 years.

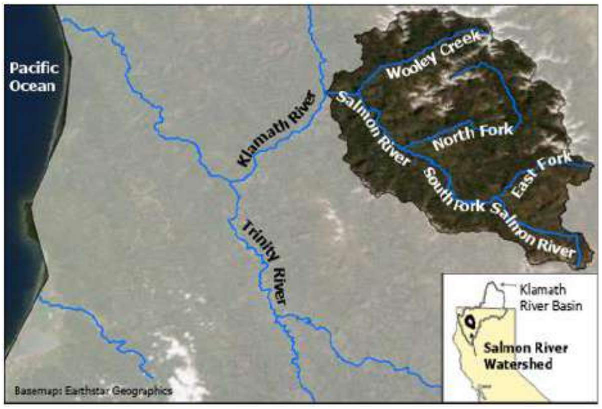
Figure 3. Salmon River Spring-Run Chinook Salmon Abundance (Number of adult fish*)



Source: CDFW, 2022a; SRRC, 2021

** These counts reflect adult Chinook salmon returning to their spawning grounds after having spent 3 to 4 years maturing in the ocean. Fish surveys in 2006 were not conducted due to regional wildfires; instead, the value for 2006 is an estimate based on the historic average (see Technical Considerations).*

Source: Michael Bravo, SRRC



Source: USGS, 2019

The Salmon River in northern California has the largest remaining wild run of spring Chinook salmon in the Klamath River watershed (map, right). As adults, spring-run Chinook (pictured, left) migrate upstream from the ocean in late spring/early summer and seek refuge in cool pools during the summer months before spawning in early fall. Juvenile fish reside in the river until the following summer and then outmigrate to the ocean.

Figure 3 shows spring-run Chinook salmon abundance in the Salmon River, from 1990 to 2021. Spring-run Chinook abundance has fluctuated with an average annual number of 568 fish over the 32-year period. A record low count of 78 fish in 2005 was attributed to extremely low flows and high prevalence of disease in 2001-2002 that limited both juvenile and adult salmon survival during their migration through the Klamath River. Numbers have been declining since 2011, and despite an increase in 2016, abundance has generally plummeted over the last decade. The salmon count of only 89 in 2021 was the fifth year in a row with population levels far below average.

Why is the indicator important?

Salmon are among California's most valued natural resources (CDFW, 2013; Moyle et al., 2017). The Chinook salmon is the largest Pacific salmon species. This iconic fish is legendary for its migration from the streams in which it is hatched to the Pacific Ocean, where it can travel as far as a thousand miles, only to return to its natal stream to spawn and die. California marks the southern end of the range of all salmon on the Pacific coast, and has two large basins that support most of the state's Chinook salmon runs: the Central Valley, which contains the Sacramento and San Joaquin River basins, and the Klamath Basin, which contains the Klamath and Trinity Rivers and their respective tributaries (including the Salmon River).

Highly valued for its flavor and nutritional benefits, salmon are an important source of revenue for the commercial fishing industry, and a prized catch for both ocean and freshwater sport fishers. In 2021, Chinook salmon commercial fisheries in California took in about $17.5 million in revenue (CDFW, 2022b). In 2008 and 2009, when escapement in the Sacramento River was extremely low, commercial and recreational fisheries were heavily impacted by closures.

Salmon are celebrated in many aspects of Tribal culture, not only as a food source, but also as species of cultural significance. For example, the Karuk Tribe's First Salmon Ceremony invokes the spring salmon run in the Klamath River; the Karuk also use the presence of salmon as an indicator of both riverine and forest habitat quality to guide traditional land management practices (Karuk Tribe, 2022; also see *Impacts on California Tribes* section of this report). Prior to European contact, different runs of fish entering the Klamath River (of which the Salmon River is a tributary) provided for the needs of several tribes, including the Yurok, Karuk and Hoopa, with the spring-run Chinook as the only salmon available between late spring and early summer. Today, due to the greatly diminished abundance of the spring-run salmon, tribal harvest is limited in the Salmon River and sport fishing is prohibited (SRRC, 2022).

Salmon play a key role in marine and inland ecosystems and thus can serve as an indicator of the health of both ecosystems (CDFW, 2013; Naiman et al., 2002). While at sea, Chinook salmon accumulate nitrogen, phosphorous and other nutrients in their bodies as they feed and grow to adulthood. When fish return to their spawning ground, their carcasses contribute to nutrient cycling and productivity of riparian systems.

Naturally-spawning Chinook salmon populations are at historically low levels despite regulatory and management efforts, restoration work, and sizable federal and state hatchery programs (Herbold et al., 2018). Scientists suggest that nearly all of California’s salmon face extinction within 50 to 100 years, with about 45 percent of the population at risk of extinction within 50 years, if current trends in climate change and other anthropogenic stressors persist (Moyle et al., 2017; UC Davis, 2017).

Estimates of spawning escapement are extremely important to salmon management as an indication of the actual reproductive population size (Wells et al., 2014). The number of reproducing adults is important in defining population viability, as a measure of both demographic and genetic risks. It is equally important to managing harvest in the fishery, which typically aims at meeting escapement goals such that the population remains viable (for Endangered Species Act-listed populations) or near the biomass that produces maximum recruitment (for stocks covered by a fisheries management plan).

Sacramento River Chinook Salmon

Sacramento River Chinook salmon winter-, fall-, late-fall and spring-runs demonstrate different migratory approaches that exploit varying landscapes and seasons. As noted above, the staggered runs have allowed Chinook populations to spread risk across seasons and changing habitats, stabilizing their numbers. However, beginning in the 1930s, mining, water diversions and other human activities have threatened their survival. In recent decades, climate-related disturbances have since placed additional stresses on the salmon populations (Munsch et al., 2022).

- Sacramento River ***fall-run*** Chinook salmon have been the largest contributor to ocean salmon harvest off California and Oregon for decades (O’Farrell et al., 2013). This historically large run is now the dominant fish population in the Central Valley due to declining spring and winter runs and the naturally small size of the late-fall run (Yoshiyama et al., 1998). It is designated as the indicator stock for guiding Central Valley salmon population management and habitat restoration plans. Unfavorable climate conditions and other anthropogenic impacts have led to the fall-run Chinook salmon’s designation as a s*pecies of special concern* by the California Department of Fish and Wildlife (CDFW) (CDFW, 2022c).
- The ***late–fall*** Chinook salmon have been eliminated from most of their native spawning habitat and for the most part are now dependent upon cold water releases from reservoirs and habitat mitigation efforts (CalTrout, 2022a). Additionally, since 2000 hatchery fish have made up at least half the adult fish returning to spawn. Because late-fall run Chinook salmon spend more time feeding in the ocean than the other salmon runs, they tend to be larger fish and highly coveted by sport fishers. Central Valley fall-run Chinook salmon are designated by CDFW as a *species of special concern* (CDFW, 2022c).
- The Sacramento River system is home to the only ***winter-run*** Chinook salmon in the world (US NMFS, 2019). Winter–run Chinook salmon are especially

vulnerable because they spawn during the summer months when temperatures are their warmest. This run has persisted largely due to managed cold water releases from Shasta Reservoir during the summer and artificial propagation from a fish hatchery (NOAA, 2022a). Ironically, the dam above the reservoir has blocked access to high elevation cold waters and is largely why the winter-run has suffered huge declines. Winter-run Chinook was the first Pacific salmon to be state and federally listed as *endangered* in 1989 and 1994, respectively (Phillis et al., 2018).

- ***Spring-run*** Chinook salmon were a historically abundant salmon stock in the Central Valley prior to habitat degradation and the construction of dams which blocked access to their native habitats. Now only remnant runs remain in the main-stem Sacramento River and three of its tributaries. Central Valley spring-run Chinook salmon were state and federally listed as *threatened* in 1999 (CDFW, 2022d).

Salmon River Chinook Salmon

The Salmon River is the second largest tributary to the much larger Klamath River system (SRRC, 2020). Spring-run Chinook salmon were once widely dispersed throughout tributaries of the Klamath River upstream of the Trinity River confluence. Mining activities beginning in the late 1800s and dams built between 1918 and 1962 severely impacted the fish population in the Klamath region. These fish are critical to the food security, cultural survival and well-being of indigenous people in the Klamath Basin including the Karuk Tribe (Karuk Tribe, 2016). The Salmon River does not have a hatchery, making this a unique refugia for wild salmon. Efforts to restore the Salmon River from mining, logging and other past land management practices have left it a remaining stronghold tributary in the Upper Klamath-Trinity River system for wild spring-run Chinook salmon. (Very low numbers of spring-run salmon are also found in the South Fork Trinity River and the New River, a tributary to the Trinity River).

Because spring-run Chinook salmon stage in cold water pools throughout the summer when stream flows are reduced and temperatures approach their upper tolerance, their abundance is a good indicator of ecosystem health (CalTrout, 2022b). Spring-run Chinook salmon were declared *threatened* in the Upper Klamath-Trinity River by the State of California in January 2022 (California Fish and Game Commission, 2022) and are currently being considered for listing by the federal government (NMFS, 2021).

The Salmon River also supports fall-run Chinook salmon, the most abundant salmon population in the Klamath watershed (SRRC, 2022). Fall-run Chinook salmon enter the river in the late summer and early fall, making them less vulnerable to warm summertime water temperatures and drought conditions. However, diminished water quality and flow in the Klamath River may be tied to fall-run numbers well below average for five of the past seven years (Meneks, 2022).

What factors influence this indicator?

The multi-year life history of Chinook salmon is essential to understanding how climate change can impact salmon in different habitats and during all life stages, including escapement. California Chinook salmon spawn and rear in fresh water bodies and migrate to the ocean to feed for three to four years on average until they become adults. Changes in climate can alter freshwater, estuarine, and marine habitats, putting salmon populations at risk. Studies have identified warm temperatures and low flows as harmful to salmon in the Central Valley (Herbold et al., 2018; Moyle et al, 2017; Munsch et al., 2019). As noted above, anthropogenic influences such as dams and fish hatcheries can also affect salmon population abundance. These stressors amplify the impacts of climate change; for example, dams block access to higher elevations where water temperatures are cooler, water withdrawals reduce stream and river flow, and warmer water temperatures render juvenile fish more vulnerable to predators.

This section describes factors influencing Sacramento River Chinook salmon runs and Salmon River spring-run Chinook salmon in fresh water and marine environments.

Fresh water environment

California salmon abundance in fresh water streams and rivers is influenced by dynamic interactions between natural landscape features (e.g., climate and topography) and human activities. Anthropogenic influences on salmon populations include urban and agricultural runoff, dams, water diversion for agricultural and domestic uses, and mining (Moyle et al., 2013; Wells et al., 2014). Land and water use changes over the past century have eliminated or blocked access to important habitats, limited habitat diversity, and constrained salmon distribution (Herbold et al., 2018; Munsch et al., 2022).

California Chinook salmon now encounter more stressful climatic conditions than those in which they evolved (Herbold et al., 2018; Moyle et al., 2013; Wells et al., 2014). As air temperatures rise, river and stream temperatures have increased and will likely continue to increase. With warming temperatures, more precipitation falls as rain instead of snow in the mountains (see *Precipitation*, *Snowmelt runoff* and *Snow-water content* indicators), reducing the amount of snowmelt that provides cold water year-round to rivers and streams. During drought periods, wetlands habitat availability and connections between salmon habitat areas are reduced and water quality is compromised (Crozier et al., 2019).

Streamflow is an important determinant of water temperature (Moyle et al., 2017; Wells et al., 2014). River and stream temperatures are cooler when flows are high and warmer during years with diminished flows. Low summertime flows from lack of snowmelt together with warmer temperatures in salmon freshwater habitats can alter prey composition, riparian vegetation, and stream morphology. These changes in habitat affect salmon physiology and behavior in freshwater, which can in turn have consequences for growth and survival in the marine life stage. Significant reductions in cold-water river and stream flows in the summer may directly affect spawning, egg viability, rearing conditions and juvenile and adult migration (Munsch et al., 2019; Wells et al., 2014). Temperature and flow constraints on seaward migration timing may result in premature migrations when fish are small and vulnerable or before ocean conditions are favorable. Scientists have identified threshold levels of flow that are necessary for juvenile salmon survival and habitat use that could be used to assist in watershed restoration efforts (Michel et al., 2021; Munsch et al., 2020).

Sacramento River Chinook salmon

Historically, the Central Valley was characterized by a diversity of landscape features that allowed for salmon populations to develop resilience to climate change (Munsch et al., 2022). The four Chinook salmon subpopulations encounter different climate conditions due to differing life history patterns (set of events and traits that define the life cycle) and area-specific environmental conditions, as discussed above (CDFW, 2013). For example, while fall- and late-fall run Chinook salmon migrate upstream and spawn in the river during the cooler months, spring- and winter-run Chinook salmon enter the river and spawn during the warmer months and for longer periods of time. Before the building of dams, the spring- and winter- runs adapted to natural habitats at higher elevations with access to colder summertime waters. The winter-run's reliance on dam releases for cold water make them especially vulnerable to warming freshwater temperatures.

Chinook salmon populations were much more abundant across the Central Valley before anthropogenic influences described above caused severe population declines. (Wells et al., 2014; Yoshiyama et al., 1988). The trends shown in Figures 1 and 2 reflect data since 1983, a time when populations had stabilized at lower abundance levels, largely sustained by hatchery programs.

The Sacramento River and its tributaries rely on Sierra Nevada snowpack to provide cold waters for Chinook salmon habitat. When water is cold and flows are high, egg survival increases; juveniles use habitats for longer time periods--they grow larger, survive better, and can better avoid predators (CCIEA, 2022). Scientists have shown that Sacramento fall-run Chinook salmon adult returns in a given year are correlated with snowpack levels from two years prior because high snowpack indicates cold, wet conditions in the watershed. Because the Sacramento River Basin has suffered from loss of salmon habitat and life history diversity, salmon abundance is expected to increasingly track snowpack (Munsch et al., 2022). It is predicted that adult returns will decline in 2022 and 2023 relative to 2021 based on below average snowpack in 2020 and 2021.

A severe and prolonged drought from 2012-2016 resulted in reduced winter and spring flows in the Sacramento River watershed, increased fish energy expenditure during outmigration due to slow water velocities, elevated temperatures within outmigration corridors, decreased food availability, and increased risk of predation and disease

(Herbold et al., 2018; PFMC/NMFS, 2020). As shown in Figure 1, the impacts of drought conditions and exceptionally warm air temperatures on fall-run Chinook salmon population abundance were evident for four years beginning in 2014. For winter-run Chinook salmon, very low abundance numbers in the 1990s due to anthropogenic stressors prompted habitat enhancements and cold water releases from the Shasta Reservoir to manage water temperatures. The lack of cold water behind Shasta Dam during the drought led to unsuitable stream temperatures in spawning grounds and 95 percent mortality of eggs and fry in 2014 and 2015 (Voss and Poytress, 2017). Consequently, winter-run abundance was alarmingly low in 2016 and 2017 as shown in Figure 2 (Meyers, 2021). During the drought years, young spring-run Chinook salmon had low out-migration survival rates; once flows were restored escapement numbers began to rebound beginning in 2018 (Cordoleani et al., 2021; Notch et al., 2020).

The year 2021 was one of the warmest and driest years on record (see *Air temperature and Precipitation* indicators). During the summer, scientists estimated that about 75 percent of winter-run salmon eggs died in the Sacramento River due to high temperatures driven by extreme drought conditions and historically low reservoirs (NOAA, 2022b). The 2021 freshwater conditions likely limited survival of the 2021 brood year and is expected to impact winter-run escapement numbers in 2023 and 2024.

Fish hatcheries in the Sacramento River watershed sustain salmon populations for the four runs by promoting increased juvenile survival to adulthood during periods of poor freshwater and ocean conditions (Herbold, 2018). Hatcheries release artificially propagated juvenile salmon into freshwater, estuary or marine habitats to supplement natural-origin salmon production. The number of hatchery fish released in the Central Valley has remained fairly stable over the past decades; however the need to transport hatchery fish downstream has increased in recent years to reduce outmigration mortality in increasingly hot, degraded waterways (Huber et al., 2015; Sturrock et al., 2019). Emergency downstream trucking of salmon in 2014-2015 was implemented to improve survival rates during this extreme drought period.

Future reductions in stream flow and increases in stream temperature are expected in the Sacramento River and its tributaries, fed by the northern Sierra Nevada (its lower elevation makes this region more vulnerable to warming than the southern Sierra Nevada) (Moyle et al., 2017). Management strategies that aim to mimic historic diverse habitats and conditions under which the salmon runs evolved could promote climate resilience for salmon populations in the years to come (Munsch et al., 2022; PFMC/NMFS, 2020).

Salmon River spring Chinook

Starting at the turn of the 20th century, the spring-run Chinook population in the Salmon River suffered precipitous declines due to habitat degradation from mining, over-fishing, logging, diversions and dams in the Klamath River Basin. The construction of dams in other rivers in the basin blocked access to much of their historical spawning grounds. The Salmon River itself, however, has no dams or hatcheries, a rugged terrain preventing the introduction of infrastructure and relatively little water diverted for human uses due to the area's low population density (SRRC, 2020). Few anthropogenic influences allow scientists to better assess how climate change may be impacting wild spring-run Chinook salmon on this river.

Water temperatures in the Salmon River and its tributaries are warming due to increases in air temperatures and decreases in snowpack and river flow (see *Salmon River Water Temperature* indicator). During the period 1995-2017, mean August water temperatures warmed at a rate of 0.38°F per decade and mean daily maximum August water temperatures warmed at a rate of 0.70°F per decade. Spring-run Chinook salmon live in these habitats through the entire summer, and under current conditions peak summer temperatures in portions of the river and its tributaries are likely at or exceeding thermal suitability for this species (Strange, 2010).

As noted above, years of low snowpack and snow water runoff tend to yield decreases in stream and river flow in watersheds. Low August flow rates in the Salmon River coincided with warmer stream temperatures in 2014 and 2015 (Asarian et al., 2019), which likely impacted juvenile Chinook salmon survival and adult escapement numbers three to four years later. Conversely, higher flow rates in 2010 and 2011 corresponded with much cooler stream temperatures and high salmon abundance.

An indicator of warmer temperatures and less snow in the region is the dramatic melting in recent decades of glaciers in the Trinity Alps at the headwaters of the Salmon River's South Fork (Garwood et al., 2020; see also *Glacier change* indicator). These glaciers historically fed cold water to streams during the summer. Declining glacial ice and snowpack in the Trinity Alps foretell how climate change threatens the unique distributions and resiliency of fish in the Klamath River watershed.

Marine environment

Changes in physical, chemical and biological components and processes in the ocean affect the viability of young salmon as they feed and grow to adulthood. Salmon survival during the initial months of ocean life depends on available prey (largely krill, forage fish and crab larvae) (Wells et al., 2014; 2017). Increasing ocean temperatures can negatively alter the food web on which salmon depend, changing the range of predators, competitors, and prey species. In addition, water temperature affects fish metabolism, development, behavior, and distribution. Overall, warming ocean temperatures are expected to result in range changes for California salmon, a phenomenon that is already occurring with other fishes (Crozier et al., 2019; Wells et al., 2014).

Along the California coast, the timing and intensity of "coastal upwelling" — a wind-driven motion of dense, cooler, and usually nutrient-rich water towards the surface — also affect salmon (Crozier et al., 2019; Wells et al., 2016). Salmon feed on krill, phytoplankton and other prey in upwelled waters and have suffered population declines during years of weak upwelling conditions. Warming surface waters can increase water column thermal stratification and reduce upwelling of cold nutrient-rich water. Evidence suggests that warm sea surface temperatures, weak upwelling, and low prey densities in 2005 and 2006 resulted in unusually poor survival of juvenile Sacramento River fall-run Chinook (Lindley et al., 2009). During this time, warm water temperatures compressed salmon prey species towards the coast where out-migrating juvenile salmon are foraging (Well et al., 2017). This concentration of forage species also attracted salmon predators (e.g., common murre), and likely impacted juvenile salmon survival. The steep decline in fall-run salmon abundance in 2007 (see Figure 1) may have been in part a response to these ocean conditions.

Another ocean condition that may threaten Chinook salmon is the acidification of coastal waters as a consequence of increasing atmospheric carbon dioxide (Wells et al., 2014; Crozier et al., 2019). Although acidification will likely have little direct effect on salmon, increasing ocean acidity may have a significant impact on invertebrate prey species such as squid, crabs and krill that are important to the salmon diet (see *Acidification of coastal waters* indicator).

Along the Pacific coast, rising sea levels can lead to inundation of low-lying lands and increases in salinity, transforming estuary habitats for migrating salmon (Wells et al., 2014). Because the success of salmon rearing in coastal estuaries strongly influences later survival in the ocean, the physical and biological conditions of estuaries is very important.

Technical considerations

Sacramento River Chinook Salmon Abundance

Data characteristics

Total spawning escapement values for the four salmon runs were taken from the California Central Valley Chinook Population Database Report (Azat, 2022). The report, also known as “GrandTab,” is a compilation of sources estimating the late-fall, winter, spring, and fall-run Chinook salmon total populations for streams surveyed. Estimates are provided by the California Department of Fish and Wildlife, the US Fish and Wildlife Service, the California Department of Water Resources, the East Bay Municipal Utilities District, the US Bureau of Reclamation, the Lower Yuba River Management Team, and the Fisheries Foundation of California.

The *Central Valley Chinook Salmon In-river Escapement Monitoring Plan* is used by fisheries resource managers across the basin for estimating numbers of adult Chinook salmon returning to spawn (Bergman et al., 2013). After completing the ocean stage, hatchery-origin fish generally return to tributaries concurrently with natural salmon and are part of abundance counts. Escapement estimates are based on counts of fish entering hatcheries and migrating past dams, carcass surveys, live fish counts, and ground and aerial redd counts. This comprehensive plan includes a spatially and temporally balanced sampling protocol that when implemented allows for statistically defensible estimates of population status.

Strengths and limitations of the data

Chinook salmon monitoring has been conducted on the Sacramento River since 1950; however, abundance data in the early decades were lacking in precision and consistency (Bergman et al., 2013). The National Oceanic and Atmospheric Administration (NOAA) Northwest Fisheries Science Center in their salmon indicator report present Chinook salmon abundance trends beginning in 1985, citing lower data quality and consistency prior to this year (Wells et al., 2014).

Salmon return counts lack precision because the numbers are generated by combining data from multiple sources (e.g., red counts, carcass counts, hatchery returns). Although salmon return data do not provide estimates of variance, the data are still useful for trend analysis.

Escapement estimates can be underestimated when fish returning to spawn stray into other rivers that are outside the sampling area.

Salmon River Spring-run Chinook Salmon Abundance

Data characteristics

Spring-run Chinook salmon estimates for the Salmon River are collected during an annual cooperative spawning survey. Since 1995, the Salmon River Restoration Council (SRRC) has helped coordinate with the US Forest Service the annual Spring Chinook and Summer Steelhead Cooperative Fish Dive. A crew of 80 trained divers from state and federal agencies and local tribes work together to swim the entire Salmon River to survey the fish population. The dive event covers the upper mainstem and the North, South and East forks of the river in a single day. The lower mainstem and Wooley Creek (a large tributary) are surveyed separately in the same week. The survey area is about 89 miles measured in intervals or “reaches” of two to four miles. The dive takes place in late July when fish are holed up in deep pools and near cool side streams, making possible an actual count of individual fish (SRRC, 2022).

Strengths and limitations of the data

Both the methodology and effort made when conducting the summer dive events have been consistent over the years with the exception of 2006 and 2020. Wildfire closures in 2006 prevented the mainstem Salmon River and Wooley Creek from being surveyed. An expansion equation was developed to estimate the number of spring-run Chinook salmon that would have been counted on those reaches based on the historic average. In 2020, the COVID-19 pandemic restricted divers to a core number of individuals and the survey was spread out over two days instead of one. The entire survey area was covered with the exception of two lower priority reaches and was not expected to significantly affect the count (Personal communication, Sophie Price, SRRC, April 2022).

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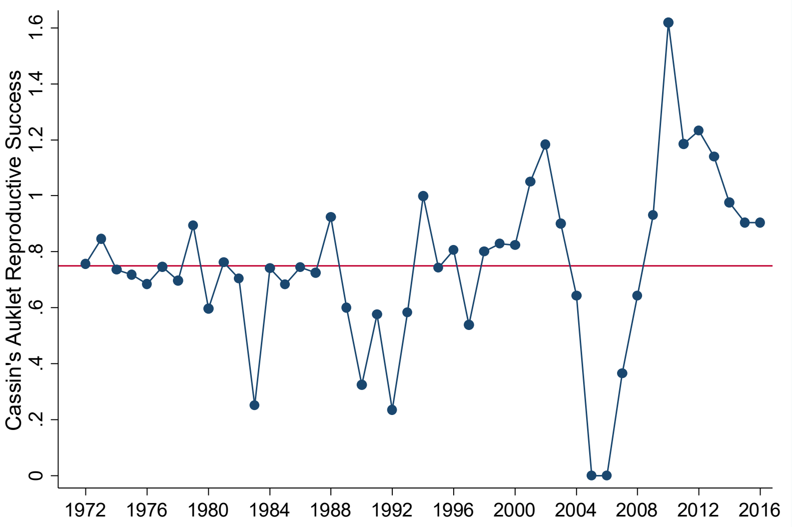
CASSIN'S AUKLET BREEDING SUCCESS (NO UPDATE)

Over a 45-year period, the reproductive success of the Cassin's auklet has exhibited increasing variability (extremely low and extremely high reproductive success) with time, while showing an overall increase in reproductive success over the past 25 years.

Figure 1. Breeding success of Auklets on the Farallon Islands, CA*



Source: Point Blue, 2017

** Chicks fledged per breeding pair.*
Red line shows long-term mean (1972-2016).

What does the indicator show?

Figure 1 shows the variable year-to-year reproductive success of Cassin's auklets over the period 1972-2016 in study sites on Southeast Farallon Island (see map, Figure 2). Reproductive success, measured as the mean number of offspring produced per year per breeding pair declined slightly until about 1992 but since then has exhibited a significantly increasing trend. In the last 15 years, reproductive success has averaged 0.842 chicks produced ("fledged") per pair, above the previous 15-year average of 0.704 (see Table 1); the 45-year mean value is 0.75 chicks per pair.Notable is the increase in year-to-year variability: reproductive success during the last 15 years was three times

Figure 2. Map showing location of Southeast Fallon Island (SEFI)

Source: Point Blue, 2017

more variable than during the first 15 years (see Table 1). The two years with the lowest values and the five with the highest also occurred during the last 15 years.

Table 1. Annual variability in Cassin's Auklet breeding success, divided into three 15-year intervals

Time period	Reproductive success, Mean (Standard deviation)	Proportion of double-brooding	Rate of abandonment
1972-1986	0.704 (0.143)	0.137	0.215
1987-2001	0.704 (0.230)	0.234	0.251
2002-2016	0.842 (0.451)	0.334	0.239

The Cassin's auklet (*Ptychoramphus aleuticus*) is a small, diving seabird. Its breeding range extends from the Aleutian Islands, Alaska to islands off the middle Baja California peninsula. Its center of distribution is located off British Columbia, on Triangle Island (Rodway, 1991). Important colonies in California occur on Southeast Farallon Island (part of the Farallon Islands National Wildlife Refuge, located 30 miles west of San Francisco) and on the Channel

Cassin's auklets lay one egg per breeding attempt, and are the only species in the Alcidae family which show regular behavior of "double-brooding," that is, rearing a second chick after successfully fledging their first chick (Johns et al., 2017). Double-brooding allows productivity of the population to exceed 1.0 chick per pair in exceptionally good years. There have only been six years when mean reproductive success for the population exceeded this threshold, all since 2000. The rate of double-brooding varies among years, and as shown in Table 1, has increased over time (P = 0.043).

Double-brooding and the rate of abandonment of eggs during incubation are two components that account for much, but not all, of the annual variation in reproductive success. While double-brooding has increased over time, the abandonment rate has shown no such trend (Table 1). Two recent years (2005 and 2006) were unusual in that reproductive success was zero and the abandonment rate was also extremely high (100 percent and 86 percent, respectively). Neither of these years were El Niño years, but they were years in which krill were absent from the diet fed to chicks (see below). In the other 43 years, the relationship between abandonment and reproductive success was more variable. Some years with low reproductive success also had high abandonment (67 percent in 1983 and 65 percent in 1992); in 1990 reproductive success was low but abandonment was also low (17.5 percent compared to the 45-year mean of 24 percent).

Why is this indicator important?

Seabirds such as the Cassin's auklet respond to changes in prey availability and prey quality, which in turn are influenced by climate (Lee et al., 2007; Wolf et al., 2009). Hence, seabirds can be, and have been, used as reliable indicators of food web changes in marine ecosystems (Piatt et al., 2007). Seabirds are among the most conspicuous of all marine organisms and changes in their populations or vital rates may reflect changes in their prey base, such as krill, that are more difficult to study (Ainley et al., 1995; Piatt et al., 2007; Manugian et al., 2015).

Studies of seabirds suggest that ocean warming and other forms of marine climate change are affecting the coastal food web, particularly krill. Krill is a major food resource not only for seabirds, but also for salmon, other fish, and marine mammals, including whales (Dransfield et al., 2014, Sydeman et al. 2014). Ocean warming may reduce the efficacy of upwelling — the upward movement of deep, cold, nutrient-rich waters to the surface, where plankton growth occurs (Snyder et al., 2003; Manugian et al., 2015). Reduced upwelling decreases nutrient availability and photosynthesis by phytoplankton, ultimately leading to a reduction in krill and other zooplankton. Hence, upwelling is key for many seabirds in the California Current.

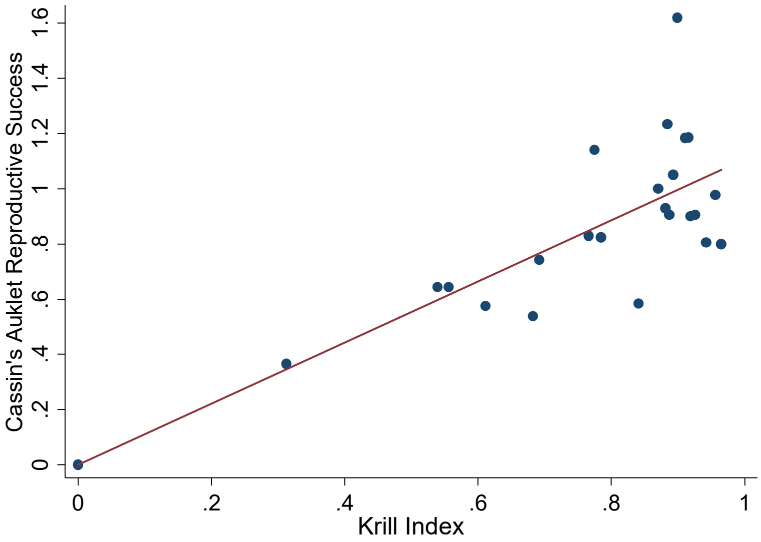
Measurements of auklet reproductive success provide a strong signal of changes in ocean conditions — as reflected in prey availability — in the ecosystem over the period of time when the birds are reproductively active each year (March through August). Recent years of record-high auklet productivity on the Farallones have been associated with large local increases in krill, as documented below. In addition, seabird reproductive success has been shown to correlate with salmon abundance (Roth et al., 2007), suggesting that the reduction of krill abundance may be affecting salmon as well. Thus, the auklet reproductive success indicator reflects bio-physical processes occurring in the marine ecosystem. The recent increase in both overall reproductive success and annual variability of this indicator provide insights into temporal patterns of variation in the local marine ecosystem.

What factors influence this indicator?

Cassin's auklet breeding success on Southeast Farallon Island is most closely associated with variation in the availability of their prey, particularly krill. Krill are the main prey consumed by auklet chicks on Southeast Farallon Island, accounting for about 80 percent of their diet in typical years (Abraham and Sydeman, 2004). Auklets feed primarily on two krill species — *Euphausia pacifica* and *Thysanoessa spinifera — as* well as mysids and some larval fishes (sanddabs, rockfish, etc.). Years characterized by low krill biomass in the auklet's foraging grounds in the Gulf of the Farallones (e.g., 2005 and 2006) were associated with low reproductive success (Sydeman et al., 2006; Jahncke et al., 2008; Manugian et al., 2015). Conversely, during years when krill was abundant in the region (e.g., 2010 and 2011), auklets exhibited high productivity, more specifically high rates of double-brooding, as described below.

Auklet reproductive success is strongly related to measures of krill abundance and/or availability. There was a strong, linear relationship between the “krill diet index” for Cassin’s auklets and their reproductive success (see Figure 3 below). The krill diet index is the proportion of prey fed to Cassin’s auklet chicks that consists of the two krill species listed above. The median value of the krill diet index was 87 percent (n = 25 years). However, in years when the krill diet index was less than 75 percent, reproductive success was in every case (n = 8 years) below the mean (and median) value for the entire time series. The krill index in 2005 and 2006 was zero. Conversely, high krill index values are associated with moderate to high reproductive success, though, even then, auklets exhibit considerable variability in outcome.

Figure 3. Auklet mean reproductive success and krill diet index* (1991-2016)



Source: Point Blue, 2017

*Chicks fledged per pair in relation to the krill diet index, i.e., proportion of diet fed *to chicks that are euphausiids. The line of best fit is shown (P < 0.0001)*

In addition, measures of krill abundance or biomass (to 30 meters deep, estimated by acoustic surveys conducted by Point Blue’s ACCESS Project) (Manugian et al., 2015) were more closely related to reproductive success than the krill diet index alone. In particular, the frequency of double-brooding is more closely related to krill biomass than the krill diet index. These results make clear that krill abundance and/or availability determines both high values of reproductive success (when double-brooding is common) and low values.

The influence of seasonal, wind-driven upwelling processes off the California coast on the productivity of the marine food web is well established (Garcia-Reyes et al., 2015). Upwelling brings deep, nutrient-rich waters to the surface. These nutrients are vital to the growth of plankton, which form the base of the marine food chain. Upwelling is driven by oceanographic conditions, especially wind patterns, which in turn reflect large-scale climate signals associated with the tropical Pacific Ocean – El Niño-Southern Oscillation (ENSO) (WRCC, 1998) — as well as with the North Pacific (Pacific Decadal Oscillation and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008)). ENSO is a cyclic interaction between the atmosphere and ocean in the tropical Pacific that has manifold effects, including the periodic variation between below-normal and above-normal sea surface temperatures. NPGO is part of a large-scale pattern of climate variability in the North Pacific that affects sea surface height and sea surface temperature; it also influences the strength of ocean circulation in the North Pacific Gyre, which includes waters transported into the California Current Ecosystem.

Cassin's auklet reproductive success, in turn, has been associated with these underlying patterns of climate variability (Abraham and Sydeman, 2004; Sydeman et al., 2006; Jahncke et al., 2008; Wells et al., 2008). During two of the strongest El Niño periods in the last four decades (1982-83 and 1991-1992), there was a substantial decrease in auklet breeding success. In contrast, recent years have shown auklet reproductive success to be less linked to ENSO signals and more strongly associated with the NPGO (Di Lorenzo et al. 208, Schmidt et al., 2014). Changes in both the characteristics of the El Niño Southern Oscillation (such as a shift in the center of the warm water anomaly from the eastern Pacific to central Pacific) and a shift to greater positive values of the NPGO (which is associated with the earlier onset of upwelling favorable conditions) are likely playing a role in the shift in the auklet response (Schmidt et al., 2014). It is hypothesized that local changes in upwelling winds in the California Current are more consistent with changes in the NPGO index than indices of ENSO.

Technical Considerations

Reproductive success of Cassin's Auklets is measured by monitoring breeding birds in 44 nest boxes on Southeast Farallon Island (Abraham and Sydeman, 2004; Lee et al., 2007). Greater than 90 percent of the boxes are occupied by breeding birds each year, although fewer pairs attempt reproduction in years of poor food availability. Each nest box is checked every 5 days for nesting activity. Parent birds are uniquely banded for future identification. The date of egg-laying, number of eggs laid and hatched, and the number of chicks raised to independence by each breeding pair is counted. For this indicator, the overall annual reproductive success is assessed as the average number of offspring fledged per breeding pair per year. "Double brooding" rate, as discussed here, is defined as the proportion of birds that initiate a second reproductive effort (i.e., lay an egg) after fledging a chick successfully in their first attempt. "Abandonment rate" is defined as the proportion of breeding pairs which permanently left eggs unattended during incubation, leading to egg failure.

Strengths and Limitations of the Data

Cassin's Auklets and other breeding seabirds have been monitored on the Farallon Islands using standardized methods since 1972 (Boekelheide et al., 1990; Johns et al., 2017). During the 45-year period, great care was taken to keep the methodology as comparable as possible. Field biologists are intensively trained by professional biologists from Point Blue Conservation Science. Thus, methodology has remained highly consistent over the past 45 years.

Seabirds have demonstrated that they are excellent indicators of ecological conditions (Parsons et al., 2008). One strength of the indicator is the ability to correlate reproductive success directly with a key determinant of this ecological variable, the availability and/or abundance of two key prey species. The time series reflecting krill in the chick diet is now 25 years. The time series based on direct measures of krill biomass in the areas near the breeding colony is now 13 years. The longer time series has provided a better understanding of determinants of krill abundance (Manugian et al., 2015).

Their ability to initiate a second clutch after a successful first breeding make Cassin's auklets particularly valuable as an ecosystem indicator among seabirds. Their flexible reproductive strategy allows for tracking both positive deviations (when double-brooding is more common) and negative deviations (when mortality of eggs and/or chicks is high). Thus, the range of outcomes for Cassin's auklets is greater than that of species that lay only one clutch of a single egg.

A limitation of the indicator is that identifying a climate change signal due to anthropogenic influences is difficult to discern, compared to the effect of natural climate variability (e.g., impacts of the El Niño Southern Oscillation). In this regard, the increased variability of the indicator in recent years is a finding of note; it improves the understanding of what may be underlying both the especially low and especially high values of auklet reproductive success.

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CALIFORNIA SEA LION PUP DEMOGRAPHY (NO UPDATE)

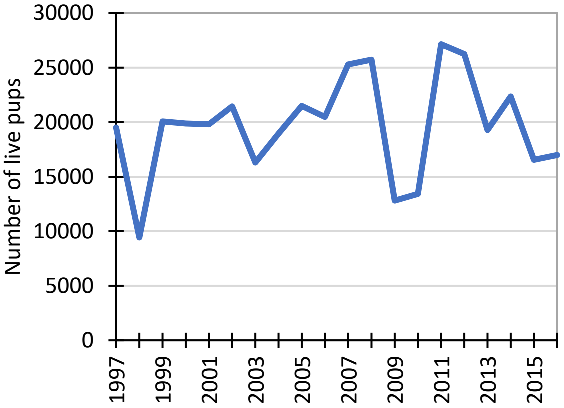
Unusually warm sea surface temperatures have been associated with declines in pup births, increased pup mortality and poor pup condition among California sea lions.

The California sea lion (Zalophus californianus) is a permanent resident of the California Current System. Females give birth to a single pup between May and June. For about 11 months, lactating females travel to sea for 2-5 days to feed and return to nurse their pup.

The Point Bennett Study Area at San Miguel Island (off Santa Barbara) is a large sea lion breeding area used as a long-term index colony for monitoring pup production and mortality.

Photo: Eric Boerner, NOAA

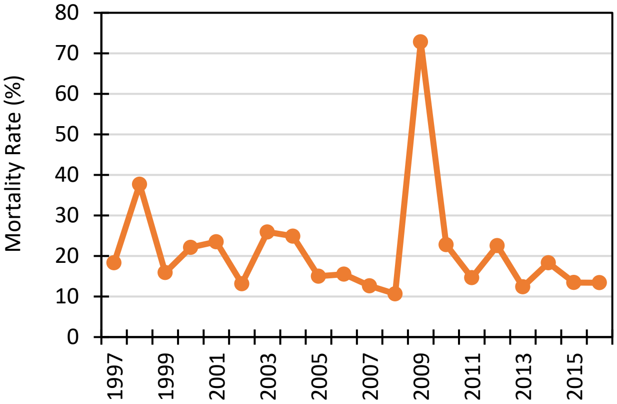
Figure 1. Sea Lion Live Pup Count*



** Based on live pups counts conducted July 20-30 annually*

Source: Harvey et al., 2017

Figure 2. Sea Lion Pup Mortality Rate*



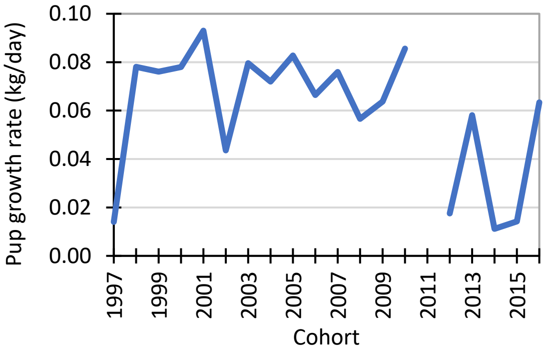
** At 5 weeks of age in the Point Bennett Study area*

Source: NMFS, unpublished data

What does the indicator show?

Sea lion demographic parameters fluctuate with oceanographic conditions, particularly warm surface water temperatures. The indicator consists of three metrics based on monitoring of California sea lion population indices (pup births, pup mortality, and pup growth) and oceanic conditions between 1997 and 2016 at San Miguel Island's Point Bennett Study Area (see map, Figure 4). (Melin et al., 2010).

Figure 3. Female Sea Lion Pup Growth Rate*



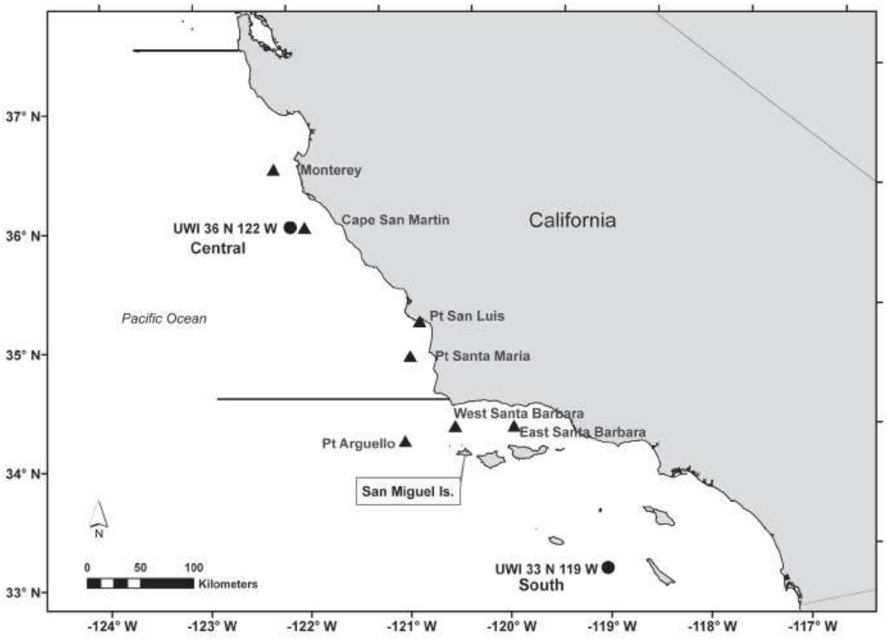
**Estimated mean daily growth rate of female pups between 4 and 7 months of age; no count was conducted in 2011.*

Source: Harvey et al., 2017

Annual pup counts at San Miguel Island between 1997 and 2016 ranged from a low of 9,428 to a high of 27,146 (Figure 1). The counts occurred in 1998, 2009, and 2010, all years characterized by warm ocean conditions (Wells et al., 2017).

Pup production is a result of successful pregnancies and is an indicator of fish and cephalopods that serve as prey for sea lions. The high pup counts in 2011 and 2012 suggest that pregnant females experienced good foraging conditions in these years when cooler ocean conditions prevailed. The number of births declined again in 2015 and 2016 in response to warmer ocean waters due to a marine heat wave and El Niño conditions in 2015 (McClatchie, 2016; Wells et al., 2017).

Figure 4. Location of San Miguel Island



Source: Melin, et al., 2010

Figure 2 shows that in 2009, early pup mortality among sea lions during the first 5 weeks of life was exceptionally high, almost four times greater than the long-term average (73 percent in 2009, compared to about 20 percent long-term). The high pup mortality rates in 1998 and especially 2009 were associated with anomalously high sea surface temperatures (SSTs). However, during more recent warm ocean events in 2014-2015, pup mortality was near average, while pup growth rate during this period was low. This suggests that lactating females were able to support their pups for the short-term (first 5 weeks) but that females could not provide enough energy for long-term growth of their pups.

Pup growth from birth to 7 months of age is an indicator of the transfer of energy from the mother to the pup through lactation, which is related to prey availability during this time period. The lowest female pup growth rates occurred in 1997, 2014, and 2015 (Figure 3). (No data are available for 2011; researchers were unable to conduct a count that year.) These years were characterized by unusually warm ocean temperatures that were associated with El Niño conditions (1997, 2015) and a marine heat wave (2014-

2015) (Wells et al., 2017). Pup growth for the 2014 cohort was the lowest observed over the time series. As ocean conditions returned to near-normal in 2016, pup growth improved, returning to the long-term average (Wells et al., 2017). The very low growth rate for the 2012 cohort occurred during an unusually cold period of ocean conditions during winter 2012/2013 that normally would have resulted in good growth rates; the causes of the low growth rates for the 2012 cohort remain unexplained.

Why is this indicator important?

Sea lions and other marine mammals are prominent animals that reflect ecosystem variability and degradation in the ocean environment. Animals at higher levels in the food chain provide insights into relationships among marine community structure and oceanographic conditions (Weise, 2008). Scientists use marine mammals as sentinels of ocean production and changes in food webs, and increasingly include them in studies of changing oceanographic conditions (Moore, 2008).

Sea lions are among the most abundant top predators of the food chain in the coastal and offshore California waters. They are vulnerable to the seasonal, annual and multiyear fluctuations in the productivity of the ocean. Sea lion prey such as fish and cephalopods are also influenced by particular sets of environmental conditions along the California coast.

One of the greatest threats to the California sea lion comes from changes in their food resources due to climate and other influences (Learmonth et al., 2006). Air and ocean temperatures are warming and projected to continue to warm, especially in the summer. The biological impacts of these changes may be a lower rate of ocean productivity and thus less food for many species. This can lead to shifts in the geographical distributions of marine species (for example to higher latitudes or deeper waters), and cause changes in community composition and interactions (IPCC, 2014). More resilient species may gain predominance and abundance while others become less competitive or easier prey. Shifts in the abundance and distribution of prey have had serious consequences for sea lion reproduction and survival.

Tracking pup population indices provides insight into how the California sea lion population is responding to environmental and anthropogenic changes. Although the population of California sea lions in coastal waters from the United States-Mexico border to southeast Alaska has steadily increased since the early 1970s, recent declines in pup production and survival in this area suggest that the population may have stopped growing (Laake et al., 2018).

What factors influence this indicator?

The California Current System (CCS) has a large impact on the food supply and survival of sea lion pups along the coast. A regional process known as “upwelling” carries the deep, cooler waters transported by the current upward, closer to the surface where photosynthesis by phytoplankton occurs. This productive zone supports important commercial fisheries as well as marine mammal and sea bird populations. CCS waters are influenced by large-scale processes resulting from the El Niño-Southern Oscillation (ENSO). El Niño conditions associated with the warm phase of ENSO occur irregularly at intervals of two to seven years, often leading to a weakened upwelling, low-nutrient waters and higher SSTs. Increased summertime SSTs due to decreased upwelling strength of ocean currents is reported to reduce availability of prey in the sea lion foraging zone.

Sea lion pups are solely nutritionally dependent on their mother’s milk for the first six months of their lives. Sea lion pup survival is highly dependent on the lactating mother’s ability to find food in in coastal waters near the colony. While their mothers are at sea on feeding trips, the pups are fasting at the colony. When prey availability is reduced near the colony, lactating females must travel farther to obtain food, resulting in longer periods away from their pups. Consequently their fasting pups are more vulnerable to starvation. Further, if the female does not obtain enough prey for her own nutritional and energy needs, she may not be able to provide sufficient energy for her pup to grow. Newly weaned pups just learning to forage on their own may also be vulnerable when prey availability is low because they have less fat to sustain periods of poor feeding conditions and fewer behavioral options to acquire food (e.g., limited diving ability). During periods of reduced prey conditions, increased numbers of malnourished sea lion pups are found stranded along the coast.

The low pup count, highest pup mortality rate and record number of strandings in 2009 were associated with anomalous oceanographic conditions along the California coast between May and August. During that year, upwelling was the weakest in the past 40 years; this was accompanied by uncharacteristically warm June SSTs. Negative upwelling patterns and warmer SSTs during the summer required lactating females to take longer than average foraging trips (averaging 7 days, approaching the maximum duration for which pups survive without nursing, 9 days). Additionally, the diet of California sea lions in 2009 varied significantly from other years, with cephalopods and rockfish occurring more frequently. The combination of longer foraging trips and a diet principally of rockfish and cephalopods did not provide adequate energy for lactating females to support their pups.

Since 2013, fisheries surveys confirm that the primary prey fish of sea lions (e.g., anchovy, sardine, hake) have not been abundant in the foraging area, probably in response to warmer ocean conditions (McClatchie, 2016; Wells et al., 2017). This was especially evident in 2014-2015, when the Pacific Coast experienced unusually warm SSTs due to the marine heat wave and El Niño conditions (Leising et al., 2015). Consequently, nursing females were not able to provide enough energy for their pups to grow, pups weaned too early or weaned in poor condition, and large numbers of pups stranded along the California coast in 2015 (McClatchie, 2016). When ocean conditions began returning to neutral conditions in 2016, sea lions responded fairly quickly with higher numbers of pup births, reduced pup mortality and improved pup condition and growth, further supporting their utility as an indicator of CCS conditions.

Harmful algal blooms periodically occur along the California coast, especially during years when water temperatures are unusually warm. During the 2014-2015 marine heatwave, a record-breaking algal bloom extended across the entire west coast, and included the phytoplankton *Pseudo-nitzschia*, which produces the neurotoxin domoic acid. This toxin can enter the marine food web, contaminate sea lion prey species and pose a threat to foraging sea lions and their offspring. Although incidents of sea lion poisoning from domoic acid have been reported, scientists have not quantified the effects of this toxin on sea lion pup births and growth. However, in a warming marine environment, harmful algal blooms and related toxins may become an increasingly important threat to the coastal food web, including the sea lion population.

Technical considerations

Data characteristics

San Miguel Island, California (34.03˚N, 120.4˚W), contains one of the largest colonies of California sea lions. The Point Bennett Study Area contains about 50 percent of the births that occur on San Miguel Island and provides a good index of trends for the entire colony. This site has been used as a long-term index site since the 1970s for measuring population parameters.

Population indices (live pups, pup mortality, pup growth) were measured by observers at San Miguel Island. Because of the large size of the colony, index sites were used to estimate population parameters.

Live pups were counted after all pups were born (between 20–30 July) each year. Observers walked through the study area, moved adults away from pups, and then counted individual pups. A mean of the number of live pups was calculated from the total number of live pups counted by each observer. The total number of births was the sum of the mean number of live pups and the cumulative number of dead pups counted up to the time of the live pup survey.

Pup mortality was assessed to calculate mortality at 5 weeks of age, 14 weeks of age, and the total number of pups born. Pup mortality surveys conducted every 2 weeks from late June to the end of July were used as an index of pup mortality at 5 weeks of age and to calculate total births for the study area. A final survey was conducted the last week of September to estimate pup mortality at 14 weeks of age. On each survey, dead pups were removed from the breeding areas as they were counted. The total number of observed dead pups for each survey described the temporal trend in pup mortality and was an estimate of the cumulative mortality of pups at 5 weeks or 14 weeks of age. Cumulative pup mortality rate was calculated as the proportion of the number of pups born in each year that died by 5 weeks of age or 14 weeks of age of the total number of pups born in each year.

Female sea lion **pup growth rates** are shown in Figure 3. Data for male pup growth rates (not presented) show the same trend over this 18-year period. To estimate sea lion pup growth rate, between 310 and 702 pups were selected from large groups of California sea lions hauled out in Adams Cove (part of the Point Bennett Study Area) over 4–5 days in September or October in each year (pups about 14 weeks old). Pups were sexed, weighed, tagged, branded, and released. Because the weighing dates were not the same in each year, the weights were standardized to an October 1 weighing date. A mean daily weight gain rate multiplied by the number of days from the weighing date to October 1 was added or subtracted from the pup weight based on the number of days before (–) or after (+) October 1 when the pup was weighed. The number of days between October 1 and the actual weighing day was included as a parameter (days) in models to describe the annual variability in pup weights. Similarly, pups were recaptured in February a second time and weights were adjusted to a February 1 date to determine growth rate between October 1 and February 1. Growth rate data are missing in 2011 because the investigators were unable to conduct field sampling in February of that year.

The response of sea lions to warmer ocean conditions was determined from models of SST and the sea lion population indices (Melin et al., 2012). Sea surface temperature anomalies were calculated from seven buoys along the central coast (from San Luis Obispo to the San Miguel Island area). This length of coastline represents the foraging range of the juvenile and lactating female sea lions. The buoy data were obtained from the NOAA National Data Buoy Center (http://ndbc.noaa.gov/rmd.shtml). The mean daily SSTs from the seven buoys were used to calculate mean monthly SSTs and averaged to create monthly sea surface temperature anomaly indices for the years 1997 to 2016 used in the analysis.

Strengths and limitations of the data

The study area represents about 45 percent of the US sea lion breeding population (Melin et al., 2010), thus providing a representative measure of trends in population responses to changes in the ocean environment. Because the area is large, index sites across the colony were used to measure population parameters. Instead of using total counts for pup production and mortality, mean values were used to estimate these parameters.

The use of SST from buoys represents a very localized view of ocean conditions at the surface but does not reflect more complex oceanographic processes occurring offshore or deeper in the water column that also may influence prey availability and the resulting population responses.

OEHHA acknowledges the expert contributions of the following to this report:

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Impacts on Human Health

More frequent and intense climate extremes, warming temperatures, and altered precipitation patterns have led to widespread, pervasive impacts on human health and well-being (IPCC, 2022). Climate change affects health directly through exposures to heat, floods, and other weather events, and indirectly through exacerbated health threats, such as higher levels of air pollutants, degraded water quality, and increased populations of disease vectors (Balbus et al., 2013; Ebi et al., 2018; NIH, 2022).

In California and across the US, heat causes more reported deaths per year on average than any other weather hazard (NOAA, 2021). In addition to emergency room visits and hospitalizations due to heat-related illness, other impacts are evident in California. Reports of occupational heat-related illnesses are increasing, especially among wildland firefighters and farmworkers. As drought and elevated temperatures fuel wildfires across the state, the threat of exposure to hazardous smoke has increased in recent years for many communities. Warming temperatures and changes in precipitation patterns have altered the seasonality, distribution, and behavior of insects that act as vectors of infectious disease, such as the *Culex* mosquito, the vector of West Nile virus. The number of West Nile virus cases have increased in California during periods of above-normal temperatures and drought conditions. Warming temperatures, drought, aridity, windstorms, and wildfires, contribute to the proliferation of the Valley Fever fungus and the dissemination of its spores, leading to a rise in the number of cases.

Climate change is often described as a threat multiplier. Communities in California confronted by multiple climate hazards must also deal with the challenges posed by environmental pollution, poorly maintained infrastructure, poverty, and other economic and institutional factors. Low-income communities, rural communities, communities of color and Tribes are often disproportionately impacted by such compounding vulnerabilities. The same communities also generally have less capacity and resources to prepare for, adapt to, or recover from the impacts of climate change. To address this gap, the State Adaptation Strategy aims to strengthen climate resilience in the most climate-vulnerable communities in California. Similarly, in recognition that the burden of extreme heat falls disproportionately on the most vulnerable of populations in the state, the State's Extreme Heat Action Plan commits to near-term actions to accelerate readiness and protect such communities.

INDICATORS: IMPACTS ON HUMAN HEALTH

Heat-related deaths and illnesses *(updated)*
Occupational heat-related illness *(new)*
Valley fever (Coccidioidomycosis) *(new)*
Vector-borne diseases *(updated)*
Wildfire smoke *(new)*

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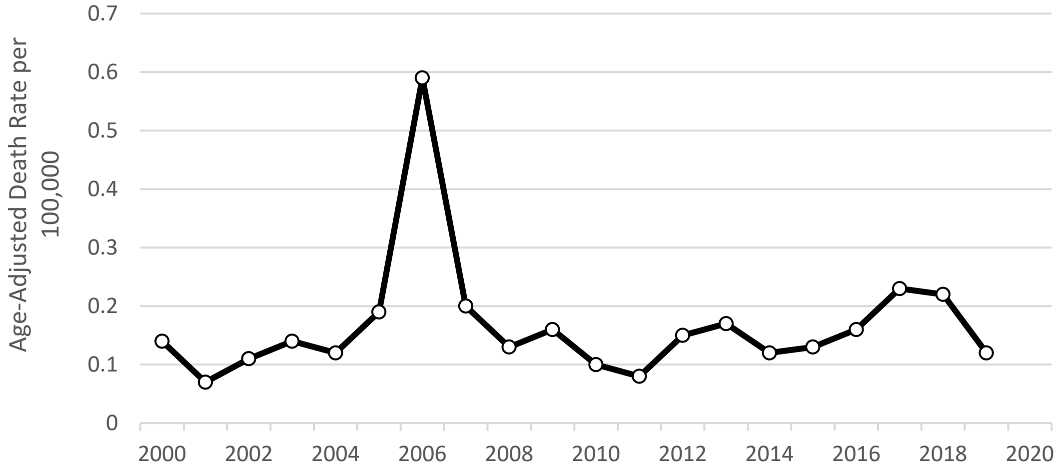
HEAT-RELATED DEATHS AND ILLNESSES

Deaths and illnesses from heat exposure are often unrecognized, misdiagnosed and thus, severely underreported. In 2006, when summertime temperatures were especially high, the reported number of deaths attributed to heat was much higher than any other year. Reported deaths and emergency department visits were also elevated in 2017, another notably warm year.

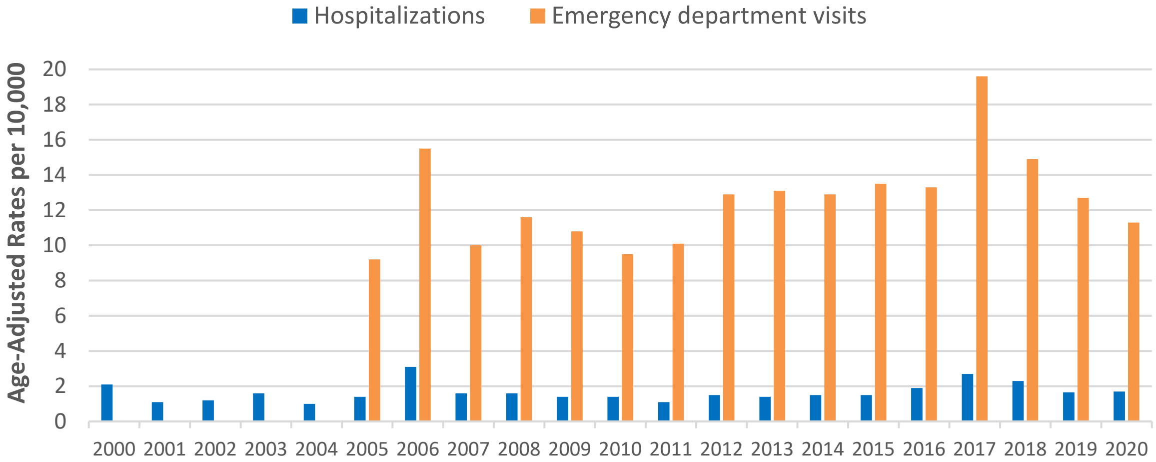
Figure 1. Heat-related deaths in California*



Source: Data set compiled by Tracking California (2021), using data from the Center for Health Statistics

* *Reported deaths in May to September due to heat exposure as a main or contributing cause.*

Figure 2. Heat-related illness in California*



Source: Data set compiled by Tracking California (2022), using data from the data from the Office of Statewide Health Planning and Development

* *Reported hospitalizations and emergency department visits in May to September. Data for emergency department visits were not available until 2005.*

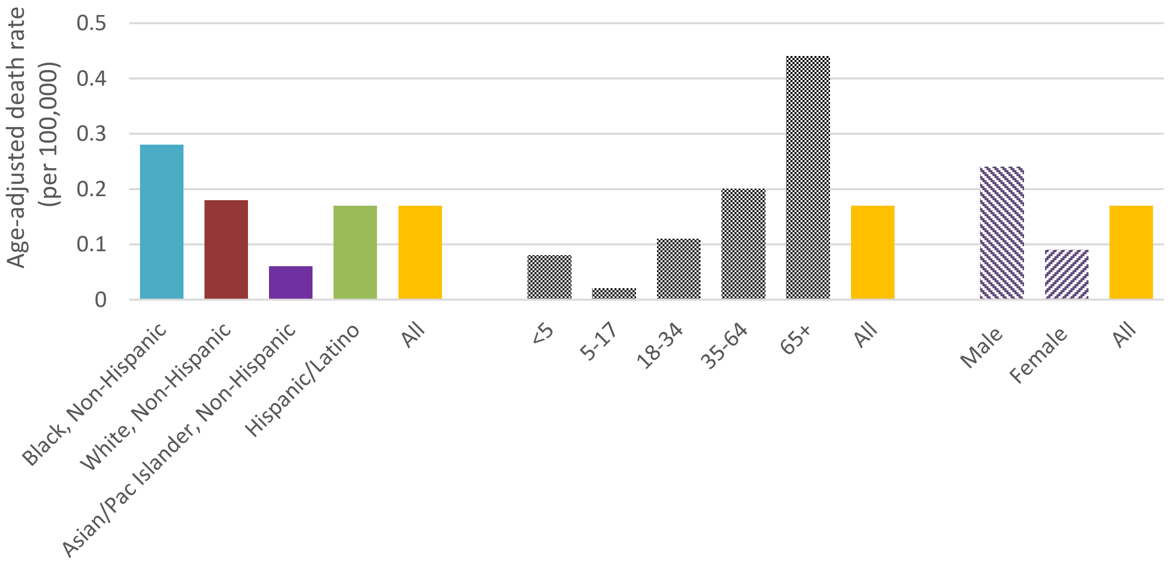
What does the indicator show?

The association between exposure to high temperatures and illness or deaths is well established. The classical case definition of heat illnesses includes ailments such as heat rash, heat cramps, heat exhaustion, and heat stroke. However, because of the stress that elevated ambient temperatures can exert on the body, heat exposure can produce health effects and exacerbate a broad range of health conditions (see below under *Why is this indicator important)*. Health records may not capture heat-related illness if exposure to excess heat is not explicitly documented. Consequently, health cases related to heat are often unrecognized and misdiagnosed. For example, a study of about 300 populous counties across the US estimated that the annual number of deaths attributable to heat was substantially larger than previous estimates reported by the Centers for Disease Control (CDC) and others (Weinberger et al., 2020). A substantial number of deaths occurred at only moderately hot temperatures. While recognizing that lack of consistency in the identification and recording of heat-related death and illness underestimates impacts (Berko et al., 2014), tracking the number of deaths and illnesses attributed either wholly or in part to heat illnesses can provide an indication of the trend in health impacts related to climate change.

Figure 1 presents annual age-adjusted death rates in California for diagnoses specifically attributed to heat, either as a primary or underlying cause, from 1999 to 2019. Figure 2 shows both heat-related hospitalizations (2000 to 2018) and heat-related emergency department (ED) visits (2005 to 2018) in California. No trend is evident for heat-attributed deaths or hospitalizations in California; rates were highest in 2006 (for deaths) and 2017 (for emergency department visits), when summertime temperatures were especially high. The mortality data, and to a lesser extent hospitalization data, do capture the impact of extended heat waves on health over large geographical areas. Emergency department visits show a statistically increasing trend, as expected with the warming temperatures associated with climate change.

Examining these indicators among specific demographics points to greater susceptibility to heat illnesses among adults aged 65 and older, males, and non-Hispanic Blacks. These groups have higher rates of identified heat-related deaths, emergency department visits and hospitalizations than those in other comparable demographic groups (Figures 3 and 4).

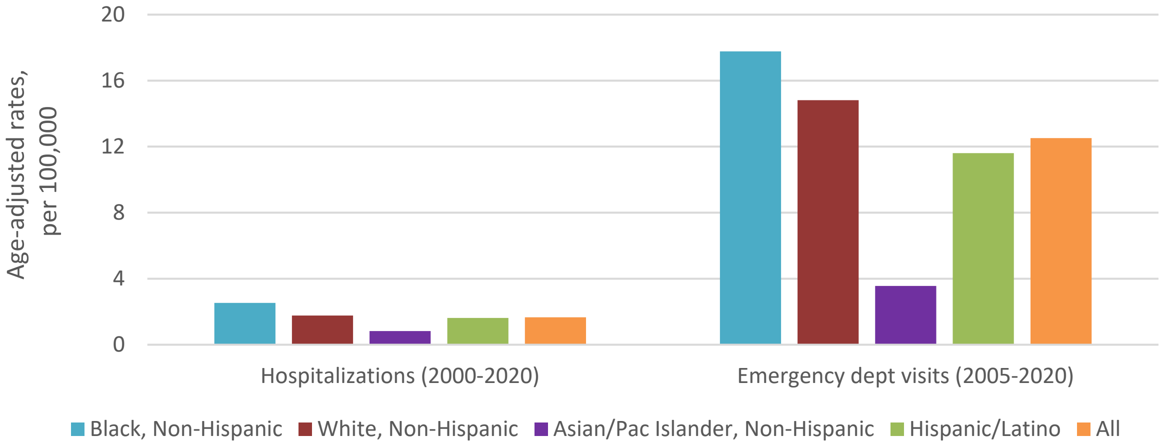
Figure 3. Heat-related death rates in California, by race, age and gender (2000-2019)



Source: Data set compiled by Tracking California (2021), using data from the Center for Health Statistics

** Reported deaths in May to September due to heat exposure as a main or contributing cause.*

Figure 4. Heat-related illness, by race



Source: Data set compiled by Tracking California (2022), using data from the data from the Office of Statewide Health Planning and Development

**Includes death with heat identified as a primary or underlying cause.*

Why is this indicator important?

Heat causes more reported deaths per year on average in the United States than any other weather hazard, yet heat-related illnesses and deaths are generally preventable (Luber et al., 2014; NOAA, 2021). A comprehensive analysis of heat-related deaths in the US by the CDC found an average of 702 deaths occurred annually during 2004-2018 (Vaidyanathan et al., 2020). CDC noted that understanding patterns of heat-related deaths (for example, by race or ethnicity, age, or income level) is critical to developing more effective surveillance and intervention strategies. Their *Heat and Health Tracker* provides local heat and health information for communities to better prepare for and respond to extreme heat events.

Assessing how heat-related deaths and illnesses change with time provides a specific measure of how climate change-related temperature shifts are impacting human health. As noted above, the cases identified will represent only a small selection of heat-related health effects. Higher temperatures have been linked with increased deaths from all non-accidental causes, and more specifically cardiovascular and respiratory causes (Basu and Malig, 2011; Song et al., 2017). Heat waves and generally higher temperature exposures in California are related to increased health care usage for a wide range of diagnoses including electrolyte imbalance, diabetes, renal, cardiovascular and respiratory diseases (Basu et al., 2012; Guirguis et al., 2014; Green et al., 2010; Knowlton et al., 2009; Malig et al., 2019; Sherbakov et al., 2018). Increases in apparent temperature (measure of ambient temperature adjusted for relative humidity) have also been linked with adverse birth outcomes such as preterm birth, stillbirth, and low birth weight (Bekkar et al., 2020). Additionally, hotter temperatures may increase emergency department visits for mental health-related outcomes, such as for psychiatric conditions and self-harming or aggressive behaviors (Basu et al., 2017b; Liu et al., 2020; Thompson et al., 2018).

Tracking heat-related illnesses and deaths provides critical information for developing adaptation plans and evaluating their successes, especially in relation to heat waves. State and local policies, plans, and programs focusing on heat are already in place in some locations. These may include heat wave early warning and surveillance (observation) systems, accessible cooling centers, public education campaigns on preventing heat-related illnesses, and worker heat-safety regulations. The use of air conditioning has been associated with significant reductions in heat-related hospital visits in California (Ostro et al., 2010). However, during periods of high heat, there is likely to be a greater risk of brownouts or blackouts from overuse of gas and electricity.

Periods of warmer temperatures and heat waves are expected to rise in frequency, duration, and intensity over the next century (IPCC, 2021; Luber et al., 2014). In California, annual average maximum daily temperatures are projected to increase by about 4.4 to 5.8 degrees Fahrenheit (°F) by mid-century, and by about 5.6 to 8.8°F by the end of the century (Bedsworth et al., 2018). These projections suggest an increasing public health burden from heat-related deaths and illnesses.

What factors influence this indicator?

Heat-related illnesses are affected by characteristics of the heat exposure, such as frequency, intensity and duration. Other factors relate to the exposed individuals themselves, such as age, health status, and the degree to which protective measures against heat are taken by individuals and instituted through policy on a broader population-level.

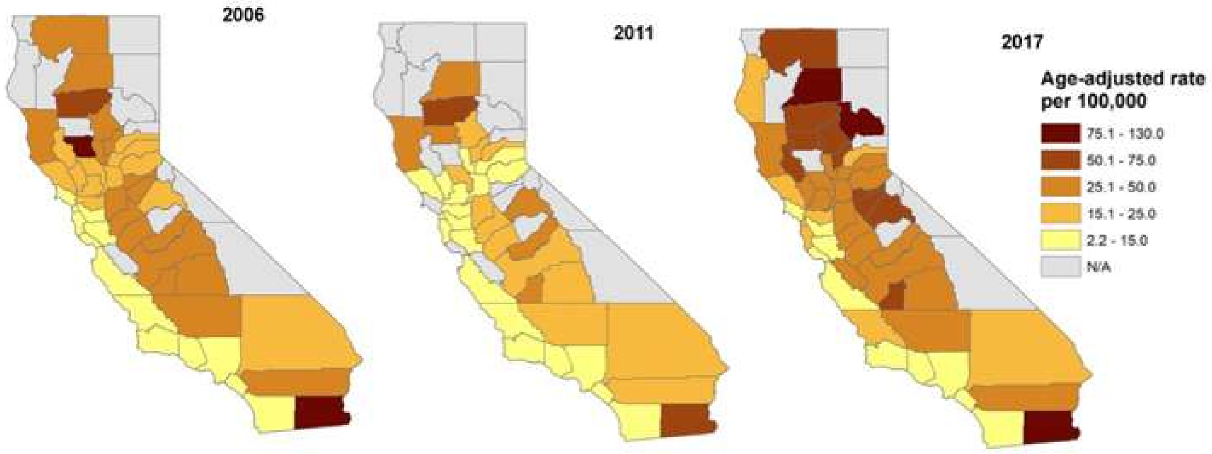
High temperatures and heat waves can impact air quality and pose a threat to public health (Nolte et al., 2018; O'Lenick et al., 2019). Heat can accelerate the formation of ground-level ozone and also trap ozone, particulate matter and other harmful air pollutants. Exposure to these pollutants has been linked to adverse respiratory, cardiovascular, mental health, and reproductive outcomes (Bekkar et al., 2020; Nguyen et al., 2021; US EPA 2019). Air pollution may also work in synergy with extremely high temperatures to increase adverse cardiovascular, respiratory and other health effects (Anenberg et al., 2020).

As shown in Figures 1 and 2, heat-related illnesses and deaths in 2006 peaked during the prolonged heat wave that occurred from July 16 to 26 (Knowlton et al., 2009; Margolis et al., 2008). Average apparent temperatures ranged from 81°F to 100°F, which is 4°F greater than the average statewide temperatures in July. The Central Valley region had the highest number of uninterrupted hot days ever recorded, with each day reaching 100°F and greater. Multiple locations in California broke records for the highest number of uninterrupted days over 100°F ever recorded: 11 in Sacramento; 12 in Modesto; and 21 in Woodland Hills near Los Angeles (Kozlowski and Edwards, 2007). In 2017, California experienced record summer heat, with numerous daytime and nighttime heat waves and record high temperatures (DWR, 2018). Death Valley set a new record for highest average monthly temperature in July with a value of 107.4°F. In Redding, the temperature topped 100°F a record 72 times. Statewide, the June/July/August average temperature was also a record high.

Specific characteristics of prolonged heat events may influence the degree to which heat-related health effects are felt. Higher night-time temperatures during heat waves may incur greater effects by preventing respite from high daytime temperatures (Gershunov et al., 2009). Heat waves accompanied by high humidity are especially dangerous, as the humidity prevents sweat from evaporating to cool down the body. Studies report that even short periods of high temperatures are associated with health impacts (Gasparinni and Armstrong 2011; Sherbakov et al., 2018).

Studies of California heat waves found that health impacts were greatest in the Central Valley and along the coast (Guirguis et al., 2014; Knowlton et al., 2009). Coastal populations tend to be less acclimated to higher temperatures and have lower rates of air conditioner ownership. Buildings, dark paved surfaces, lack of vegetation and trees, and heat emitted from vehicles and air conditioners cause cities to generate and retain heat, a phenomenon known as the “urban heat island effect” (CDPH 2007). Thus, urban residents may experience more heat than people who live in surrounding suburban and rural areas. Figure 5 shows emergency department visit rates across California in 2006 (extended summer heat wave), 2011 (a cool summer season), and 2017 (exceptionally hot summer). Note the distinction between 2006 vs 2017 and which counties are most impacted.

Figure 5. Emergency department visits by county due to heat illness in 2006, 2011 and 2017*



Source: Tracking California 2021

** Maps present age-adjusted rates for emergency department visits by county during two unusually hot summer years (2006 and 2017) and a relatively cool summer (2011).*

As noted above, certain demographic groups may be more vulnerable to heat illness (adults aged 65 and older, males, and non-Hispanic Blacks). Other factors that can increase susceptibility to temperature are young age (5 years and under), pre-existing health conditions (such as heart or lung disease) or certain medications or substances (Ebi et al., 2018; Gronlund et al., 2018; Vaidyanathan et al, 2020). Furthermore, socially isolated people, the poor, and those who have difficulty accessing medical care likely face increased risks during hot weather (Basu and Ostro, 2008; Luber et al., 2014). Pregnant women may be more likely to suffer adverse birth outcomes with heat exposure (Bekkar et al., 2020).

Those engaged in vigorous physical activity, such as workers in construction, firefighting, and agriculture are also at risk. Over the past two decades, reported heat-related illnesses have increased in California (see *Occupational heat-related illness* indicator). In contrast, occupational heat-related deaths has not been well studied. An analysis of worker death rates in the United States from 2000-2010 reported a rate of 0.24 deaths per 1 million workers in California (Gubernot et al. 2016). Compared to the states with the ten highest rates (Mississippi had the highest, at 1.05 per 1 million workers), California's rate is relatively low, likely due to the promulgation in 2005 of the state's enforceable regulation for prevention of heat illness in outdoor workers.

As adaptation measures are implemented and become more effective, the impacts of higher temperatures on heat illness rates may be mitigated. Measures – both planned and already under way –by state and local government and other entities include early warning and surveillance systems, access to air conditioning through cooling centers or through grants, and public outreach and education, particularly those targeting vulnerable populations. The state's priorities and goals addressing the risks posed by warming temperatures and other climate change impacts are outlined in California's Climate Adaptation Strategy.

Technical considerations

Data characteristics

Heat-related hospitalizations and emergency department visits were identified for the months of May to September by the California Environmental Health Tracking Program (CEHTP, recently renamed "Tracking California"). Tracking California is a program of the Public Health Institute, in partnership with the California Department of Public Health. Cases were included when heat stress was explicitly listed as the primary diagnosis or any other diagnosis. Heat-related diseases were identified using International Classification of Diseases (ICD-9 for 2000-2015, ICD-10 for 2015-2018) codes for: heat stroke and sunstroke; heat syncope; heat cramps; heat exhaustion; heat fatigue; heat edema; other specified heat effects; unspecified effects of heat and light; and exposure to excessive natural heat or sunlight. Causes that were due to a man-made source of heat were excluded. Hospitalization data were available for the years 2000 to 2018, and data on emergency department visits for the years 2005 to 2018.

CEHTP also identified heat-related deaths for the months of May to September, from 2000 to 2019, using ICD-10 codes for the following as the main or contributing causes of death: heat stroke and sun stroke; heat syncope; heat cramps; heat exhaustion; heat fatigue; heat edema; other specified heat effects; unspecified effects of heat and light; and exposure to excessive natural heat; and sunlight. As with the illness dataset, deaths due to a man-made source of heat were excluded. More information about data and methods, including rate calculations, can be found at the Tracking California website.

Strengths and limitations of the data

As noted earlier, the available data on heat-related illnesses and death likely underestimates the full health impact of exposure to heat. Heat-related health effects can manifest in a number of clinical outcomes, and people with chronic health problems are more susceptible to the effects of heat than healthy individuals. Heat-related illnesses and deaths are often misclassified or unrecognized.

The number of heat-related deaths from coroners' reports rely on deaths coded as "heat-related" without universally applied classification of these diseases, and often require knowledge of the circumstances around death to be communicated by other parties. Consequently, few deaths are recorded on death certificates as being heat-related and heat is rarely listed as a main cause of deaths that occur in hospitals or emergency rooms, even when exposure to heat is a contributing factor (English et al., 2009). It is likely that there were three to four times as many deaths in the July 2006 heat wave than were actually reported (Ostro et al., 2009; Joe et al., 2016). Recent studies of annual heat-related deaths in the US explain how the number of deaths is substantially larger than what has been previously reported (Weinberger et al., 2020; Vaidyanathan et al., 2020).

Non-fatal endpoints may similarly be undercounted, as it is often difficult to determine that an illness is heat-related when it involves other organ systems, and there is no standardized training among healthcare providers who make the determination (Madrigano et al., 2015). For example, during the 2006 California heat wave, over 16,000 excess emergency department visits and 1,100 excess hospitalizations were observed. These were much larger than the 2,134 ED visits and 538 hospitalizations officially identified as heat-related, so the majority of cases were not explicitly diagnosed as heat illnesses (Knowlton et al., 2009).

For hospitalizations and emergency department visits, the change in usage of ICD-9-CM to ICD-10-CM in the 4th quarter of 2015 may have resulted in differences in classification of heat-related visits that impact observed patterns in those indicators.

Despite these known limitations, heat-related emergency department visits, hospitalizations and deaths can be used to document changes over place and time, monitor vulnerable areas, and evaluate the results of local climate-adaptation strategies. They are tracked at the national level as part of the National Environmental Public Health Tracking Network, allowing comparisons across states. This tracking provides a better understanding of risks to specific groups, and helps with designing interventions and communication efforts (CDC, 2021).

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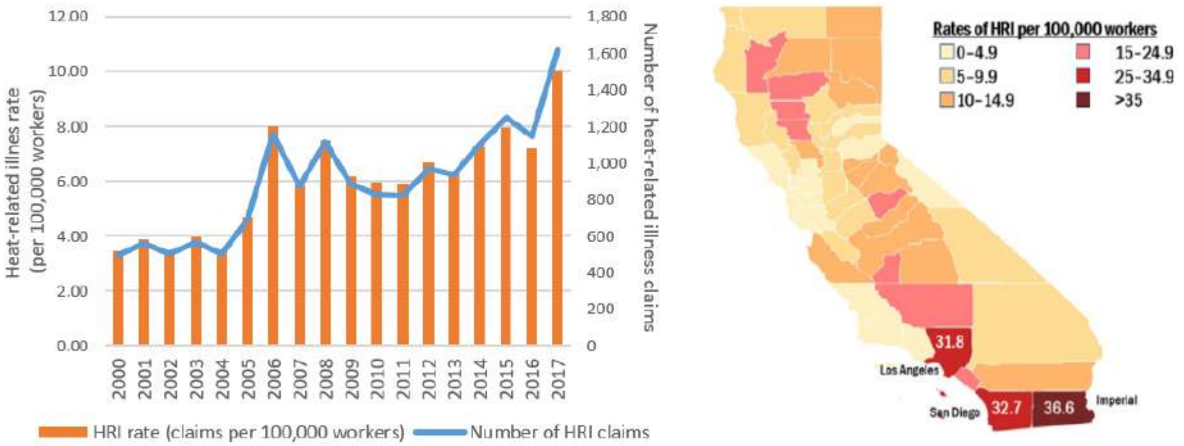
OCCUPATIONAL HEAT-RELATED ILLNESS

Heat-related illnesses reported by California workers have increased from 2000 to 2017.

Figure 1 Occupational heat-related illnesses in California, 2000-2017



Source: Workers' Compensation Information System data,
California Department of Industrial Relations (Heinzerling et al., 2020)

What does the indicator show?

Exposures to high temperatures while at work can lead to a range of heat-related illnesses (HRI). Figure 1 presents annual rates of occupational HRI per 100,000 California workers from 2000 to 2017 based on an analysis of workers' compensation claims data. HRI cases were identified from claims that listed heat as the cause of injury or that specified heat-related illness key words (e.g., "heat stroke") or disease codes. Occupational HRI rates started to climb in 2005, reached about 8 cases per 100,000 workers in 2006, and in 2017 saw the highest number of cases (1616), with a rate of 10.1 cases per 100,000 workers. Occupational HRI rates over six-year periods also increased over time: the rate from 2012 to 2017 was two times greater than the rate from 2000 to 2005.

The map in Figure 1 shows worker HRI rates by county from 2000-2017. HRI rates were calculated by dividing the total number of cases over the study period by the total number of workers and multiplying by 100,000 to yield rates per 100,000 workers. Imperial County had the highest rate of 36.6 per 100,000 workers, followed by San Diego and Los Angeles counties, with rates of 32.7 and 31.8 per 100,000 workers, respectively. Orange, Kern, Kings, Mariposa, Trinity, Tehama, Glen, and Colusa counties (shaded pink) reported HRI rates of 15 to 25 per 100,000 workers.

Why is this indicator important?

The link between heat exposure and adverse health outcomes in workers is well documented across the globe (Fatimaa et al., 2021). HRIs are a broad spectrum of diseases, ranging from headaches, dizziness, cramps, rapid heartbeat, and disorientation to more serious outcomes including heat stroke (Gubernot et al., 2014). In many cases employees have little control over their work environment and limited ability to adapt when faced with extreme heat conditions. Workers who are socially isolated and economically disadvantaged, have chronic illnesses, or have no health insurance are especially vulnerable to HRI; these workers are often from communities of color. HRI is a preventable occupational illness, with well-established strategies to protect workers (Heinzerling et al., 2020). While there is no federal workplace standard that protects workers from heat exposures and related illnesses, California's Division of Occupational Safety and Health (Cal/OSHA) enacts and enforces its own workplace standards for public and private sector employees. In 2005, in response to a series of heat-related farmworker deaths, California enacted an HRI prevention standard for outdoor workers, requiring employers to provide employees with HRI training and access to water, shade, and rest (https://www.dir.ca.gov/title8/3395.html). In spite of prevention and mitigation efforts, occupational HRI continues to increase in California.

As climate change increases, average daily temperatures and the frequency and intensity of extreme heat events, occupational HRIs, and deaths are projected to rise (ILO, 2019). A study of rising heat exposure and health risk faced by U.S. crop workers estimates that climate change at its current pace will double occupational HRI by the middle of the century (Tigchelaar et al., 2020). As more and more workers are placed at risk, additional strategies and interventions will be needed to protect workers from HRI.

The effects of rising temperatures on workers are impacting global employment sectors and economies. Borg et al. (2021) reviewed 20 studies to estimate the past and potential future global economic burden of workplace heat exposure. They estimated substantial heat stress-related expenses from lost productivity, decreased work efficiency, and healthcare costs and highlighted the need for workplace heat management policies to minimize future economic burden. A study of workplace heat-related injuries in California estimated financial costs at between $525 and $875 million per year, considering health care expenditures, lost wages and productivity, and disability claims (Park et al., 2021).

Exposure to elevated workplace temperatures may also exacerbate trends in labor market inequality. Park et al. (2021) report that lower wage workers are more likely to live and work in places with greater heat exposure and experience larger increases in risk on hotter days. People in the state's lowest household income tier are approximately five times more likely to be affected by HRI or injuries on the job than those in the top income tier. Moreover, workplace injuries for low-income workers can lead to large direct health care costs and persistent wage impacts that affect subsequent earnings trajectories.

What factors influence this indicator?

California has been experiencing higher temperatures and extreme heat events, particularly since the 1980s (see *Annual air temperature and Extreme heat events* indicators). These warming trends coincide with increasing reports of worker HRI, as shown in Figure 1. In 2006 there was an uptick in HRI cases that coincided with a prolonged heat wave in California.

Excessive heat during work restricts a worker's physical functions and leads to loss of productivity (ILO, 2019). Workplace temperatures above 75-79 degrees Fahrenheit (˚F) are associated with reduced labor productivity. At 91-93˚F, a worker operating at moderate work intensity loses 50 percent of his or her work capacity. In California, a comparison of workers' compensation claims with local weather data from 2001 to 2018 showed that on days with a high temperature above 90˚F, workers have a 6 to 9 percent greater risk of injuries than on days with high temperatures of 50 to 60˚F (Park et al., 2021). When temperatures top 100˚F, the risk of injuries increases by 10 to 15 percent.

Workers who perform exertional tasks or work outdoors are particularly vulnerable to HRI (Heinzerling et al., 2020). Between 2000 and 2017, most of the 15,996 HRI cases in California identified from workers' compensation data occurred in summer months. July had the highest number of cases (4199 cases; 26.3 percent), followed by August (3161 cases; 19.8 percent), and June (2915 cases; 18.2 percent). Certain demographic groups were found to be at higher risk of occupational HRI: rates among men were 2.3 times higher than among women, and rates were highest among young workers (the highest age group was 16-24 years). Younger people may be at higher risk of HRI because they tend to work in industries or occupations with higher risk of HRI, may be more likely to undertake more physically demanding work, and may also lack work experience and adequate acclimatization to hotter temperatures. Relatively high HRI rates for temporary employees in service industries suggested they may be particularly vulnerable to occupational health threats.

Rates of occupational HRI also varied by industry and occupation. The occupational group with both the highest number of cases and highest HRI rate was *protective services*, which includes police and firefighters, with 3380 total cases and an HRI rate of 57 per 100,000 workers (Heinzerling et al., 2020). When exposed to high ambient temperatures, the body depends on evaporative cooling and is susceptible to anything that restricts evaporation, such as personal protective equipment or clothing (Gubernot et al., 2014). Firefighting presents significant challenges for heat illness prevention, given the high heat exposure and exertion involved and heavy personal protective equipment required (West et al., 2020). Risk of HRI in this group, especially among wildland firefighters, is likely to continue to increase as wildfires become larger and more severe and as the fire seasons lengthen (see *Wildfires* indicator).

The *crop production* industry, which includes most types of farming, reported 1335 total HRI cases with a rate of 41 per 100,000 workers. The majority of farmworkers in California are migrant workers, work long days during the summer season, and have limited control over their work schedule and job tasks (ILO, 2019). The common payment system is based on the amount of produce harvested, which discourages workers from taking breaks to eat, drink water, or rest. A study of heat strain in California farmworkers found increased odds of acute kidney injury after a day of work, especially in female workers paid by amount harvested (Moyce et al., 2017).

In a California Heat Illness Prevention Study, core body temperature (CBT) increase and work rate (monitored using a personal accelerometer) over a work shift were used to monitor HRI risk in 587 farmworkers throughout the state (Langer et al., 2021).

Almost seven percent of workers were at higher risk of HRI based on elevated CBT. With an estimated 829,000 farmworkers in California, this translates to about 58,000 workers at risk of elevated CBT. Despite consuming more water compared to less active workers, those at risk became dehydrated (15.7% of men and 3.3% of women). The study concluded that risk of HRI was exacerbated by work rate and environmental temperature despite farms following Cal/OSHA HRI regulations (described above).

Technical considerations

Data characteristics

Workers who experienced HRI were identified through the California Workers' Compensation Information System (WCIS) electronic database managed by the California Department of Industrial Relations (Heinzerling et al., 2020). Since 2000, California has required workers' compensation claims administrators to report to WCIS any claim resulting in more than one day of lost work time or requiring treatment beyond first aid. Claims were considered HRI cases if they included specific WCIS heat-related cause of injury codes (e.g., temperature extremes); if they contained certain HRI key-words in the injury description (e.g., “heat stroke”); or if their billing data contained an International Classification of Diseases (ICD) (Ninth or Tenth revision) code indicating heat illness. All claims with date of injury from January 1, 2000 to December 31, 2017 meeting these criteria were extracted from WCIS in January 2018. Claims meeting only ICD criteria were manually reviewed, and only those deemed to be heat-related based on the injury description were included as HRI cases.

HRI cases were categorized by sex and age group, month and year of injury, county of injury (using ZIP code), industry, and occupation. WCIS reports do not include worker race, ethnicity, or medical comorbidities. Employment denominators used in rate calculations for all variables except county were obtained from the National Institute for Occupational Safety and Health (NIOSH) Employed Labor Force tool, which estimates total numbers of workers based on the U.S. Census Current Population Survey and includes all non-institutionalized civilian workers aged 16 and older. Employment denominators by county were obtained from the California Employment Development Department.

Strengths and limitations of the data

There is limited public health surveillance of occupational HRI in the United States. The primary source of this information in most states comes from the Bureau of Labor Statistics Survey of Occupational Injuries and Illnesses (BLS SOII). These data, based on self-reporting from a small sample of employers nationwide, underestimate the true number of occupational illnesses and injuries. Numbers of HRI cases identified using California’s WCIS database, shown in Figure 1, are higher than those from other sources, such as BLS SOII. They are, however, still likely to be underestimates, as they do not include other types of illnesses and injuries where heat may have been a contributing factor, and occupational illnesses are not always reflected in workers’ compensation data (Heinzerling et al., 2020).

Rates of reporting may also differ by industry and occupation. Those in certain occupations may be unaware of workers' compensation eligibility. Occupational groups that are particularly vulnerable to employer reprisal, such as farmworkers, may be less likely to report illnesses or injuries and file workers' compensation claims.

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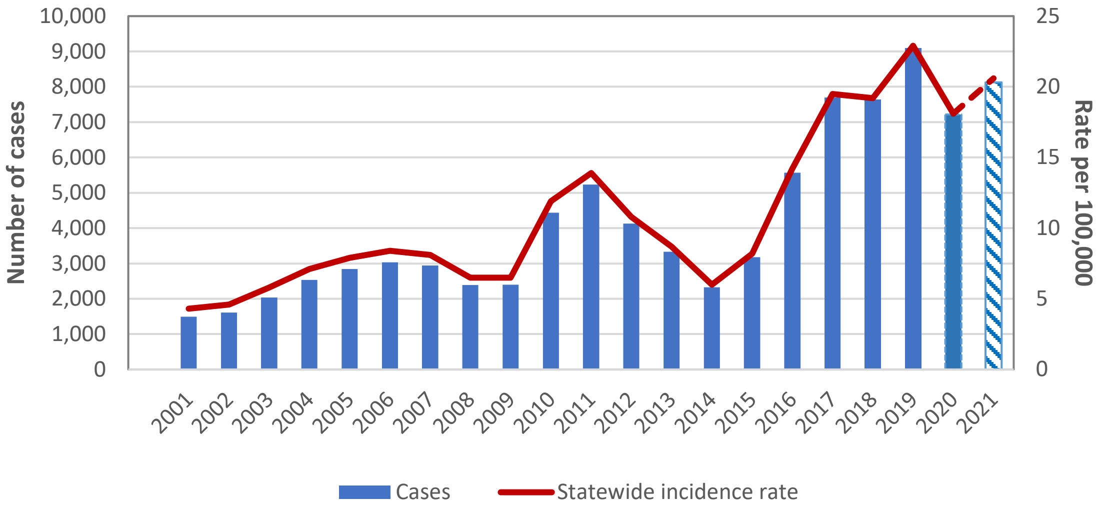
VALLEY FEVER (COCCIDIOIDOMYCOSIS)

The incidence of Coccidioidomycosis, commonly known as Valley fever, has increased over the past 20 years. Valley fever is caused by inhaling spores of the Coccidioides fungus that is endemic in the soil in parts of southwestern United States, including California. The fungus usually infects the lungs, causing respiratory symptoms.

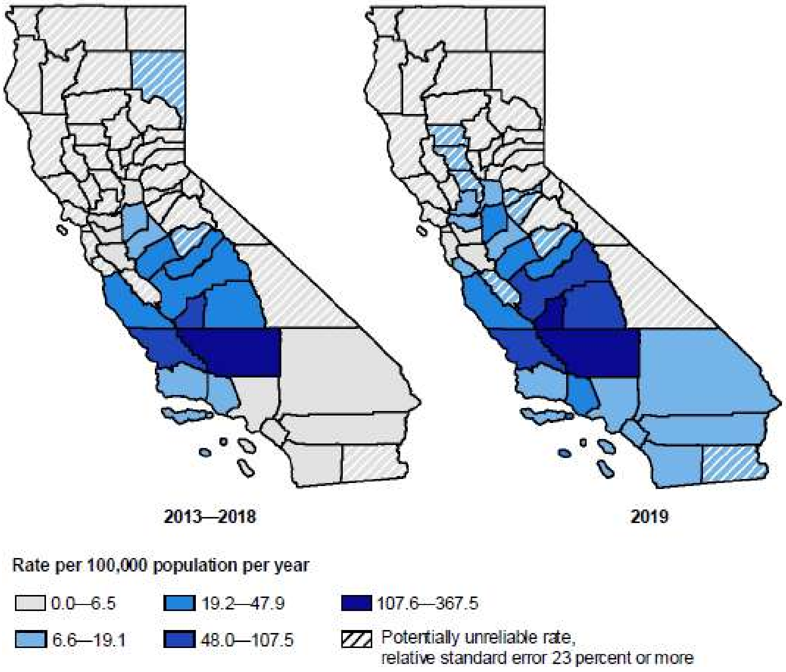
Figure 1. Valley fever cases and incidence rates by year of estimated illness onset in California (2001-2021*)



Source: CDPH 2020a; CDPH 2022a,b

**Note: 2021 values are provisional.*

Figure 2. Coccidioidomycosis, annual incidence rate by county, California, 2013-2019



Source: CDPH 2020a

What does the indicator show?

Figure 1 presents the number cases of Valley fever reported in California each year, from 2001 through 2021, along with the statewide incidence rate. The annual incidence of reported cases of Valley fever has increased almost fivefold from 2001 (with a rate of 4.3 cases per 100,000 population) to 2021 (rate of 20.6, based on preliminary data). The number of new cases reported in 2019 is the highest reported in a given year since reporting began in 1995.

Figure 2 compares the change in Valley Fever rates from 2013-2018 and 2019, with a number of new counties reflecting substantial increase in cases in 2019. Regionally, Valley fever incidence has consistently been highest in the counties of Fresno, Kern, Kings, Madera, Merced, Monterey, San Luis Obispo, and Tulare. Kern County historically had the highest number of new cases, with 338 cases reported in 2019 (CDPH, 2020b). A recent regional analysis of surveillance data from 2000 to 2018 suggested that, despite the consistent high rates of Valley fever in the Southern San Joaquin Valley, the largest increases in incidence have occurred outside of that region, primarily in Northern San Joaquin Valley, Central Coast, and Southern Coast regions (Sondermeyer Cooksey et al, 2020).

The California Department of Public Health (CDPH) has an established surveillance system to track Valley fever cases and has been collecting individual case data since 1995 (Tabnak et al., 2017). Because Valley fever may occur as a chronic condition and be reported more than once, only the first report of the onset of illness is counted (CDPH, 2020). Valley fever is likely underdiagnosed and under-reported, as symptoms are similar to many other respiratory illnesses, such as influenza, COVID-19, or bacterial pneumonia.

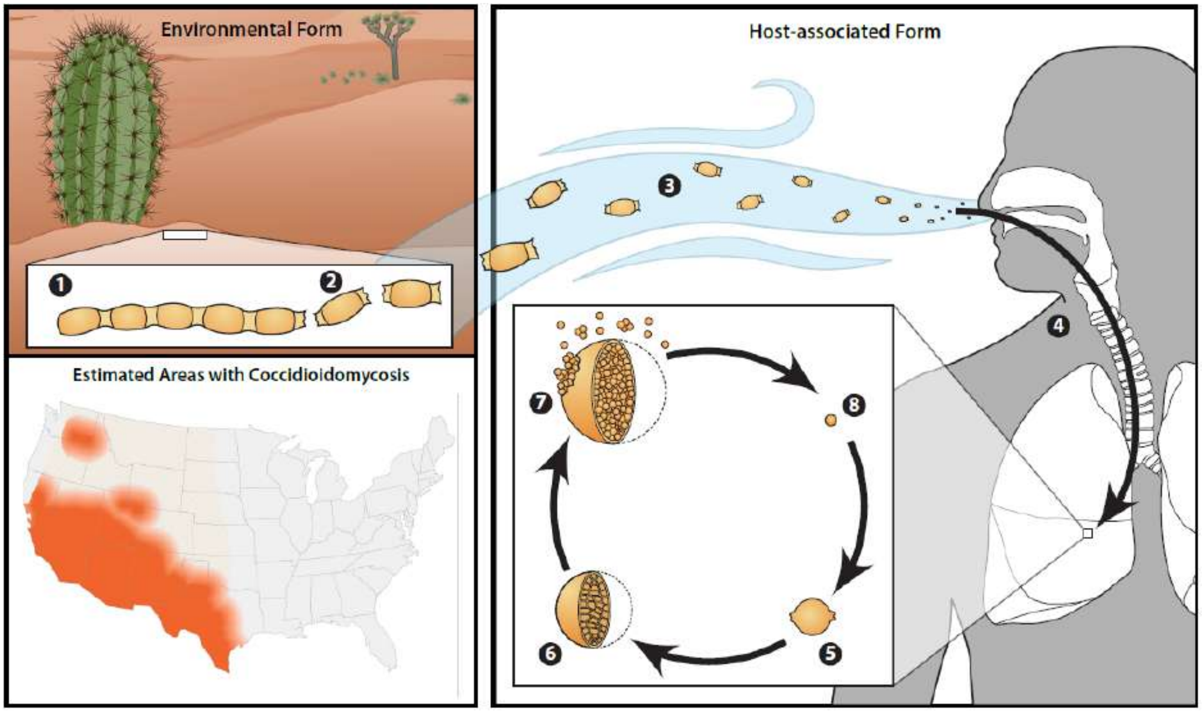
Why is this indicator important?

Approximately 97% of coccidioidomycosis cases in the United States are reported from California and Arizona. The disease usually manifests as a mild self-limited respiratory illness or pneumonia. While most people recover fully, experiencing only mild symptoms, up to five percent exhibit more serious health consequences, including severe respiratory, disseminated disease - where the infection has spread from the lungs to the skin, bones and central nervous system, or meningitis (Ampel et al., 2010; CDPH, 2015). Severe Valley fever can lead to hospitalization, and in the most severe cases, death. Even in those with milder disease, days lost to low productivity and poor health create significant burdens for the patients and the economy at large. Those of Black or Filipino background, pregnant women, older adults, and people with weakened immune systems are at increased risk for severe disease (CDPH, 2020).

Robust CDPH surveillance of Valley fever over the last couple of decades indicates an increase in disease burden. Each year in California, around 80 deaths and over 1,000 hospitalizations are attributed to Valley fever. It is not transmitted directly from person to person, but rather from the direct inhalation of fungal spores. Pets and other animals can also be infected (CDPH, 2020).

Two species of the soil-dwelling *Coccidioides* fungus cause coccidioidomycosis: *C. immitis*, which is found primarily in California, and *C. posadasii*, which is found primarily in Arizona, other parts of the southwestern United States as well as Central and South America (CDPH, 2015; Tintelnot et al., 2007). The life cycle of the fungus is illustrated in Figure 3. Since there is no commercially available test to determine whether the fungus is growing in the soil in an area, the current understanding of the geographic risk for infection is largely based on human surveillance data. As mentioned above, most cases of Valley fever in California are reported in people who live in the Central Valley and Central Coast regions.

Figure 3. The life cycle of *Coccidioides*



Modified from: CDC, 2020

The *Coccidioides* fungus exists in different forms in the environment (left) and in the host (right). In the environment, the fungus exists as filaments or chains divided into cellular compartments (1). These compartments can fragment into spores called arthroconidia (2), which measure only 2-4 µm in diameter and are easily aerosolized when disturbed (3). Arthroconidia are inhaled by a susceptible host (4) and settle into the lungs, where they become spherules (5). Spherules divide internally until they are filled with endospores (6). When a spherule ruptures (7), the endospores are released and disseminate within surrounding tissue. Endospores are then able to develop into new spherules (6) and repeat the cycle. The map in the lower left shows where the Valley fever fungi live in the United States.

Population influx into endemic areas, increased construction and other soil-disturbing activities, and climatic changes that induce fungal proliferation and dissemination through air could be factors working in unison to increase Valley fever incidence in California. Tracking the incidence and geographic distribution of Valley fever therefore provides valuable information to inform public health decisions, particularly given projected changes in climate-related factors. There is currently no vaccine to prevent Valley fever, but antifungal medications are available for treatment, particularly for severe disease (CDPH, 2015). Understanding the dynamics among climatic, ecological niche, lifestyle and demographic factors could help control the spread of the disease (Pearson et al., 2019). Informing people whether their occupation, residence or travel destination could expose them to the spores could help in preventing disease propagation or help identify early disease symptoms before they get worse, disseminate in the body, or even lead to death. Fact sheets and other information help communicate the potential association between high wind events, like the Santa Anas, wildfire and Valley fever infection (CDPH, 2013; Ventura County DPH, 2018).

Valley fever presents an ongoing and increasing public health burden in California. Since mild cases are less likely to be diagnosed and reported, incidence data likely reflect cases with moderate or severe illness. Hence, impact on the economy and health costs are also grossly underestimated (Thompson et al., 2015). A study estimated that lifetime costs in 2017 from Valley fever in California were $94,000 per hospitalized person – with $58,000 in direct costs (including diagnosis, treatment, and follow-up) and $36,000 in indirect costs (including productivity losses) – totaling $700 million for the state (Wilson et al., 2019). At the same time, severe infections have costly implications: from 2000 to 2011, patients hospitalized with Valley fever in California spent a median of six days receiving care at a median charge of $6,800 per day ($55,062 per stay). For the same time period, the total charge for all Valley fever-associated hospitalizations in the state was $2.2 billion (Sondermeyer et al., 2013).

What factors influence this indicator?

People are more likely to get Valley fever if they live, work, or visit in areas where the fungus grows in the soil or is in airborne dust. The majority of outbreaks in California have been associated with dirt-disturbing work settings, including construction, military, archeologic sites, wildland firefighting, and correctional institutions, where high attack rates have been seen even among relatively young people. Drought, aridity, dust storms and wildfires – all related to climate change in California and projected to increase in frequency and severity over the years (Abatzoglou et al., 2016; Cook et al., 2015; Prein et al., 2016; Seager et al., 2007; Tong et al., 2017) – could directly or indirectly affect fungal proliferation and spore dissemination, and eventual human and animal infection with Valley fever. These and other climate-related phenomena can work together to spread *Coccidioides* infection to people who live beyond the historically-endemic Central Valley (Pearson et al., 2019). Valley fever cases have been increasing, although not linearly, likely due to the complex interaction between various climatic and environmental factors that impact *Coccidioides,* changes in work or recreational travel patterns that influence exposure, changes in population susceptibility, and testing and reporting practices.

Geography, drought and precipitation

"Valley" in Valley fever refers to the disease being endemic to the Central Valley of California where most cases in the state have been consistently reported. However, over the last decade, increasing cases have been detected in surrounding counties and even more northerly locations, like eastern Washington State (Johnson et al., 2016). The geographic niches within California that are hospitable to *Coccidioides* also appear to be expanding, as evidenced by increasing rates of Valley fever outside of the Central Valley, particularly in the Northern San Joaquin Valley and Central Coast (Sondermeyer et al., 2020). Central Coast counties like Monterey and Santa Barbara, where numerous large fires have recently occurred, are seeing more cases, particularly among firefighters who participate in ground-disrupting fire prevention activities (Bubnash 2017; Laws, et al., 2021; Wilson 2017). There is also some evidence indicating cases are increasing in geographic range around Los Angeles County. One study found that compared with 2000 through 2003, 19 of 24 health districts in Los Angeles County had a 100% to 1,500% increase in overall cases during 2008–2011 (Guevara et al., 2015). Although the reasons for these increases are likely multifactorial, drought and aridity and other climatic changes likely play a major role. In the Antelope Valley, a high desert area containing parts of San Bernardino, Los Angeles, and eastern Kern County, researchers found the fungal pathogen in 40% of soil samples; they also found an association between the incidence of Valley fever and both land use and particulate matter of 10 micrometer (μm) or less in air (Colson et al., 2017).

Drought desiccates soil, creating dust and coarse particulate matter in endemic areas containing *Coccidioides* spores, which escape deeper into the soil (Gorris et al., 2018). Because the *Coccidioides* fungus is quite hardy, it can become dormant deep in parched soil whereas other organisms would have succumbed to drought and lack of nutrients. When rain and more ideal conditions return, the dormant fungus becomes active, growing in soil and often multiplying in larger numbers than usual since competing organisms have become less plentiful (Coates and Fox, 2018; Fisher et al., 2000; Kirkland and Fierer, 1996; Zender et al., 2006). Then, when dry, hot conditions return, infections fragments called arthroconidia (refer to Figure 3) can be released into air when soil is disturbed (Gorris et al., 2018; Johnson et al., 2014; Lewis et al., 2015).

Patterns of Valley fever incidence and drought have been consistently observed in California, with large increases occurring following periods of drought. After several years of drought, increased rainfall in California in early 2016 might have resulted in more favorable conditions for *Coccidioides* and, consequently, more infections (Benedict et al., 2019). In another study, both temperature and drought variability were positively correlated with Valley fever vulnerability based on case incidence in California from 2000 through 2014 (Shriber et al., 2017). Researchers have predicted that prolonged dryness and drought in the American Southwest will render much of the area west of the Rocky Mountains hospitable to *Coccidioides* (Gorris et al., 2019). In fact, scientists have designated Arizona cases as being related to the effects of climate change (Park et al., 2005); cases in Arizona far outnumber those of California. Evidence of the expanding geographic range of *Coccidiodes* indicate a need for safety precautions aimed to limit Valley fever transmission when proceeding with development in these areas.

Wind and dust storms

Increased winds linked to global climate change (Tong et al., 2017) could also be driving Valley fever infections. There is evidence that a dust storm in 1978 in the Central Valley carried the pathogen hundreds of miles, infecting individuals in Sacramento County, for example (Williams et al., 1979). Dust storms, particularly those attributed to Santa Ana winds that take place in the fall in Southern California, could also help spread the spores to farther locations. Santa Ana winds and the ensuing dust storm that occurred after the 1994 Northridge earthquake have been linked to distributing *Coccidioides* spores to local communities after the earthquake, triggering an outbreak in Simi Valley (Schneider et al., 1997). In Arizona, researchers found a moderate correlation (r = 0.51) between frequency of dust storms and Valley fever incidence in Maricopa County (Tong et al., 2017).

Wildfire

With the increasing risk of wildfires (see *Wildfires* indicator), research has begun investigating their potential influence on Valley fever. Anecdotal evidence and interviews with firefighters have provided insight into this relatively new area of research. Although these associations are not yet well understood and research is ongoing, wildfires can impact soil composition and ground cover. Firefighting can lead to soil disruption when firefighters create fire lines using hand tools for digging. These factors could impact the ability of *Coccidioides* to proliferate and spores to be dispersed through the air. Santa Ana winds, which occur in the fall, coincide both with the seasonality of Valley fever and when fire danger is also highest, particularly in coastal Central and Southern California. Valley fever outbreaks have occurred among wildland firefighters, particularly among those involved in soil disruptive activities used to contain wildfires (Laws et al., 2021).

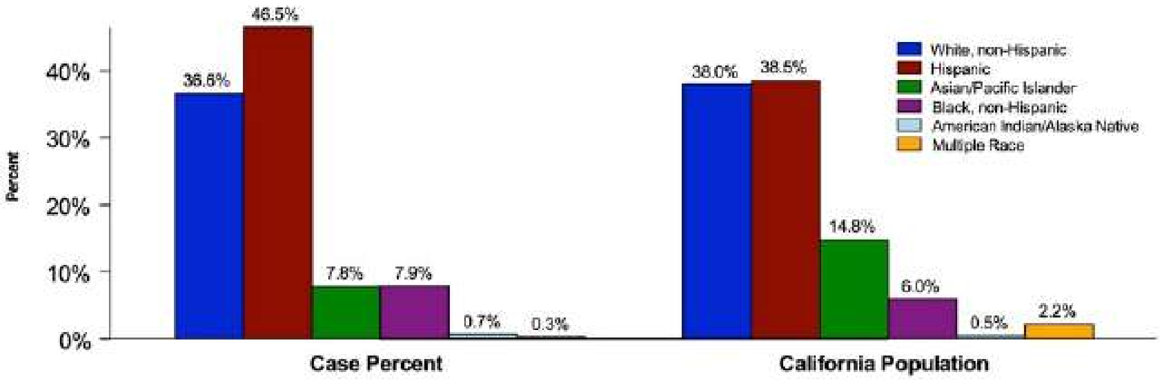
Seasonality

The number of Valley fever cases have generally shown an uptick during the late summer and fall seasons in California since disease surveillance attempts began in the 1940s, indicating possible associations with season, temperature, precipitation, and/or wind (Smith et al., 1946). With climate change experts predicting an earlier start to summer and a later beginning for fall/winter (Wang et al., 2021), there is the potential for an extension of Valley fever season, leaving residents and summer visitors in endemic areas more vulnerable to infection for longer periods of time. Although most people become immune to the pathogen after a primary illness, newcomers moving into endemic areas and children born to current residents remain susceptible to infection. However, surveillance data indicate that people who have lived in highly-endemic areas for years without becoming sick can develop symptoms, which are sometimes very severe. Compromised immunity, due to age or comorbidities, can lead to relapse (CDPH, 2018).

<u>Vulnerable Populations</u>

Different population groups in the state face additional risk of exposure to *Coccidioides* (e.g., outdoor workers) and of severe disease if infected (e.g., pregnant women, those 65 and older, and immunocompromised persons, including those who have diabetes) (Bercovitch et al., 2011; CDPH, 2018; Johnson et al., 2014; Nguyen et al., 2013). Black persons are consistently reported to have the highest rates of Valley fever throughout California and are known to have increased risk for severe and disseminated disease and hospitalization. Additionally, a higher proportion of Hispanics are reported among Valley fever cases than would be expected based on the California population. Racial-ethnic disparities (see Figure 4) in Valley fever cases are not well understood and are likely due to a variety of factors including occupation, genetics, and other factors, including the differential distribution of underlying health conditions across racial or ethnic groups.

Figure 4. Coccidioidomycosis, cases and population by race/ethnicity, 2013-2019



Source: CDPH 2020

34.5% (n=13363) of reported incidents of Coccidioidomycosis did not identify race/ethnicity and 5.6% (n=2176) of reported incidents identified as “other” race/ethnicity and are not included in the Case Percent calculation. Information presented with a large percentage of missing data should be interpreted with caution.

Outbreaks among incarcerated individuals imprisoned in endemic areas have been ongoing during the last twenty years. Many of these individuals have no previous exposure to Valley fever. In one outbreak, exposure stemmed from fugitive dust from building construction near where prisoners were housed or engaging in outdoor physical activity; despite mitigation efforts, such as planting vegetation, high Valley fever attack rates continued (Wheeler et al., 2015). (“Attack rate” refers to the proportion of persons in a population who experience an acute health event during a limited period, such as during an outbreak.) Black race was found to be a risk factor for disseminated disease.

Prisons include a continual rotation of new inmates who are likely immunologically naïve to Valley fever infection. California prisons house a disproportionately larger black population (Lofstrom et al., 2020), a group also identified as bearing a disproportionately poor health outcome burden from Valley fever. Again, many incarcerated individuals engage in wildland firefighting, putting them at greater risk.

Technical considerations

Data characteristics

California regulations require local health officers to report cases of Valley fever to CDPH. Up until 2019, a case was defined as a person who had laboratory and clinical evidence of infection that satisfied the most recent surveillance case definition published by the Council of State and Territorial Epidemiologists (CSTE). Effective January 1, 2019, CDPH changed its Valley fever case definition to require only laboratory confirmation of disease (CDPH, 2018). CDPH accepts all cases determined by the local health department as confirmed.

Strengths and limitations of the data

The number of reported cases of Valley fever shown in Figure 1 are likely to underestimate the true magnitude of the disease. Factors that may contribute to under-reporting include ill persons not seeking health care, misdiagnoses, failure to order diagnostic tests, and limited reporting by clinicians and laboratories. Asymptomatic or minor cases are likely not diagnosed and not reported and Valley fever is likely often misdiagnosed since it presents like many other respiratory illnesses such as influenza, COVID-19, and bacterial pneumonia. Factors that may enhance disease reporting include increased exposure and disease severity, recent media or public attention, and active surveillance activities. Surveillance data include serious cases, which are more visible and have been increasing, and are less likely to identify those with fewer symptoms but still lead to missed worked days and illness. Increased surveillance could explain some of the increased number of cases, though not all.

Because race/ethnicity information was missing or incomplete for 34.5 percent of all 2013-2019 cases (shown in Figure 4), incidence rates by race/ethnicity were not calculated for this indicator. However, the proportion of cases representing race/ethnicity categories are presented alongside statewide averages for these categories during the seven-year surveillance period. Nonetheless, race/ethnicity information based on a high percentage of missing data should be interpreted with caution. Data presented in this indicator may differ from previously published data due to delays inherent to case reporting, laboratory reporting, and epidemiologic investigation.

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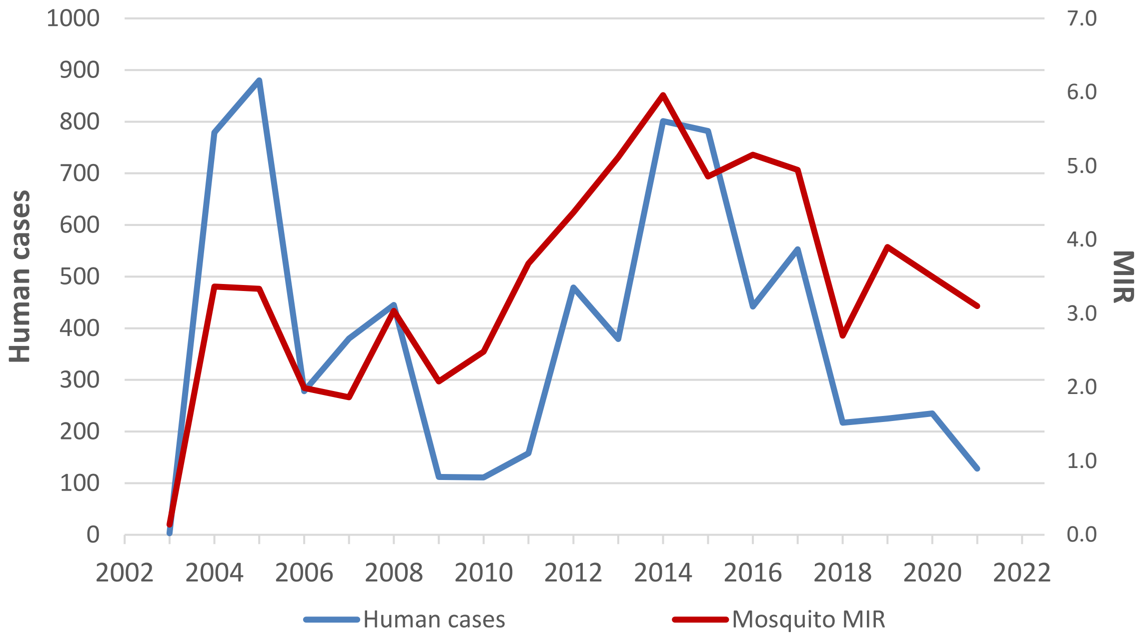
VECTOR-BORNE DISEASES

Warming temperatures and changes in precipitation affect vector-borne disease patterns in California through impacts on the vector, such as mosquitoes or ticks, the pathogen, and animal reservoirs. West Nile virus poses the greatest mosquito-borne disease threat to California residents and visitors. Higher temperatures shorten the development time of mosquito vectors and the viral (pathogen) incubation period in the mosquito, resulting in a greater number of infected mosquitoes.

Figure 1. Human West Nile virus cases[1] and mosquito minimum infection rates (MIR)[2] in California, 2003-2021



Source: CDPH 2021a

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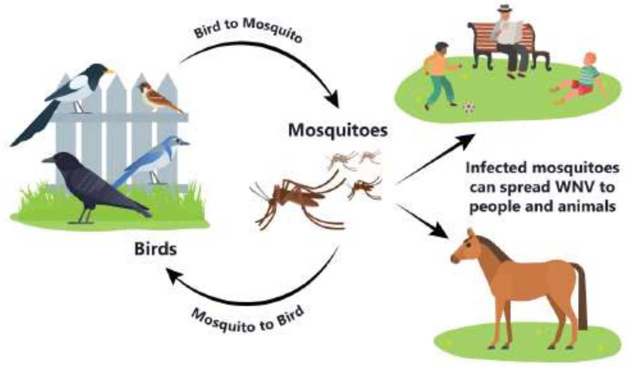
[1] **Cases** – reported human infection (neuroinvasive and nonneuroinvasive cases; does not include asymptomatic blood bank positive individuals). Infections are substantially underreported, especially the less severe, often undetected cases.

[2] **MIR** – number of positive mosquito samples divided by the total number of mosquitoes tested multiplied by 1,000. (A sample is a group of ≤ 50 trapped female mosquitoes that is used for virus testing.)

What does the indicator show?

Vector-borne diseases are caused by pathogens transmitted by living organisms, such as mosquitoes and ticks. Of the 15 mosquito-borne viruses known to occur in California, West Nile virus (WNV) in particular continues to seriously impact the health of humans, horses, and wild birds throughout the state (CDPH, 2020; CDPH, 2021a). Figure 1 shows human cases of WNV and mosquito minimum infection rates (MIR) (see *Technical Considerations*) reported in California during 2003-2020. The MIR is a standardized measure of WNV prevalence; the word “minimum” indicates that at least one infected mosquito in a pool may be detected. Figure 2 shows how WNV is transmitted to humans and animals.

Figure 2. West Nile Virus Transmission Cycle



Source: CDPH, 2020

In California, most vector-borne diseases are caused by viruses, bacteria, or other pathogens spread from animal reservoirs to incidental humans and domestic animal hosts. West Nile virus is an arthropod-borne virus, or arbovirus, which is the largest class of vector-borne human pathogens (NAS, 2016). *West Nile virus is most commonly spread by the bite of an infected mosquito* (CDPH, 2021a).

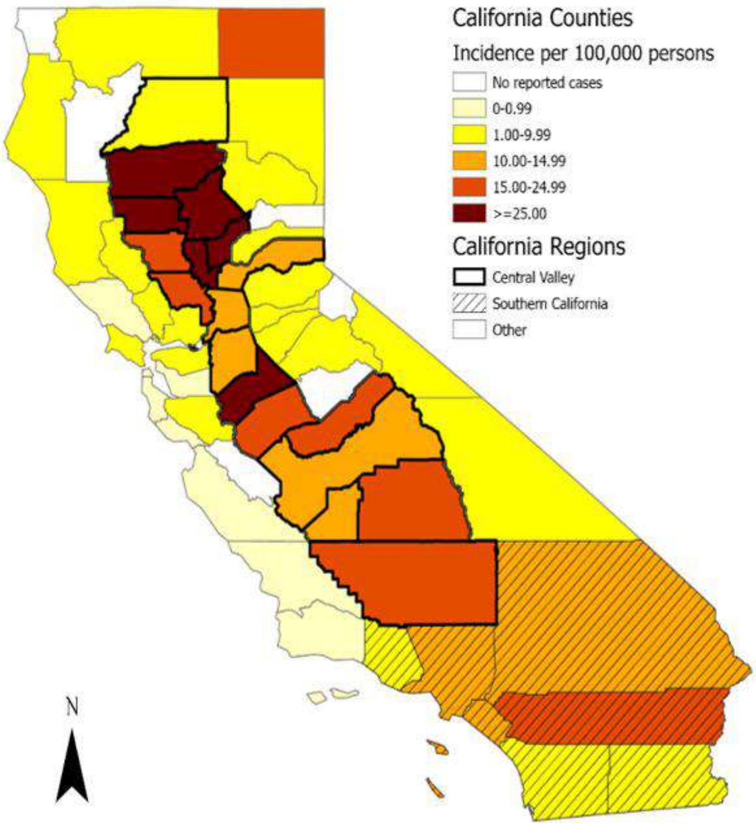
WNVs human cases in Figure 1 show no clear trend, varying from year to year over the 18-year period shown. The number of cases peaked in 2004-2005, and in 2014-2015. WNV cases are driven in part by the MIR which measures the level of WNV infection in *Culex* mosquitoes. The MIR typically increases as temperatures rise due to the shortened incubation period in the mosquito vector and more frequent feeding on hosts by the mosquito (see *What factors influence this indicator?*). MIR is used along with mosquito abundance levels at county or agency scales to evaluate human risk and plan for seasonal response as outlined in the California Mosquito-Borne Virus Surveillance and Response Plan (CDPH, 2021a). In areas of the state where there are no human WNV cases reported, and where mosquito testing is conducted, the mosquito MIR can provide a measure of annual risk.

First detected in the state in 2003 (when three human cases were reported), the majority of WNV infections are not reported. The more severe cases, which involve neurological symptoms, tend to be reported; however, for every neuroinvasive case reported, there is likely an additional 140 to 256 infections that go unreported (McDonald et al, 2019; Busch et al., 2006; Mostashari et al., 2001). Lack of health care, access to testing, or the mild symptoms associated with most infections are some of the reasons that cases are under-reported or undetected (CDPH, 2015; Lindsey et al., 2016). Though current data does not show a clear trend in the number of human WNV cases nor the MIR, long-term monitoring is important as a warming climate will increase the frequency and intensity of short term weather events that impact the activity of this virus.

Why is this indicator important?

For most Californians, WNV poses the greatest mosquito-borne disease threat (Snyder et al., 2020). Not all WNV infections result in disease: about 1 in 5 develop fever and flu-like symptoms;1 in 150 develop a serious, sometimes fatal neurological illness (CDC, 2021). Symptomatic infections may include fever, headache, body aches, nausea, vomiting, swollen lymph glands, skin rash, and in some cases fatigue or weakness that lasts for weeks or months. West Nile virus neuroinvasive disease cases can result in encephalitis or meningitis, with symptoms that may include high fever, neck stiffness, disorientation, tremors, numbness and paralysis, and coma, and in the most severe cases, death; approximately 10 percent of these severe cases are fatal (CDC, 2015).

Figure 3 West Nile neuroinvasive disease cumulative incidence by county, 2003–2018



Source: CDPH 2021a
(based on Snyder et al., 2020)

Figure 3 shows the cumulative incidence of WNV neuroinvasive disease during 2003-2018 for all California counties (data from Snyder et al., 2020). While for most years, densely populated southern California had the highest number of reported cases, the incidence per 100,000 was highest in the Central Valley (thick black outline) where MIR is also typically elevated (CDPH, 2021b). The high WNV incidence in the Central Valley reflects the historically high risk of mosquito-borne diseases in the region. Sparsely populated Glenn County, situated in the northern Central Valley, had the highest cumulative incidence of WNV neuroinvasive disease among all California counties. Temperature and precipitation patterns and the expansive tracts of land for rice-growing in Glenn and its neighboring counties are conducive to high mosquito production in the summer. Although the number of cases are fewer, the low populations in these counties result in higher incidence rates compared to more populated counties. Warm southern California counties (hatched areas) had the next highest reported incidence.Six counties have not reported any human WNV infections to date: Alpine, Del Norte, Mariposa, San Benito, Sierra, and Trinity. Surveillance for cases in these counties will provide insights into future changes in the distribution and occurrence of the virus in a warming climate.

Tracking vector-borne disease trends, such as WNV activity, is critical to understanding the impact of climate change on disease prevalence. Climate change will affect vector-borne disease transmission patterns because changes in temperature and precipitation can influence the seasonality, distribution, and prevalence of vector-borne diseases (USGCRP, 2016). In fact, due to their widespread occurrence and sensitivity to climatic factors, vector-borne diseases have been closely associated with climate change (Smith et al., 2014).

Through the ongoing surveillance carried out by the California Department of Public Health (CDPH) and local partner agencies, the state has the capacity and readiness to detect increasing WNV transmission risk by monitoring mosquito infection rates and human WNV cases in the face of climate change. The surveillance system also includes the testing of dead birds (animal reservoirs) and sentinel chickens (domestic animal hosts).

In addition to WNV, other mosquito-borne viruses that can cause significant illness are western equine encephalomyelitis virus (WEEV) and St. Louis encephalitis virus (SLEV) (Reisen and Coffey, 2014). Although WEEV has been detected only rarely in California in recent years (Bergren et al., 2014), SLEV re-emerged in California in 2015 after more than a decade without detection (White et al., 2016); human SLEV cases have been detected annually since 2016 (http://westnile.ca.gov). WEEV activity has been thought to decrease with increasing temperatures (Reeves et al., 1994), whereas SLEV activity and outbreaks have long been associated with elevated temperatures (Monath, 1980).

Two invasive mosquito species, *Aedes aegypti* (the yellow fever mosquito) and *Aedes albopictus* (the Asian tiger mosquito), detected within the last decade in many Central Valley and southern California counties, could potentially spread to other areas of the state (Metzger et al., 2017). (See map posted at: https://arcg.is/00j1P8). Both mosquitoes have the potential to transmit Zika, dengue, chikungunya, and yellow fever viruses, and like West Nile virus, spring-fall temperatures in much of California are suitable for efficient transmission of these viruses (Winokur et al., 2020). Although all detected human infections with these viruses in California through 2020 have been associated with travel, the presence of competent vectors adds to the potential risk of local mosquito-borne transmission, especially as these species become more widely established in the state (CDPH, 2021b). The emergence of new infectious diseases associated with invasive species can be influenced by a number of factors, including land use changes (e.g., urbanization), the introduction of new hosts, and climate change (NAS, 2016).

In addition to mosquito vectors, climate change will impact the prevalence of tick-borne pathogens in California. Lyme disease, the most commonly reported tick-borne disease, is transmitted by the western blacklegged tick (*Ixodes pacificus).* Western blacklegged tick abundance is limited by abiotic conditions during the summer dry season (Swei et al., 2011), which impact microclimates where certain life stages of ticks survive (Kilpatrick et al., 2017). Western blacklegged tick distribution is expected to expand, particularly on public lands, under various climate change models (Hahn et al., 2021). The influence of climate change on the abundance and distribution of insect vectors is discussed in the next section.

What factors influence this indicator?

Focused geographical analyses of WNV human cases in California and in other locations demonstrate that an increase in temperature and drought conditions are associated with an increase in WNV cases (Hernandez et al., 2019; Paull et al., 2017; Lockaby et al., 2016; Hartley et al., 2012). Record hot temperatures and extended drought in 2015 may have contributed to the high number of human WNV cases and highest ever fatal cases reported that year.

Above-normal temperatures are among the most consistent factors associated with WNV outbreaks (Hahn et al., 2015). Mild winters have been associated with increased WNV transmission possibly due, in part, to less mosquito and resident bird mortality. Warmer winter and spring seasons may also allow for transmission to start earlier. Such conditions also allow more time for virus amplification in bird-mosquito cycles, possibly increasing the potential for mosquitoes to transmit WNV to people. The effects of increased temperature are primarily through acceleration of physiological processes within mosquitoes, which results in faster larval development and shorter generation times, faster blood meal digestion and therefore more frequent mosquito biting, and shortening of the incubation period required for infected mosquitoes to transmit WNV (Hoover and Barker, 2016). Coastal cities that are currently at low risk for WNV due to cooler summer temperatures may see increasing MIRs and transmission risk as average summer temperatures rise.

A useful measure of the efficiency of transmission of a vector-borne pathogen is the number of bites or blood meals required by the vector before the pathogen can be transmitted. Investigators have studied the efficiency of transmission of mosquito-borne viruses when mosquitoes were incubated at different temperatures (Reisen et al., 2006; Danforth et al., 2015). They report that with increasing temperatures, fewer blood meals are required for transmission and there is a higher probability that the virus can be transmitted within a mosquito's lifetime. Similar data have been used to delineate the effective global distribution of different malaria parasites and how climate change may have altered this pattern (Chaves and Koenraadt, 2010; Parham and Michael, 2010).

Precipitation and associated hydrological impacts also influence the likelihood of WNV transmission. Expected shifts of winter precipitation from snow to rain at high elevations (see *Precipitation* indicator) will limit water storage and cause spring runoff to occur earlier and faster, which would result in increased mosquito habitat during wet years (DWR, 2017). Periods of elevated rainfall (for example, during El Nino events) can increase immature habitats for mosquitoes and increase population survival due to higher humidity (Linthicum et al., 2016).

Mosquitoes tend to thrive during periods of drought, especially in urban areas, due to changes in stormwater management practices. Under drought conditions, mosquitoes in urban areas can become more abundant due to stagnation of underground water in stormwater systems that would otherwise be flushed by rainfall. Runoff from landscape irrigation systems mixed with organic matter can create ideal mosquito habitat (Hoover and Barker, 2016). During a drought, more birds may move into suburban areas where water is more available, thereby bringing WNV hosts into contact with urban vectors (Reisen, 2013). Drought was found to be an important predictor of reported annual WNV neuroinvasive disease cases in California and nationwide (Paull et al., 2017). However, on smaller geographic scales, drought can reduce WNV transmission. Water use restrictions in urban and suburban areas can reduce larval habitat, thus lowering the risk of WNV transmission (Bhattachan et al., 2020).

Changes in temperature and precipitation may also alter the transmission risk of other vector-borne diseases, including hantavirus and tick-borne diseases like Lyme disease, by affecting the distribution and abundance of key species of vertebrate hosts and vectors (Carver et al., 2015; Ogden and Lindsay, 2016; Hahn et al., 2021). As discussed above, a changing climate may also create conditions favorable for invasive mosquito species to expand their geographic range into California (Ogden et al., 2014).

Prolonged hot and dry periods may reduce tick abundance and therefore decrease Lyme disease risk in some locations, although if relative humidity is maintained, an increase in temperature may increase the longevity of ticks (Eisen et al., 2003). In contrast, the distribution of one vector of Rocky Mountain spotted fever (RMSF), the brown dog tick (*Rhipicephalus sanguineus),* may expand with increased frequencies of El Nino Southern Oscillation (ENSO) events. This could cause an increase in RMSF cases (Fisman et al., 2016). The ongoing outbreak of RMSF in northern Mexico, which occasionally results in human cases in the United States through imported dogs or ticks, is a multifactorial problem involving climate and socioeconomic factors (Foley et al., 2019; Álvarez-Hernández et al., 2017). Recently, host preferences of *R. sanguineus* have been shown to be altered by temperature, notably with increased feeding of tropical lineages on humans at high temperatures (38°C) (Backus et al., 2021).

Extreme precipitation events often associated with ENSO events are thought to impact hantavirus activity by expanding rodent habitat, particularly in normally arid habitats adjacent to humans (Carver et al., 2015). Hantavirus prevalence in rodents, particularly in deer mice, continues to be monitored in California in locations where rodents and humans may come into contact. Although the 2012 hantavirus outbreak in

Yosemite National Park was associated with rodent habitat enrichment provided by cabin construction rather than with weather abnormalities, it was an example of how human hantavirus infection risk can increase when rodent densities are given the opportunity to increase (Nunez et al., 2014).

The devastating environmental impacts of wildfires may impact pathogen, vector, and host interactions, leading to changing risks of vector-borne disease in humans and other animals (Pascoe et al., 2020; MacDonald et al., 2018). Forested habitats support the tick and host populations necessary for maintenance and transmission of numerous tick-borne pathogens. One California study reported that wildfire may potentially increase risk of exposure to vector ticks in the first year following wildfire but that risk decreases substantially in following years due to tick population declines and loss of hosts from the system (MacDonald et al., 2018).

It is important to recognize the role of other anthropogenic factors influencing vector-borne disease transmission. These include changing ecosystems and land use, socio-economic status, human behavior, the status of public health infrastructure, and mosquito and vector control activities (USGCRP, 2018; Rochlin et al., 2016; Carney et al., 2011). In particular, WNV infections have been linked with local-level factors such as income, sanitation, and population density (Watts et al., 2021; Hernandez et al., 2019; Harrigan et al., 2010). People in low income communities may find it difficult to afford mosquito repellents, air conditioning, and property upkeep (to prevent or drain standing water). They may be less aware of WNV activity in their area, of symptoms associated with the disease, and of the need to get tested. Furthermore, inadequate waste water management, flood protection, sanitation, upkeep of infrastructure, and other hazard prevention efforts can create favorable conditions for mosquito breeding.

Technical considerations

Data characteristics

California has a comprehensive mosquito-borne disease surveillance program that has monitored mosquito abundance and mosquito-borne virus activity since 1969 (CDPH, 2021a). Statewide, diagnosis of human infection with WNV and other arboviruses is performed at the CDPH Health Viral and Rickettsial Disease Laboratory, nine local county public health laboratories, and multiple commercial laboratories. Arbovirus surveillance also includes monitoring virus activity in mosquitoes and wild birds that enzootically amplify the virus for purposes of providing warning of human disease risk.

Mosquito and dead bird testing is performed by the UC Davis Arbovirus Research and Training laboratory and several local vector control agencies. The mosquito surveillance program utilizes minimum infection rate to evaluate local virus activity patterns (CDPH 2021a). It is calculated as the number of WNV-positive mosquito pools divided by the total number of mosquitoes tested multiplied by 1,000. In addition to mosquito-borne diseases, CDPH works with local, state, and federal agencies, universities, the medical community and others in its efforts to monitor, prevent, and control rodent-, flea-, and tick-borne diseases.

The ability to use surveillance data effectively in real-time to support public-health and vector control decisions is a key part of California's efforts to mitigate the growing effects of climate change on vector-borne diseases, and California is a national leader in the development of such decision-support systems that are being used already to inform local and state policies. Public-facing data on WNV and other vector-borne pathogens are served via maps, reports, and other visualizations through CDPH's website. Statewide data on surveillance of vectors and vector-borne pathogens are managed, analyzed, and shared through the CalSurv data system, which is supported by funds from the State of California and housed at UC Davis through a partnership with CDPH and the Mosquito and Vector Control Association of California. The CalSurv system provides a wide range of tools for data entry, analysis, and visualization that are used by agencies throughout California on a daily basis. Maps showing CalSurv's data are available at https://maps.vectorsurv.org.

Strengths and limitations of the data

For human disease surveillance, local vector control agencies rely on the detection and reporting of confirmed cases to plan emergency mosquito control and prevention activities. However, human cases of mosquito-borne viruses are an insensitive surveillance measure because less severe fever cases are rarely diagnosed and most infected persons do not develop disease (CDPH, 2021a). For zoonotic pathogens that circulate in natural cycles between arthropod vectors and vertebrate hosts and may spill over to infect humans, testing of vectors or non-human hosts can provide valuable information about infection risk. In areas with robust mosquito testing, MIRs are useful indicators of WNV transmission risk and local vector control agencies can use MIRs to target mosquito control efforts. However, sampling effort and spatial coverage varies widely across the state, so the intensity of surveillance should be considered when comparing MIRs among counties and regions. Although 90 percent of California's population lives in an area with a vector control agency, not all agencies have the capacity to conduct robust mosquito surveillance and testing.

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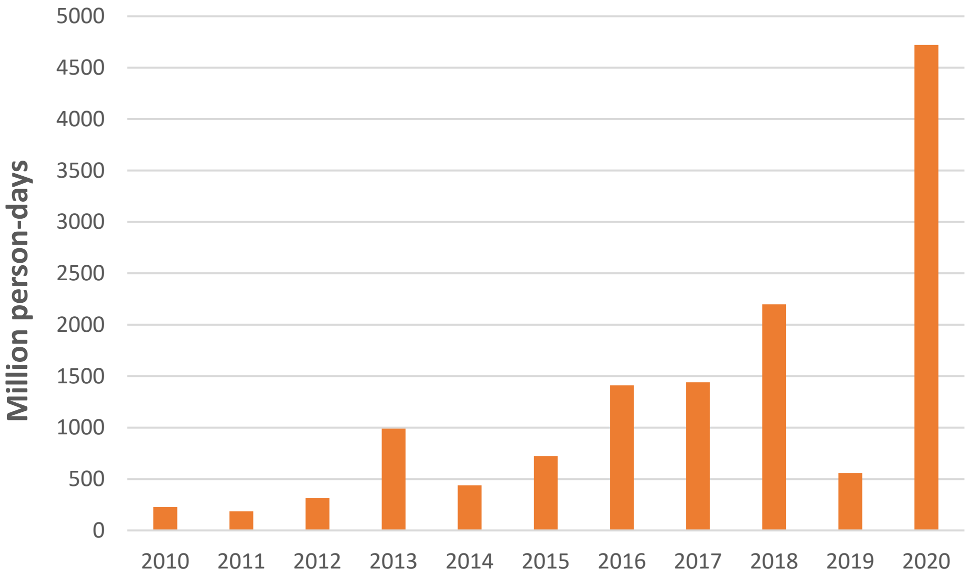
WILDFIRE SMOKE

Potential wildfire smoke exposures have been increasing in California since 2010, due to the increasing frequency, duration and severity of wildfires. This is reflected in the annual number of "person days" in areas where wildfire smoke is present.

Figure 1. Potential population exposures* to wildfire smoke, 2010-2020



Source: NOAA, 2021; US Census Bureau, 2010 (analysis based on Vargo, 2020)

** Graph presents the estimated number of people living in areas where smoke plumes were present multiplied by the number of days when the plumes were present in those areas.*

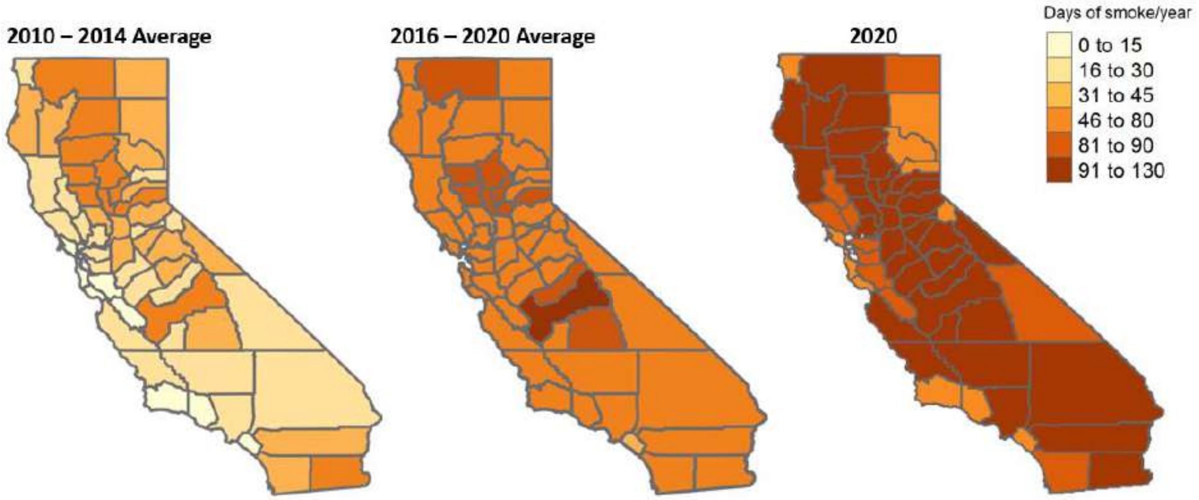
What does the indicator show?

Potential population exposures to wildfire smoke have been increasing in California since 2010, based on "person-days," a metric that is calculated as the number of persons living in the areas where wildfire smoke plumes were present multiplied by the number of days when smoke was present (Vargo, 2020); see Figure 1. Areas of wildfire smoke plumes are based on satellite imagery from the National Oceanic and Atmospheric Administration's Hazard Mapping System's Fire and Smoke Product (HMS Smoke) (NOAA, 2021).

The maps in Figure 2 show the number of days, by county, when wildfire smoke was present at different time periods. From 2010 to 2014, 11 California counties experienced at least 46 smoke days each year on average; three of these counties had 60 to 66 smoke days per year. The rest of the counties had 45 or less smoke days per year. From 2016 to 2020, 56 of the state's 58 counties experienced at least 46 smoke days each year on average: two counties had 34 and 45 smoke days per year, 46 counties had 46 to 80 smoke days per year, and ten had more than 80 smoke days per year. About 3.5 times more acres burned on average in the latter compared to the earlier five-year period, which includes a record-high 4.2 million acres burned across the state in

2020 (see *Wildfires* indicator). That year, smoke plumes were present in every county for at least 46 days; 36 counties had at least 91 smoke plume days.

Figure 2. Number of wildfire smoke days by California county



Source: NOAA, 2021 (analysis based on Vargo, 2020)

Maps present the number of days per county when smoke plumes were present. Left, average number of smoke days per year, 2010-2014. Middle, average number of smoke days per year, 2016-2020. Right, number of smoke days in 2020.

Why is this indicator important?

With the rise in the frequency and duration of wildfires in California, human and environmental exposures to harmful pollutants are also increasing. Wildfire smoke is a complex mixture that is determined by many factors unique to the burn site, such as the type of vegetation burned and weather conditions. A large portion of the resulting air pollutants consists of particulate matter, with a higher proportion of fine particulate matter (2.5 microns or less in diameter, or PM2.5) than typical ambient air pollution (Holm et al., 2021). PM2.5 can be inhaled into the deepest recesses of the lungs, enter the bloodstream, and affect the heart and other vital organs. Recent studies, including one in Southern California, suggest that wildfire particulate matter has greater carbon

Photo Credit: Christopher Michel

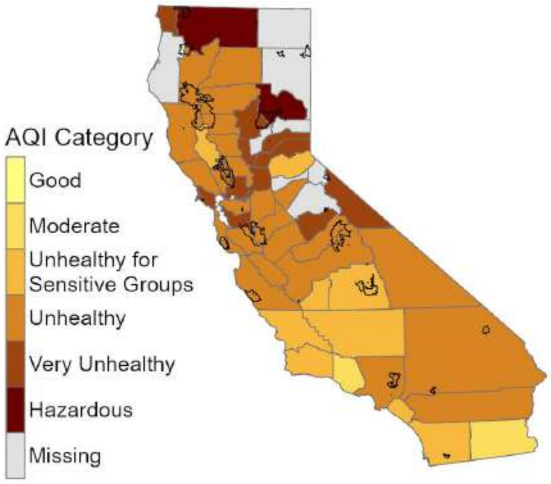
The San Francisco-Oakland Bay Bridge at noon on September 9, 2020 content and thus more potential to cause inflammation in the lungs than ambient PM2.5 (Aguilera, 2021a).

Other hazardous compounds in wildfire smoke include carbon monoxide, ozone precursor compounds, polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (Black et al., 2017). Some compounds are known human carcinogens (e.g., benzene, formaldehyde and certain PAHs). Wildfires that burn structures are reported to produce smoke that contains toxic heavy metals such as lead and zinc (CARB, 2021a).

Scientists observed that, between 2001 and 2020, wildfire emissions across the western United States led to widespread co-occurrence of high PM2.5 and ground-level ozone air concentrations (Kalashnikov et al., 2022). As summer and fall wildfires become larger and more severe, the co-occurrence of these air pollutants may pose a greater threat to public health.

Scientists are investigating the relationship between PM2.5 concentrations characterized using the HMS Smoke plume categories and those measured by ground-level monitors. Although the concentrations do not completely align and there is uncertainty in the relationship, studies have found that higher ground-level PM2.5 concentrations were more frequently observed during heavy smoke plume days (Fadadu et al., 2020). In 2015, a study in Central California found a weak, but statistically significant relationship between smoke plume locations and increased surface PM2.5 concentrations (Preisler et al., 2015). Another study found that unhealthy levels of PM2.5 were more likely to occur on days with smoke plumes than on clear days (Larsen et al., 2018). In short, satellite-detected smoke plumes often co-occur with an increase in PM2.5 concentrations but there is no real relationship between the different HMS smoke plume categories and a specific ground-level PM2.5 concentration.

Figure 3. Air quality (based on maximum daily PM2.5 concentrations) within California Counties, September 11-12, 2020



Source: US EPA, 2021b

** Map presents the Air Quality Index category based on EPA-defined PM2.5 concentration ranges[1] (μg/m^3, 24-hour average) found within each county between September 11 and 12, 2020. Black outlines indicate active fires perimeters during this period.*

Wildfire emissions can severely impact air quality both locally and beyond areas directly impacted by fires, as smoke and ash particles can travel many miles from the original fire location. The 2020 fire season was marked by several large wildfires burning at the same time, leading to unprecedented air quality impacts across the state. Maximum PM2.5 levels persisted in the "hazardous" range of the Air Quality Index (AQI)[1] for weeks in several areas of the state (CAL FIRE, 2021). September 11 to 12, 2020 had particularly bad air quality with most of the state experiencing an AQI of "unhealthy" or worse (Figure 3).

The November 2018 Camp Fire in Paradise provides a good example of the impact of wildfires on air quality in distant regions. Concentrations of PM2.5 reached 415 μg/m^3 in Chico (15 miles west), 228 μg/m^3 in Sacramento (over 80 miles south), and 134 μg/m^3 in San Jose (about 200 miles southwest) (CARB, 2021a). For comparison, the California Ambient Air Quality Standard (which is the same value as the National Ambient Air Quality Standard) is an annual average of 12.0 μg/m^3; an additional federal standard is a 24-hour average of 35 μg/m^3 (CARB, 2021b). These standards represent the maximum concentration of a pollutant in outdoor air that will not be harmful to human health. In addition to PM2.5, smoke up to 150 miles away from the Camp Fire was found to include lead, zinc, calcium, iron, and manganese (CARB, 2021b).

Wildfire smoke darkens the skies, reduces visibility, and poses a clear threat to public health. A large body of research has connected PM2.5 exposure, including wildfire-specific exposure, to respiratory and cardiovascular health outcomes (Chen et al., 2021; Reid et al., 2019). These include decreased lung function, asthma, chronic obstructive pulmonary disease, pneumonia, cardiac arrest, and congestive heart failure. Exposure to wildland smoke may have mental health impacts, particularly in episodes of chronic and persistent smoke events (Eisenman et al., 2021).

Studies have reported on wildfire smoke impacts on public health in California; examples include:

- In 2015, a year with an extensive wildfire season, smoke exposure was found to be associated with cardiovascular and cerebrovascular emergency department (ED) visits for adults in eight California air basins, particularly for those over aged 65 years (Wettstein et al., 2018).

- During the October 2017 Northern California wildfires, in nine San Francisco Bay Area counties, fire-related PM2.5 was most consistently linked to ED visits for respiratory disease, asthma, chronic lower respiratory disease and acute myocardial infarction (Malig et al., 2021).

- Between 2013 and 2018, a 14.6 percent increase in respiratory disease-related ED visits in Shasta County was observed in weeks where wildfire PM2.5 was

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[1] AQI categories are good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous; these correspond to 24-hour average PM2.5 concentrations (in micrograms per cubic meter of air or μg/m^3) of 0.0 to 12.0; 12.1 to 35.4; 35.5 to 55.4; 55.5 to 150.4; 150.5 to 250.5; or 250.5 and higher, respectively.

≥5.5 μg/m^3; a 27.0 percent increase occurred during the 2018 Carr Fire (Casey et al., 2021). Health costs related to fire-related air pollution from all California wildfires in 2018 were estimated at $32.2 billion (Wang et al., 2021).

Certain population subgroups are more susceptible to health impacts when exposed to wildfire smoke (US EPA, 2021b; Liu et al., 2017; Xi et al., 2020). These include people with cardiovascular disease, asthma or other respiratory diseases, and kidney disease. Older adults, children (18 years and younger) and pregnant people are also more vulnerable to the effects of wildfire smoke. During the 2020 wildfires, elevated PM2.5 levels were associated with increased risks of COVID-19 cases and deaths in many western US counties (Zhou, et al., 2021).

Children may be at an increased risk of negative respiratory effects from wildfire smoke due to their smaller airway size and developing lungs (Marabilli et al., 2009). A multi-country review of pediatric ED visits found an overall significant increase in respiratory symptoms and asthma hospitalizations within the first three days of exposure to wildfire smoke, particularly in children less than five years old (Henry et al, 2021). A California study found that exposure to wildfire-specific PM2.5 was associated with higher respiratory-related increases in pediatric hospitalizations compared to similar exposure to non-wildfire PM2.5 (Aguilera et al., 2021b). PM2.5 exposures are also associated with negative impacts on children's immune function, blood pressure and cardiovascular systems (Holm et al., 2021; Prunicki et al., 2021).

Studies suggest that maternal exposure to wildfire smoke during pregnancy is linked to reduced birth weight and preterm birth (Amjad et al., 2021). A California study estimated 6,974 excess preterm births as attributable to wildfire smoke exposure; this accounts for 3.7 percent of observed preterm births between 2006 and 2012 (Heft-Neal et al., 2021). Wildfire smoke exposure during pregnancy has also been associated with a variety of pregnancy complications, such as maternal gestational diabetes and hypertension (Park et al., 2021; Abdo et al., 2019).

Wildfire smoke effects can disproportionately fall on those in particular socioeconomic and occupational groups. People with lower income often have higher rates of respiratory conditions, fewer resources to employ measures that reduce smoke indoors (e.g., air conditioning or air purifiers) and less access to health care. Wildland firefighters (USDA, 2013; Black et al., 2017; Jung et al., 2021) are especially at risk due to unavoidable exposure to wildfire smoke. Some agricultural workers, already disproportionately affected by racial discrimination, exploitation, economic hardships, limited access to health care, language barriers, and fear of deportation, experience high levels of smoke exposure. During the December 2017 Thomas Fire, which burned over 280,000 acres in Santa Barbara and Ventura Counties, thousands of farmworkers continued working in the fields – most without respiratory protection – to prevent crop loss from smoke and ash (Mendez et al., 2020). This led to health impacts including coughing, headaches, difficulty breathing, nausea, and nosebleeds, as well as long-term effects such as respiratory illness. In addition, farmworkers are often exposed to other workplace hazards, such as pesticides and extreme heat.

As the extent of exposure to wildfire smoke increases and moves from periodic acute exposures to more chronic and long-term, it is important to track trends and patterns in potential population exposures to wildfire smoke. This information can be used to distribute health-relevant resources and communications to the most impacted areas and to assist in planning and preparation efforts. For example, the *US EPA Wildfire Smoke: A Guide for Public Health Officials* (Stone et al., 2019) recommends that health officials advise people to remain indoors during smoky conditions, use indoor air filtration systems, and wear respiratory protection when outside.

Wildfire smoke can increase business costs, affect job productivity, reduce earnings and impact tourism and outdoor recreation. Wildfires in recent years have deterred people from visiting the wine country and the Sierra Nevada region (Bauman et al., 2020; Wilson et al., 2020). Wildfire smoke and reduced visibility can elicit a sense of fear, require people to stay indoors, limit traffic to enable firefighting efforts, and ultimately cause tourists to cancel travel plans. A survey of people who visit the Sierra Nevada region reported that wildfire has significantly influenced past travel to the area and will most likely continue to do so in the future. Of those surveyed, 14 percent changed accommodations to avoid wildfire smoke. Outdoor workers in businesses serving tourists face reduced work hours due to visitor cancellations and uncertain work conditions on smoky days. Federal Occupational Safety and Health Administration (OSHA) standards have been proposed to adequately protect workers from wildfire smoke-related health risks (Layton, 2020).

In addition to impacts on human health and well-being, smoke and toxic gases released by wildfires can impact the health of wildlife and ecosystems. Adverse health impacts of wildfire smoke have been reported to contribute to changes in behavior, movement and vocalization in terrestrial and aquatic species (Sanderfoot et al., 2021). Smoke is known to damage the lungs of birds and increase their susceptibility to respiratory infection. Wildfires have increasingly coincided with fall bird migration, where low visibility caused by smoke can disrupt the navigation for migratory species and create difficulties in finding food sources (Sanderfoot and Holloway, 2017; Overton et al., 2021). Wildfire smoke can also negatively impact watersheds, where deposition of smoke and ash in streams can result in dramatic increases in nutrient concentrations and fluctuations of pH, potentially harming aquatic organisms (David et al., 2018).

What factors influence this indicator?

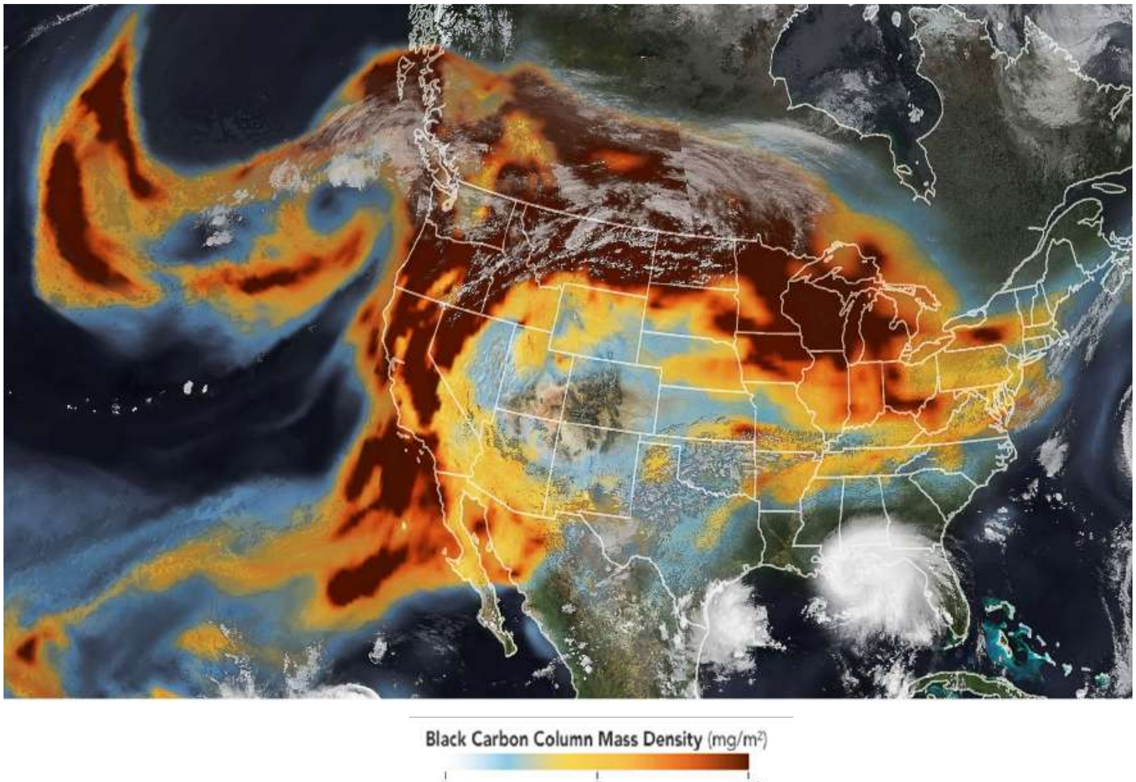
Wildfires are increasing in frequency, duration and severity due to conditions exacerbated by climate change, such as warmer temperatures, reduced precipitation and snowpack, and tree deaths (see *Wildfires* indicator; Goss et al., 2020). The fires are becoming more destructive as well, with 15 of the 20 most destructive wildfires in

California having occurred in the last ten years (Buis, 2021). Correspondingly, exposure to wildfire smoke across California has also increased substantially over time.

Particles from wildfire smoke stay suspended in the atmosphere and can be carried large distances from the source of the fire. The extent and duration of wildfire smoke are impacted by the size, severity, and duration of the source fires as well as wind and weather patterns (Sicard et al., 2019). The potential impact of human exposures is also dependent on the population density where the smoke travels.

In the summer of 2020, smoke from wildfires burning in California, Oregon and Washington drifted across northern states and reached the eastern US (Figure 4). However, the smoke did not have equally strong effects on air quality at ground level everywhere. While people living in communities near the fires in California and Oregon experienced very unhealthy air quality from September 14-16, surface air quality in the eastern US remained mostly good because the smoke was traveling high (above breathable space) in the atmosphere (NASA, 2020).

Figure 4. Satellite image of wildfire smoke plume across the continental United States (September 14, 2020)



Source: NASA, 2020

Jet stream winds transport black carbon across the United States from fires originating on the West Coast. [NASA Earth Observatory images by Joshua Stevens.]

Technical considerations

Data characteristics

Wildfire smoke plumes for years 2010–2020 are from HMS Smoke (NOAA, 2021). HMS Smoke uses visible imagery from satellites to generate smoke plumes associated with fires. Trained analysts manually validate and trace smoke plume locations from two Geostationary Operational Environmental Satellites (GOES). Visible imagery is available at one kilometer (km) spatial resolution. Aerosol Optical Depth information collected from GOES satellites, called the GOES Aerosol and Smoke Product (GASP), are used to provide an objective and quantitative estimate of smoke density. HMS Smoke layers for a specific day are created from several satellite passes, and so multiple plumes may exist over any single location on a given day. To resolve plumes to one observation for each day and location, a single day's plumes are treated as flattened layers so that the coverage of smoke plumes are defined by any HMS collection in that day. The sum of the individual days was used to derive the total smoke days per year.

Information on population was obtained from the 2010 US Census Centers of Population (US Census Bureau, 2010). The latitude and longitude fields from the “Centers of Population” file were used to create a spatial file of points and intersected with HMS Smoke plumes. The block group scale is the finest scale for which the “Centers of Population” exist, and they were used to best represent the locations where populations within Census tracts reside. To combine HMS Smoke plume information with US populations, a function written in R and implemented with RStudio was employed. The full script for processing can be accessed and amended and is available within Vargo et al. (2020).

A “person-days” metric is used to present the results and provides a way of estimating potential exposure, particularly for large areas with widely varying population densities. The use of person-days has been used previously in research to describe smoke plume exposures (Schweizer et al, 2019). Presentation of results as person-days may emphasize the burden of wildland fire smoke in densely populated areas where more people are present, even though potential PM2.5 levels may be higher or more frequent in less populated, rural areas.

AirData represents how the air quality is fluctuating at ground level. The US EPA hosts data from a collection of ground air quality monitors that is quality assured and controlled by state, local, and tribal agencies (US EPA 2021b). The data include daily PM2.5 concentrations for 164 stations throughout California. To give a snapshot of the worst-case scenario, the AQI categories based on the maximum observed PM2.5 concentration within each county are presented in the map in Figure 3. Daily averaged PM2.5 concentrations for each monitoring station were grouped by county, and the date with maximum PM2.5 concentrations for each county was noted (September 11, 2020). Some of the counties were missing data for September 11 so PM2.5 data for September 11th though September 12th were compiled.

Strengths and limitations of the data

HMS Smoke has many strengths: it is freely available, released in a timely manner, allows for daily calculations, it is available continuously across California, and can be used to compare locations across the state. In addition, HMS Smoke is particularly unique in that it gives fire-specific estimated smoke plumes (US EPA, 2021b). HMS Smoke has also been validated and shown to correlate with elevated PM2.5 concentrations measured by ground-level monitors (Preisler et al., 2015; Larsen et al., 2018; Fadadu et al., 2020).

The satellite imagery consists of visible bands and therefore is affected by cloud cover, is unable to differentiate land surface elevation or determine the height of smoke plumes. The HMS Smoke is also generated from satellite passes occurring during daylight hours, with no nighttime data. As mentioned above, presentation of results as person-days may emphasize the burden of wildland fire smoke on densely populated areas and understate the more frequent exposures occurring in rural areas.

AirData is freely available, allows for near daily calculations and is available from 1980 to the present. The sensors are located at near ground-level and are distributed throughout California (and the rest of the USA). Though the monitors are showing the air quality directly where people live, the monitors only represent air quality near where the monitors are located. The sensors are mostly located near more populated regions, leaving large spatial gaps in ground-level air quality. Furthermore, some stations do not have daily data available, which leads to gaps in daily time series analysis.

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Impacts on Tribes

Climate change poses a threat to California’s Tribes through direct impacts on the ecosystems in which they live and are connected. The health of a Tribe is tied to the health of the land and environment.

California Tribes are the original biologists, historians, climatologists, and scientists of the land. Tribal knowledge, acquired from the interaction of Tribes with the Earth over time, is a key component in understanding impact of climate change on human lives and their environment.

This is the first time Tribal Reports have been included as part of an *Indicators of Climate Change in California* report. Over 40 California Tribes contributed to documenting the Tribal impacts of climate change by producing eight Tribe-specific reports and co-hosting and participating in three listening sessions (see list of participating Tribes below). These Tribes reflect a diverse range of landscapes, perspectives, cultures, beliefs, and climate change experiences.

In this report, the term “California Tribes” refers to all Tribal Nations in the state, including those that are non-federally recognized and currently landless. Each holds the right to govern the collection, ownership, and application of its own data. This report upholds indigenous data sovereignty by presenting knowledge and data only with the explicit permission of the respective Tribes.

The Tribes see their lands not as the hard boundaries of a government-imposed reservation or rancheria, but as the ancestral lands they have taken care of since time immemorial. They do not see that contemporary maps, drawn by non-indigenous hands, reflect the extent of Tribal lands. Rather than a boundary map of the location of California Tribal lands, a linguistic map is presented in the Figure 1, showing indigenous languages spoken in California.

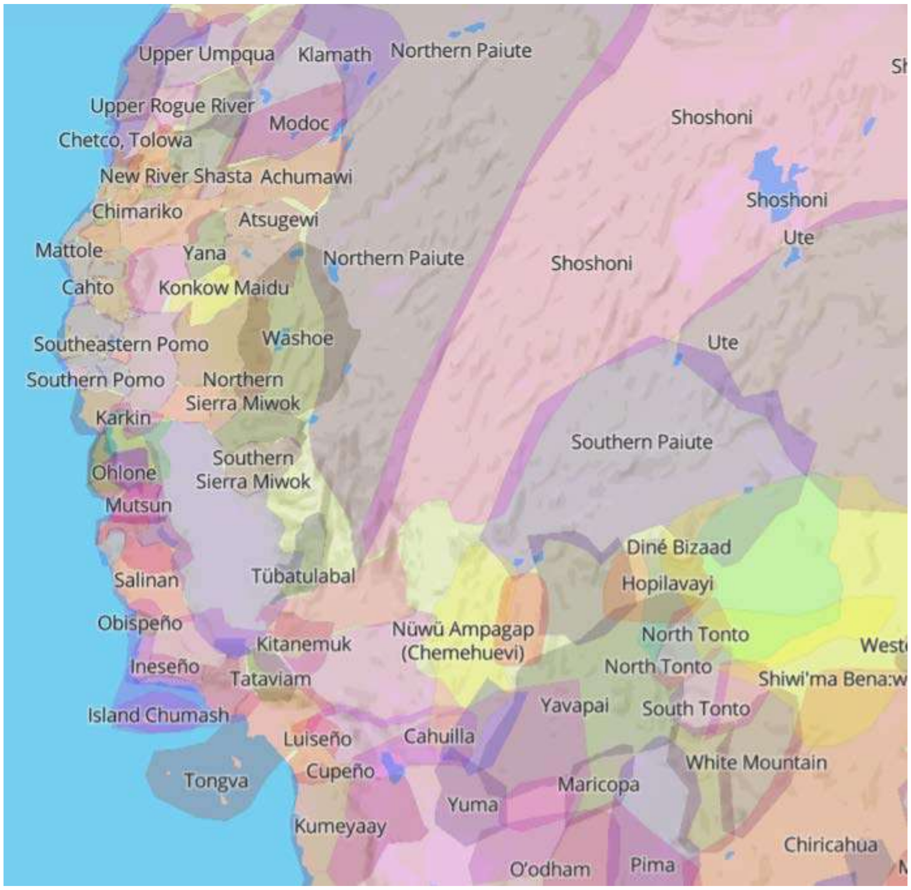

Figure 1. *Hundreds of languages were originally spoken in California before colonization. Many languages are not shown. For example, while this map shows "Island Chumash," every village in Chumash territory had its own language. These were not different dialects, but distinctly different languages. To learn more visit [Native Lands]() or the [Native American Heritage Commission Digital Atlas.]()*

When Tribes speak of nature, they include themselves. Nature and its great variety of plants and animals are on an equal level with people. The Earth provides the food, medicines, and ceremonial materials that are part of the Tribes' daily life. They are embedded within the Tribes' cultural, social, spiritual, economic and political systems. Knowledge of the unique interactions between species and their habitat provides the foundation for Tribal actions to manage the landscape. This is ever more important under the evolving conditions due to climate change.

Warming temperatures, changing precipitation patterns, and intensifying droughts throughout California have significantly impacted the Tribes. These have led to an increased reliance on groundwater, degraded aquatic habitat, stressed vegetation, and less abundant wildlife.

Coastal Tribes have witnessed sea level rise, noting that it has made access to traditional sites along the shoreline difficult, thus hampering the Tribe's ability to pass knowledge down to younger generations. Rising sea levels, along with the loss of kelp forests, have also made parts of the coast more vulnerable to erosion, exposing cultural artifacts. Kelp forests, which provide protective buffer to the coast, are collapsing along parts of the coast due in part to the cascading impacts of warming ocean waters.

Climate change has altered the landscape and has degraded habitat, affecting or displacing the plants and animal species that are important to Tribes.

Reports from the following eight Tribes bear witness to the impacts of climate change on Tribes:

Amah Mutsun Tribal Band
Big Pine Paiute Tribe of the Owens Valley
Big Valley Band of Pomo Indians of the Big Valley Rancheria
Bishop Paiute Tribe
The Karuk Tribe
North Fork Rancheria of Mono Indians of California
Pala Band of Mission Indians
Santa Ynez Band of Chumash Indians

Examples of climate change impacts described in these reports and discussed in listening sessions are highlighted below.

Marine and fresh water habitat

- ***Increasing water toxins:*** Unusually warm ocean temperatures amplify harmful algal blooms (HABs) blooms along the California coast. Marine HABs are especially widespread within Amah Mutsun historic lands, rendering many culturally important resources toxic. In lakes, rivers, and streams, warming temperatures and changing precipitation patterns are associated with increased freshwater HABs, which release harmful cyanotoxins. In Clear Lake, high levels of cyanotoxins are impacting drinking water and food and prevents activities involving contact with lake water. The Karuk Tribe is concerned that tribal members are more likely to be exposed to the toxin as low summer flows in the Salmon and Klamath Rivers create favorable conditions for HABs.

- ***Changes in ocean temperature and ocean acidification:*** have impacted species important to coastal Tribes. They have noted the collapse of kelp forests due to a combination of elevated ocean temperatures and other factors. Populations of abalone, which feed on kelp, have declined. Olivella shells, gathered by the Santa Ynez Tribe and other coastal tribes for use in regalia and as shell money, are becoming scarcer.

- ***Elevated stream and river temperatures and reduced stream flows:*** cause fish mortality, support fish pathogens and diseases, and create more suitable habitat for non-native fishes. The Owens pupfish, a staple food for the Paiute and Shoshone people in the Owens Valley has seen declining numbers along with other native fish species. The Tribes historically caught pupfish by the hundreds. A culturally significant fish for the Pomo Indians, populations of the Clear Lake Hitch have become alarmingly low; in the 1960-70s, hitch were so numerous that they made the water in creeks appear to boil. Rivers and streams where salmon used to run in abundance have reduced numbers or no salmon at all. Salmon hold cultural and spiritual importance to many Tribes. Similarly, steelhead are no longer found in the

Zanja de Cota Creek on Chumash lands, which used to be the site of steelhead fishing derbies.

Chaparral and forests

- ***Fewer culturally important pine nuts and acorns:*** Some Tribes noted that acorns are deteriorating faster with a changing climate. Eastern Sierra Tribes reported a change in the taste of the flour made with local acorns.

- ***Fallen trees in the Sierra Nevada Mountains:*** have reduced the availability of mushrooms, which grow when forest soil is exposed to air. These mushrooms are an important food resource to the North Fork Rancheria of Mono Indians. For the Karuk Tribe, tanoak mushroom (Xáyviish) is both a traditional food source as well as an indication of a balanced ecosystem.

- ***Large scale mortality among pine and oak trees:*** linked to drought, beetle infestations and sudden oak death – has occurred in the Sierra National Forest and its foothills, the Eastern Sierra, Lake, Mendocino and Sonoma Counties, the Klamath Region, and in Southern California along the Palomar Mountain Range.

- ***A loss of tules in Clear Lake and Owens Valley:*** Tules are used as a food source and as materials for weaving, for traditional ceremonies, for boat-making, and for various household uses.

Figure 2. ***Piñon pine in the Owens Valley killed by drought and beetle infestations***

Photo credit: Carl Smith

- ***Elderberry plants are not as fruitful or robust as in the past:*** The Southern Sierra Miwuk Nation uses the elderberry plant for music, fire, food, and medicine. To make clapper sticks for music, the pith needs to be large and the cane sturdy for proper resonance. Without these instruments, the Tribe could lose their ability to pass their music traditions on to future generations.

- ***Climate change has allowed invasive plant species to thrive:*** Examples include water primrose at Clear Lake; pepperweed, cheatgrass, non-native asters and tumbleweed in Owens Valley; and scotch broom, star thistle, Himalayan blackberry, and non-native grasses in Karuk, Pomo, and Paiute lands. These invasive plants are often difficult to eradicate, out-compete native species, and add to the wildfire fuel load.

- ***Dead vegetation:*** Forests made dense by fire exclusion practices, invasive plants, and changing weather conditions have heightened the risk of wildfires. Tribes throughout California are seeing increasing destructive wildfires and their subsequent effects (such as erosion and landslides). They have experienced personal losses, health effects from exposures to wildfire smoke, trauma, degraded watersheds and habitat loss. Cleanup of burned areas has exposed cultural artifacts and destroyed sites important to Tribes.

Wildlife

- Bighorn Sheep, once a staple of Owens Valley Paiute life, can no longer be hunted even for cultural purposes; Jackrabbits and Cottontails are also decreasing due to a lack of vegetation and increased predator populations. The Southwestern willow flycatcher, which has not been seen at Pala since 2013, is assumed to be extirpated due to loss of habitat combined with drought. The Big Valley Band of Pomo Indians has observed fewer flicker and red-wing blackbirds, which provide the feathers used in regalia. Red-legged frogs (Waqaq̓) that used to thrive on the Santa Ynez reservation, are gone.

- Eastern Sierra Tribes, such as the Tübatulabal and Paiute Tribes, have reported changes in timing of deer migrations and a reduction of deer populations. The Bishop Paiute Tribe reported that in 2017, 120 mule deer migrating late to their winter grounds in Owens Valley ran into persistent snow and ice sheets not normally found in the area at that time of year and slid to their deaths. In Northern California, the Karuk Tribe has observed black-tailed deer migrating later in autumn, which may leave them at greater risk of sudden winter storms and predation.

The health of the environment and the health of a Tribe cannot be separated. As the environment is impacted by climate change, Tribal health suffers. From the Tribal lands in the Owens Valley, which is the largest single source of particulate matter air pollution (PM10) in the United States, to the soaring temperatures in Southern California, and the reduction of native foods throughout California, Tribal physical, cultural, and spiritual health are being impacted. Higher levels of air pollutants, such as elevated ozone concentrations on warmer days, and wildfire smoke from increased uncontrolled fires pose risks to the health of the Tribes. Toxins produced by harmful algal blooms threaten their food and water and impair their ability to use lakes and rivers.

Climate change is deeply affecting the California Tribes as it alters and disrupts ecosystems. Habitable climate is critical to protecting tribal sovereignty, culture, and community cohesion. California Tribes continue to adapt to and protect their communities from the adverse effects of a changing climate. Tribes are managing and protecting their lands to limit the impact climate change is having on their ability to hunt, fish, gather, continue their cultural practices, and maintain activities that are integral to their health, well-being, and livelihood.

Listening session participants

The Office of Environmental Health Hazard Assessment jointly convened listening session with Tribes. The listening sessions had the following objectives:

- Listen to perspectives from Tribal communities on climate change impacts they are experiencing and identify common themes
- Collect Tribal input to help the *Indicators of Climate Change in California* report raise awareness about tribal-specific climate change impacts and increase recognition of the value of tribal knowledge in reporting climate change impacts.

The following Tribes participated in listening sessions.

Antelope Valley Indian Community (Coleville Paiute)
Barona Band of Mission Indians
Big Pine Paiute Tribe of the Owens Valley
Big Valley Band of Pomo Indians of the Big Valley Rancheria*
Bishop Paiute Tribe*
Cabazon Band of Mission Indians
Campo Kumeyaay Nation
Coastal Band of the Chumash Nation
Coyote Valley Band of Pomo Indians
Elem Indian Colony
Federated Indians of the Graton Rancheria
Fernandeño Tataviam Band of Mission Indians
Fort Independence Indian Community of Paiute Indians of the Fort Independence Reservation
Iipay Nation of Santa Ysabel
Jamul Indian Village
Kashia Band of Pomo Indians of the Stewarts Point Rancheria
Los Coyotes Band of Cahuilla and Cupeño Indians of the Los Coyotes Reservation
Manzanita Band of the Kumeyaay Nation
Middletown Rancheria of Pomo Indians of California*
Mono Lake Kutzadika’a
North Fork Rancheria of Mono Indians of California
Paiute-Shoshone Indians of the Lone Pine Community
Pala Band of Mission Indians*
Ramona Band of Cahuilla
Rincon Band of Luiseño Indians
Robinson Rancheria Pomo Indians of California
Round Valley Indian Tribes
San Manuel Band of Mission Indians
Santa Ynez Band of Chumash Indians*
Scotts Valley Band of Pomo Indians of California
Sherwood Valley Band of Pomo Indians
Southern Sierra Miwuk Nation
Tejon Indian Tribe
Tübatulabal Tribe
Twenty-Nine Palms Band of Mission Indians
Washoe Tribe of California and Nevada

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[*] Co-hosted a listening session

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Appendix

While much of traditional tribal territory is now divided and regarded by colonizers as distinct districts, to Tribes, the land is physically and conceptually inseparable in terms of ecology as well as culture, spirituality, and history. Territory maps are often not agreed on, while language maps depict more fluid borders that are respected by Tribes and illustrate where Tribes historically traveled, as illustrated below (Wishtoyo, 2021).

Chumash Country

The maps depict how the hard lines of traditional maps fail to describe the flexible borders that were respected by the Chumash and neighboring Tribes. The map on the left of the figure shows how many languages make up the territories labeled simply Chumash and Island Chumash on other maps, such as in Figure 1.

Map design and content courtesy of Timara Lotah Link, Shmuwich Chumash. Please do not reproduce without express permission.

IMPACTS OF CLIMATE CHANGE ON THE AMAH MUTSUN TRIBAL BAND

Drought, wildfire, and sea level rise, as well as loss of native plants and animals, are threatening the physical, cultural, and spiritual health of the Tribe, its habitats, and ecosystems.

Background

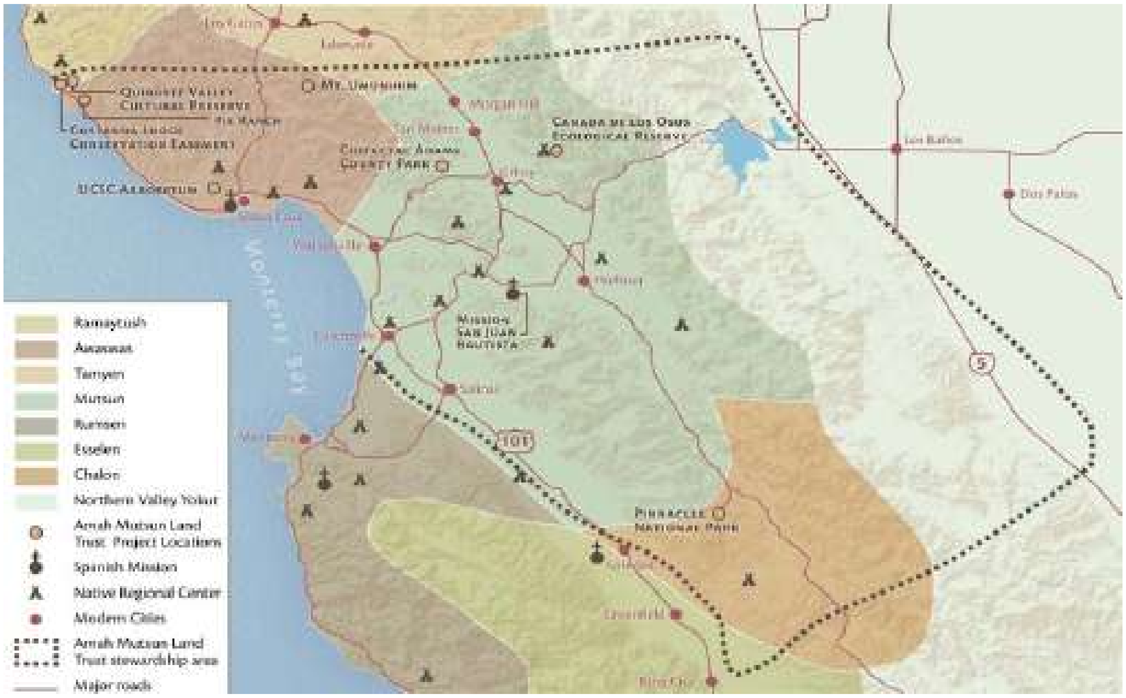
The Amah Mutsun Tribal Band (AMTB) is a continuous and historic Tribe composed of the descendants of the Indigenous peoples whose villages and territories were taken over by Missions San Juan Bautista (Mutsun) and Santa Cruz (Awaswas) during the late 18th, 19th, and early 20th centuries (AMTB, 2021). The Indigenous people were baptized as legal wards of the Franciscans and forced into labor building the missions, farms, and ranches of the colonizers (Madley, 2017). The AMTB represents the surviving descendant families of these groups. The AMTB is recognized by the State of California as a Tribal Government but lacks federal recognition. Consequently, the AMTB holds no tribal lands, nor receives financial assistance from either the Federal or State governments.

Prior to European contact, the Amah Mutsun community was made up of approximately 20 to 30 contiguous villages stretched across the Pajaro River Basin and surrounding region. These villages were united by shared cultural practices and traditions. Most significantly, Amah villages were distinct from tribes outside their valley because of their unique language. While the Costanoan/Ohlone language family was made up of eight separate languages, including Mutsun, each language was different. Mutsun was one of the first American Indian languages extensively studied in North America (AMTB, 2021).

The Amah Mutsun Tribe was drawn to the abundant resources in the triangle of land formed by the Monterey Bay and the Pajaro and San Benito Rivers by the abundant resources. These lands later attracted other settlers who drastically changed the lives of the Amah Mutsun. While the traditional territory of the Amah Mutsun encompasses all or portions of the current Counties of San Benito, Monterey, Santa Cruz, Santa Clara, and San Mateo, the high cost of living in the San Francisco and Monterey Bay areas, combined with a lack of treaty or tribal trust land, has resulted in over 80 percent of Tribal members living outside of their ancestral territory. Many members live in Fresno, Madera, Hanford, Las Vegas, and Lake County, and other areas outside of California (AMTB, 2021).

Through three periods of brutal European colonization (Spanish, Mexican Republic, and United States) (Madley, 2017), the Tribe’s traditional ecological knowledge and physical connection to their ancestral lands were disrupted.

Figure 1. Amah Mutsun (Awaswas and Mutsun) historic lands and neighboring Tribes



Source: AMTB, 2021

The AMTB continue to maintain a sacred obligation to continue in the footsteps of their ancestors, stewarding the lands and waters of their traditional homeland. In 2013, the AMTB created the Amah Mutsun Land Trust (AMLT) to help achieve this vision.

AMLT is a Native-led, non-profit organization. Through the AMLT, the AMTB is restoring Indigenous stewardship to the Mutsun and Awaswas-speaking peoples' ancestral lands and waters, which stretch from Año Nuevo Point to the Monterey Bay, and inland to include the Pajaro and San Benito watersheds (see Figure 1 above). AMLT focuses on education, stewardship, research, and cultural revitalization, in addition to land acquisition. AMLT brings an Indigenous perspective to resource management that models constructive relationships between people and place, where active engagement with the land contributes to more diverse, resilient, and meaningful landscapes. AMLT engages a Native Stewardship Corps (NSC), made up of AMTB members plus an array of state, county, University and Tribal partners, to bring Indigenous stewardship to lands that are already in conservation. Because the Tribe is currently unrecognized by the federal government, the NSC functions much as an environmental department would.

Cultural and spiritual health

Historically, the Amah Mutsun ensured a sustained yield of plant and animal foods by careful management of the lands. Controlled burning of extensive areas of land was carried out each fall to promote the growth of seed-bearing annuals.

When the Tribe speaks of “cultural resources,” they look all around at the mountains, the meadows, the waterways and wetlands, the air, and scenic vistas – as well as those buried beneath them, and those who inhabit them. Those are the Amah Mutsun cultural resources – all holds value to the Amah Mutsun Tribe (AMTB, 2021).

When non-indigenous people think of California Indian culture and cultural resources, they often look at tangible objects such as basketry, housing, clothing, food, and dance regalia such as feathers, whistles, skins, clapper sticks, etc. These are all important manifestations of Amah Mutsun culture, but to understand the culture of the Amah Mutsun Tribe, one must also understand two important axioms.

Axiom I: There is no natural hierarchy in the Amah Mutsun culture that categorizes plants, animals, minerals, or humans as being above any of the others. It is the Tribe’s belief that the Creator made all beings – therefore we are all equal. Men, women, and children were all created equally and are respected equally. The Amah Mutsun are a matriarchal society. Women can bring life – possessing the strength to bear the burden of two souls within them. Men possess physical strength to provide and protect – creating balance in the family and community. The Amah Mutsun believe human beings were gifted with a higher level of intelligence and reasoning for the express purpose of protecting and caring for all other life.

Axiom II: The Creator, using infinite wisdom, placed the Amah Mutsun in the lands of “*Popeloutchum*”, the homeland, as the protectors and stewards of the lands, waters, plants, and other creatures of this place. The Creator blessed the Amah Mutsun with these magnificent lands with a mild climate, bountiful foods from the land and sea, and a landscape that is considered among the most beautiful in the world.

As Amah Mutsun ancestors worked to fulfill their obligation to protect the plants and animals of the land, they also studied their non-human relatives for thousands of years. The Bear Clans, Bird Clans, etc. were given the responsibility to learn all they could about those creatures. The knowledge they collected was shared with their Tribe and their descendants.

The Amah Mutsun, never felt that they owned the land – rather that they belong *to it.* When the Amah Mutsun talk about “our land” – or “*makke pire*”, they are referring to the land to which *they belong*…rather than the land which they “own.”

Because the Amah Mutsun have a responsibility to care for our finned and winged brothers, they must protect and conserve the rivers (water quality) and the sky (air quality). The Tribe must help ensure that their populations can move and interact (habitat corridors) to maintain healthy and resilient populations (AMTB, 2021).

Impacts

The impacts and future threats resulting from climate change in Amah Mutsun Territory are drastic and rapidly compounding, both on land and in the sea. On land, the increasing destructive wildfires are followed by higher rates of erosion and landslides. Culturally important plant and bird species are being impacted by drought, wildfire, and increasingly variable rainfall. Tribal members living in the inland areas report drier, hotter summers, less annual rainfall, low water tables, lakes and creeks drying up, poor air quality, and more intense, more frequent wildfires. These changes, along with development and urban sprawl, impact housing and intensify destructive land-use practices. In the sea, the coast has become more vulnerable to coastal erosion resulting from high energy storms and swell events with the collapse of kelp forests that had acted as buffers. This erosion, along with sea level rise, are threatening cultural sites along the shoreline. Loss of ocean biodiversity, drastic reductions of certain species and overpopulation of others, and marine harmful algal blooms (HABS) also threaten Tribal resources.

Land

The most recent and high-profile impacts of climate change are evidenced by the August 2020 CZU Complex fires, started by lightning in an area that historically had a very low number of lightning strikes. The CZU Complex burned for over a month, torching 86,509 acres in Santa Cruz and Santa Clara counties, destroying 1,490 structures, and damaging 140 (CALFIRE, 2020). These fires led to the evacuation and displacement of the NSC, loss of a month’s work, loss of necessary field equipment, and an overall unstable, uncertain, disrupted work and life flow. Heavy rain four months after the fires led to another evacuation because of potential landslides, putting the NSC in yet another high-risk situation.

Droughts brought about by climate change are making oak woodlands more susceptible to death from pathogens and pests. Wildfire in areas with these dead and dying trees will tend to form crown fires that spread from treetop to treetop. Once removed by wildfire the woodlands may be replaced by shrubland and other vegetation types that are unable to support native plant, animal, and bird species.

Catastrophic fires impact watersheds, water and air quality, rangelands, wildlife, culturally significant sites, infrastructure, croplands, and of course, the Amah Mutsun’s way of life. These fires are intense due in part to unmanaged fuel loads. The CZU Complex is also a prime example of how the compounding impacts of fire suppression, poor land management, and climate change can result in widespread, destructive wildfires. The Tribe believes that fire can be managed more effectively if Indigenous stewardship and cultural knowledge around Indigenous peoples’ use of fire are more widely accepted and implemented by land managers.

Recent eco-archaeological research in the area provides evidence that Amah Mutsun people had regularly practiced cultural burning as a landscape management strategy prior to European colonization. Informed by traditional ecological knowledge, cultural burning by Indigenous people protects ecological and cultural resources and builds wildfire resilience. Cultural burns are properly timed, low-intensity fires that move slowly through a segmented management unit of land and promote the abundance and health of many culturally significant native plants.

Figure 2. Amah Mutsun controlled burn

Source: AMTB, 2021

The Amah Mutsun have great respect for fire as a land stewardship tool. As Chairman Valentin Lopez explains:

> "*We see fire as a gift from Creator. Like all gifts, it is important to respect and recognize it in that way. Fire is sacred and used as a prayer. A spiritual fire is placed in the middle during ceremonial dances and carries our prayers up to Creator. Fire is used as a light, and as a land management tool. Our ancestors divided the land into management units, they then burned segments when needed, on a rotating cycle, until the cycle was complete. This allowed for consumption and reduction of fuel loads and control of encroaching brush, aiding the ecosystem. Coastal prairie grasslands have diminished due to outlawing the practice of Indigenous burns. Fire has a critical role in maintaining the coastal grassland prairie. The coastal prairie*

> *grassland was one of the most viable landscapes and rich in biodiversity in North America before Europeans arrived."*
>
> *"Cultural burns help control pests, reduce buildup of heavy fuels, and aid native plants that require fire to germinate. We have a responsibility of taking care of plants, birds, and feeding the animals by taking care of native seeds. The first year of the burn cycle aids in seed and seed bed preparation. The second year after the burn, plants strengthen reproduction, and shoots are soft and nutritional for grazing wildlife. The third year, there is increased fruit productivity. The fourth year yields strong plant fibers which are utilized for crafts and housing materials. A special ceremony is held when cultural burning in oak woodlands. Smoke helps purify the trees. Smoke chokes out pests in trees, and therefore aids in the production of acorns. Insects are choked out and fall down, and then are consumed in fire. Therefore, fire and smoke aid with insect infestation in trees and killing of pests such as ticks in grasses."*

Wildland fire knows no boundary and taking care of Mother Earth requires a coordinated effort, and as Honorable Chairman Valentin Lopez says, *"Indigenous stewardship must lead the way."* Indigenous stewardship practices like cultural burning are gaining traction among land managers as effective methods of building resilience in natural systems.

To restore ecological health and resilience to the Amah Mutsun by bringing back small-scale fire as a tool to mitigate the impacts and threats of destructive wildfires, the AMLT works with:

- California State Parks and University of California (UC) campuses at Berkeley and Santa Cruz to understand the historic extent of fire as a Native landscape management tool.
- California State Parks and CALFIRE to remove thick stands of Douglas fir to create fuel breaks and restore grasslands.
- California State Parks and UC researchers in Quiroste Valley, an area east of Año Nuevo State Park to research and re-introduce traditional resource and environmental management, including cultural burning, as practiced in the valley before the arrival of Europeans. The uplands above the meadow and riparian valley contain dense Douglas fir, and coyote brush stands with little to no understory. These stands have encroached upon the open coastal prairie grassland. Due to the dense canopy cover, little sunlight reaches the forest floor, allowing little to no grasses and forbs. This reduces biodiversity and threatens the coastal prairie, which was once much more widespread.
- Inter-Tribal Fire Network to better relationships with federal and state land management agencies and with other tribes throughout California.
- A grant from the California State Coastal Conservancy, which has provided funding (cap-and-trade funds from California Climate Investments) to aid in the

development of a Cultural Burns program, where the Tribe can strive to best steward ancestral lands.

- A cooperative Habitat Restoration Project with Pinnacles National Park using an integrated approach to habitat restoration and research by incorporating traditional Native American land management practices with contemporary techniques to restore and protect the natural and cultural processes.
- The Karuk and Yurok Tribes, which host Prescribed Fire Training Exchanges (TREXs). These trainings emphasize the stewardship of cultural resources and build key working relationships and coordination with many land management organizations. Tribal members are currently becoming National Wildfire Coordinating Group Firefighters, Type 2 certified, and are gaining experience with prescribed fire.

Bird species important to the Tribe have also been impacted by climate change. The condor is a culturally important species to the Amah Mutsun and the Tribe has worked with Pinnacles National Park reintroducing the birds and providing an understanding of the cultural meanings of the California condor (AMTB, 2021). These newly released birds were again threatened when the CZU Complex burned in nesting areas with fledgling birds, unready to fly to escape (NPR, 2020).

Along with exacerbating wildfire risks, climate change has also impacted the availability of certain native plant species of ethnobotanical importance to the tribe. These are species traditionally used for building, basketry, and food. Members of the NSC have reported that many culturally important coastal prairie and woodland plants are becoming rarer and more difficult to restore, while invasive plants like Jubata grass, poison hemlock, and thistles are incredibly difficult to eradicate in grasslands.

Figure 3. Amah Mutsun Tribal members and Land Trust propagate plants

Source: AMTB, 2021

Part of AMLT's land restoration work includes:

- Working with UC Santa Cruz arboretum to propagate ethnobotanically important plants.
- A coastal grasslands propagation project at Quiroste Valley. This California Proposition 68 funded project intends to directly plant 30,000 native plants at Quiroste Valley.
- An additional 90,000 native plants at a neighboring location, which will provide additional seed to be sown directly into the Valley in subsequent seasons. Despite ongoing impacts of COVID-19 and the August 2020 CZU fire complex in the Santa Cruz Mountains impacting water supplies, the program has remained on track to meet the ambitious goal of returning culturally important grassland plants.
- Tending a permanent source of grassland seed for gathering and restoration. This is even becoming more important since AMLT can propagate and plant drought-tolerant native grasses, like Purple Needlegrass, the state grass of California.

Sea

The Amah Mutsun have lived and interacted closely with the coast since time immemorial. Their ancestors stewarded the sea through resource management practices that maintained abundant, healthy coastal waters. The rich and biodiverse kelp forests provide habitat for fish, marine mammals, and invertebrates. The sandy and rocky shorelines are filled with a myriad of seaweeds and animals. This depth of knowledge lives with the Amah Mutsun Tribal Band elders. It is further documented in ethnographic records and evidenced in archaeological sites along the coast.

Today, the Amah Mutsun witness a wide range of impacts on local coastal waters. Sea level rise is eroding ancient cultural sites from the shoreline. The loss of kelp forests due to the rapid spread of purple sea urchins because of the mass wasting of sea stars, their main predator, is leading to significant losses in biodiversity. Ocean temperatures affect the availability of food for sea lion pups and pregnant sea lion mothers. Warmer waters can reduce the abundance of phytoplankton and other organisms that make up the base of the marine food chain along the California coast. Changes to the availability of these organisms affect higher levels of the food chain, including sea lions (OEHHA, 2018). Unusually warm ocean temperatures can also amplify harmful algal blooms that periodically occur along the California coast. Certain algae species produce toxins such as domoic acid that enter the marine food web and ultimately harm sea lions (OEHHA, 2018). Harmful algal blooms are especially abundant and widespread within Amah Mutsun territory and can render many culturally important resources toxic and inedible. Rising ocean temperatures and increased carbon levels make it difficult for many native species to survive, especially considering the competition of encroaching invasive species that crowd them out. By monitoring these resources throughout the year, the Tribe can better understand the issues affecting them and contribute to protecting and managing them.

Figure 4. Amah Mutsun youth and UC Berkeley researchers getting ready for a day at the beach.

Photo courtesy of Rob Brodman

At the direction of Tribal leadership, the Amah Mutsun are now looking to build the capacity of AMTB members as ocean stewards by developing and implementing a new AMLT marine stewardship program. Work includes:

- Participating in the Tribal Marine Stewards Network (TMSN) pilot project, along with four other Tribes/Tribal organizations, who received funding from the Ocean Protection Council in 2020.
- Developing a coastal monitoring program that will return traditional resource stewardship to the coast within Mutsun and Awaswas territories. This program builds upon previous work that combined archaeological and ethnographic information to restore and revitalize resource stewardship on the land, such as fire to manage coastal grasslands.
- Partnership with the California Indian Environmental Alliance, Tolowa Dee-ni' Nation, Resighini Rancheria, Kashia Band of Pomo Indians, and Ecotrust to form a Tribal Marine Stewards Network. The Tribal Marine Stewards Network pilot project received generous funding from the Ocean Protection Council in 2021. The Amah Mutsun Tribal Band's participation is further supported by a grant made through the Sustaining California's Ocean Program of the Resources Legacy Fund.

- Monitoring other significant natural and cultural resources, especially kelp forests, rocky intertidal zones, and seagrass beds, which provide habitat for a diverse range of species and are essential for maintaining productive marine ecosystems.

Each of these projects will build the capacity of AMLT Native Stewards as stewards of the marine environment by creating opportunities for Tribal members to learn and practice new skills. These projects will also contribute new data that will be shared with the State and aid in the management of California’s Marine Protected Areas. The community outreach project will be focused on revitalizing and building upon the AMTB tribal communities’ traditional ecological knowledge about coastal and marine resources and how to steward them.

Other impacts

The creeks, streams, and rivers within AMTB historic lands have also been impacted by climate change in a myriad of ways. Rising temperatures and drought have decreased water flows and led to warmer waters in culturally important fish habitat and unfavorable spawning conditions.

Salmon populations are impacted by nutrient availability, drought, temperature, and freshwater/saltwater interfaces, all of which are affected by climate change. To gain more insight into managing habitat conditions to favor salmon populations, AMLT collaborates with:

- Researchers at Michigan State University to study ancient and modern salmon and steelhead genetics within their traditional territories.
- Researchers at UCLA to develop an environmental DNA monitoring program for species of ecological and cultural importance, many of which are influenced by climate change. As part of this research AMLT is actively working on a dam removal project in their territory geared towards salmon restoration.

Summary

Climate change is causing a loss of native plants and animals, causing droughts, wildfires, landslides, sea level rise, and increasing marine harmful algal blooms. These impacts are threatening the physical, cultural, and spiritual health of the Amah Mutsun Tribe.

Neither the lack of a permanent land base, nor the lack of federal recognition has prevented the Amah Mutsun Tribal Band from fulfilling their continuing obligation to protect the plants and animals on their Tribal homelands. The AMTB are reaffirming their role as environmental stewards of Mutsun and Awaswas territories by using innovative research, partnerships, and Tribal community education to relearn traditional ecological knowledge and apply it to the most pressing issues in natural resource management and conservation. AMLT continues to successfully apply this approach to terrestrial ecosystems, using archaeology and modern ecological science to affirm the utility of ancient traditional resource management practices to restore balance and resilience to the diverse ecosystems in AMTB territory.

The Tribe relies on historical ecological data preserved in coastal archaeological sites. These sites contain information regarding past stewardship practices and traditional ecological knowledge of coastal resources. The archaeological record is a non-renewable resource with specific windows of opportunity for the Tribe to engage. Unfortunately, due to climate change-related sea-level rise, these windows are rapidly closing as artifacts are exposed and destroyed, as they are washed out to sea or collected by treasure hunters for sale. Many of these sites are being impacted by rising seas and high energy storms, both directly linked to climate change. Without adequate monitoring and protection of these sites, this vital historical dataset for the Amah Mutsun Tribal Band could be lost forever, impacting the conservation science. Indigenous knowledge and evidence from the archaeological record hold information regarding human relationships with marine ecosystems over thousands of years.

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IMPACTS OF CLIMATE CHANGE ON THE BIG PINE PAIUTE TRIBE OF THE OWENS VALLEY

Depleted groundwater, drought, air quality and decreased traditional foods are threatening the physical, cultural, and spiritual health of the Tribe, its habitats and ecosystems, and its built environment.

This document is written by L'eaux Stewart, a member of the Big Pine Tribe, and is based on her observations of climate change in the Owens Valley.

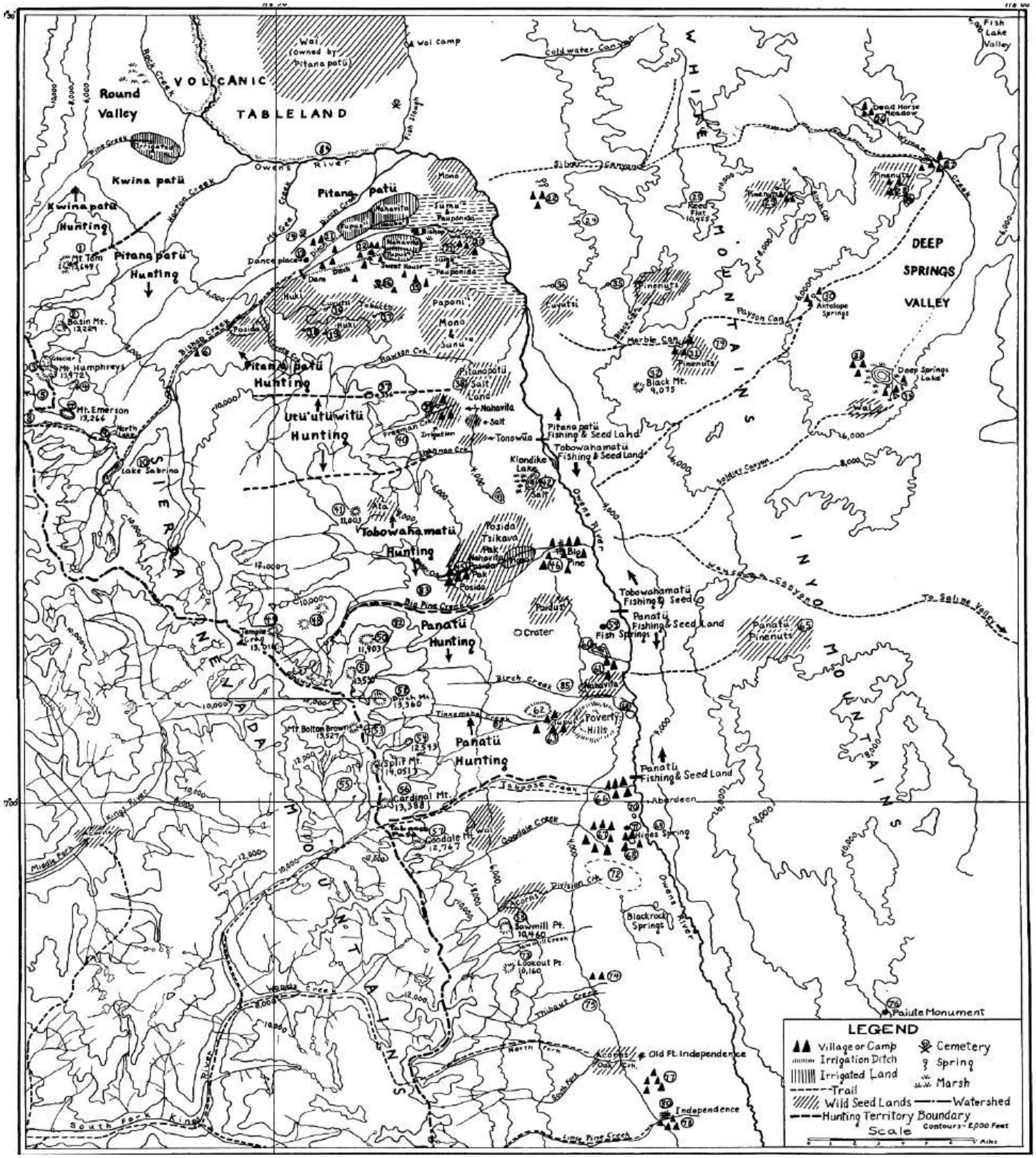
Background:

The Big Pine Paiute Peoples are comprised of three different groups from the Big Pine region: Tovowahazi, the people of Tovowahamatü (the land now currently containing the Big Pine Paiute Reservation); Panapitahahnwitü, the people of Panapita (the land on the west side of Big Pine currently known as The Indian Camp); and Tunigahahnwitü, the people of Tunigawitü (the land to the south of Big Pine known as Fish Springs). The overlapping areas inhabited by these groups and other Paiute neighbors are shown in Figure 1. The Big Pine Paiute People referred to themselves as Nümü, "The People", as did other tribes in the area, so for this document, we will refer to them as the Big Pine Nümü to differentiate them from other Paiute People in the community.

The boundaries of the traditional lands used by the Big Pine Nümü begin at Keogh's Hot Springs (seven miles north of Big Pine) and extend south to Fish Springs (two miles south of Big Pine). The two mountain ranges, the Whites and the Sierras, formed the east and west boundaries respectively. The entire area was considered territory of the Big Pine Nümü and was regarded as important to them for purposes of food and material collection, spiritual and ceremonial practices, and living space. Certain families and groups had unique sites that were important to them and those locations are passed on through lineal dependency via oral storytelling.

The traditional lands of the Big Pine Nümü have since been developed for wildland grazing, for grass grazing, for residential properties, for commercial properties, and for pumping by the Los Angeles Department of Water and Power (LADWP). The majority landowner is LADWP. Figure 2 shows the current lands of the Big Pine Nümü and the surrounding area.

Figure 1 Hand drawn map showing Paiute areas and boundaries



Source: Steward, 1933

Figure 2. Map Showing the Owens Valley and Big Pine (below the word "Owens")

When the land that is now known as the Big Pine Reservation was originally set aside for Native Americans in the 1930s, it was originally designated as a Rancheria, which designated the land to be used as small homesteads for the people who were admitted to live upon it. In the 1970s, the Rancheria was converted into a reservation, which permitted more home building upon the land and agricultural practices became reduced.

Figure 3. The Eastern Sierras route to the Palisades, part of the Big Pine traditional territory.

Source: L'eaux Stewart

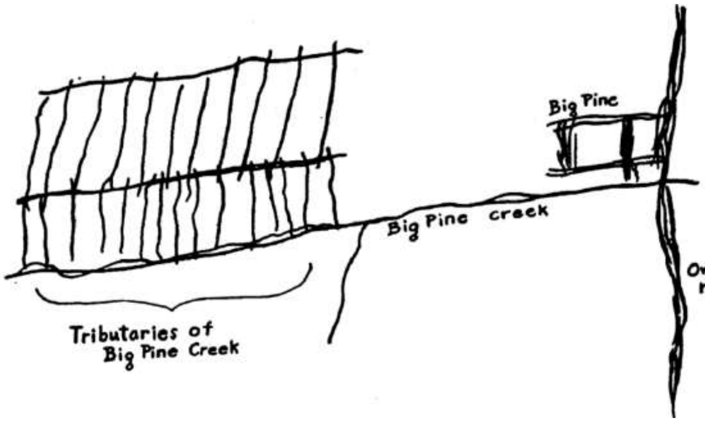
In the Big Pine (Tunigawitü or Fish Springs Band) *Creation Story of the World*, Coyote and Wolf created the Owens Valley region and by proxy the surrounding lands that other tribes live on; it is originally described as a great flood that covered the world, higher than the mountain tops and by having Mud Hen retrieve soil from the bottom of the flood, Coyote was able to rebuild mountains and cover up the water. In the *Creation of the Big Pine Peoples*, actual landmarks within the Big Pine Region are mentioned: a sub-alpine lake above Big Pine in the Eastern Sierras was the location of The Most Beautiful Woman's Mother's house; a fresh spring about a mile north of Big Pine at the base of the Eastern Sierras was The Most Beautiful Woman's home; and there are big boulders on the north end of Big Pine where Coyote hunted game for The Most Beautiful Woman.

Figure 4. Volcanic fields at Fish Springs

Source: L'eaux Stewart

Hunting was performed with bows and arrows, snares, rabbit drives, sheep drives, deer drives, atlatls and points, and clubs. (Drives are a hunting activity.) Rabbits, chuckwallas, birds, deer, elk, big horn sheep, and pack rats were hunted for meat. Fishing was performed with special baskets and woven traps to catch fish that lived in creeks and streams. Pole fishing, spears, and nets were also used to catch fish. In addition, fish were collected from the streams and rivers of the area by diverting water out of the body of water into shallow ditches so that the fish might be stranded on the ground to be picked up. As shown in Figure 5, the Big Pine Paiute Nümü would create a

Figure 5. Drawing of Paiute irrigation



Source: Drawing by Big Pine Paiute member Jack Stewart in Lawton, 1976 drain off the side of the small creek or stream with fish; the drain would lead down rows scraped out of the ground by sticks. The water would flow down the rows and the fish would be left behind. These ditches would also irrigate the surrounding areas, bringing water to wild seeds and plants that would nourish the people. There were also stories about golden trout in lakes at the top of the mountains that were fished; settlers believed these stories to be myths until the forties when aerial photography showed alpine lakes that later were found to have the golden trout.

The food of the Big Pine Nümü was bland for the most part, as only limited salts and sugars were available, but they were high in protein and nutrients. Rabbits were the most constant source of protein; both Jackrabbits and Cottontails were eaten. Rabbit meat would be added to acorn mush to create a protein and vitamin-rich meal that was very filling. Due to diseases, any rabbit that had been hunted would be checked fastidiously for signs of lumps on the body and discarded if found with any irregularities. Deer were hunted and often divided up amongst two or three family groups. Big horn sheep were a prized catch and hunted in drives in the mountains. Smaller game such as ground squirrels, porcupines, and wildcats were caught in snares. Birds were often hunted; quail, doves, and waterfowl were shot with arrows or snared. Swans and birds of prey were not eaten. There were taboos on eating bear meat as a skinned bear’s body resembles a human’s body.

Chia seeds were also a regular staple in the diet; they were often ground and kept in small buckskin pouches, where the ground chia could be snacked on while walking. Other seeds from plants in the valley were eaten frequently and provided both fiber and folic acids.

The Big Pine Nümü ate cicadas as they emerged from the ground and beetle larvae; these insects would have their heads pinched off and would be toasted in a basket and salted. Acorns and pine nuts were vital to year-round survival. Both were harvested in the fall in large quantities by entire communities. The acorns were buried next to the riverbed so that the water could leach the tannins out of the nuts and pine nuts were cooked in baskets. The buried acorns were removed from the ground up to a year later to be shelled and ground into a fine flour. Both the pine nuts and acorns were made into mushes which were seasoned with chunks of meat and fat, or bitter salt. Sweetened acorn mush was created by adding a large amount of harvested sugar to a bowl of acorn mush, which was then placed outside in the snow, where it would freeze. The mix was then scraped to create a pseudo-ice cream style treat.

Cattail and tule shoots were eaten, especially when they were young and tender. Clovers, cresses, and small greens were harvested and eaten fresh. Berries that grew in the hills were harvested and eaten fresh.

There was a “coyote potato,” an unknown fungus (likely the *Calvatia booniana*, “Western Giant Puffball”*)*, which grew in the sand around the roots of plants, particularly sagebrush. It could be dug up and cooked.

Teas were made from many of the leaves and barks of the plants; ephedra was the most common tea consumed, though pine needles and sagebrush bark were brewed and seeped as well. Wild rosehips were a quite common ingredient in teas due to the vitamin C they provided and the abundance in which they could be gathered.

In modern times, when money was scarce, a family member would go out to hunt rabbits or deer (sometimes out of season), or wild plants would be harvested. Grinding stones, metates, baskets, and pottery bowls were used in food preparation and storage.

Gatherings

Fandango, the fall gathering, was a practice shared by many of the tribes in the Owens Valley as a gathering of all peoples. It was hosted by a different group each year and provided an opportunity for everyone to see each other. Traditional activities included dancing, gambling, and a communal rabbit drive. Big Pine is the only community in the Owens Valley who has continued this gathering annually. The modern version of the Fandango involves a parade on the Reservation roads to the “Fandango Grounds” and tribal members participate in the parade with floats, horses, cars, and by foot. There have also been games such as bed races, early morning walks, and volleyball tournaments. There are also competitions for traditional and non-traditional food cooking. It is held in October each year, usually during the first weekend.

Figure 6. Photograph of a Paiute gathering circa 1906-1913, taken by Forbes

Source: Paiute Shoshone Cultural Center

Places

The burial sites of the Big Pine Nümü located throughout the territory have often been desecrated and their locations are no longer shared with outsiders. Burial was not done by water and usually in locations that were not common to visit, so as not to disrupt them.

Figure 7. Paiute men dressed and performing war dance

Source: Paiute Shoshone Cultural Center

Agriculture

While the Big Pine Paiute Nümü did not have developed agricultural processes such as row crops, they developed the practices of plant grooming, which creates ideal materials and seed collections for later usage. The creeks and streams were expanded to improve irrigation of plants and to strand fish to make them easier to catch. Basket makers would often tend to willows and maintain spacing so that in two to three seasons the willows growing would be ideal for basket making. Those who produced bows and arrows did the same with saplings, grooming them to grow the best materials for later harvest. Oak trees and pine trees had their habitats tended to so that harvests the following year were bountiful.

Climate Change Impacts:

Changes in climate

The spring and early summer seasons have become more temperate; during the 1990s, it was common for the month of May to be extraordinarily hot, with temperatures reaching the 110s+ degrees Fahrenheit. The Memorial Day Weekend has been an especially good marker for this as now it is common to bring a jacket along while watching the parade in the neighboring town of Bishop due to the slight chill in shade. It still reaches the 90s during the day, but we do not experience the heatwaves that were once so common in May. In the past, it wasn’t unusual to have at least a dozen cases involving tourists being treated for heat exhaustion or heat stroke. Heatwaves still exist in Big Pine but now occur later in the summer.

Drought conditions have become commonplace over the past twenty years; the region is a Great Basin High Desert climate, so there is not an abundance of water during the year, but over the past ten years it has become more noticeable that the amount of rainfall and snowfall has significantly decreased.

Figure 8. "Dust Devil" as seen from Route 168, heading east towards the White Mountains and Westgaard (east of Big Pine)

Source: L’eaux Stewart

High winds have always been a part of the weather in the Owens Valley, but the frequency at which these winds occur is increasing; this has led to soil erosion around the community, the uprooting of rabbitbrush and sage brush, and complications in native plants establishing root systems when the seeds try to grow. Paired with the drought conditions, this has led to areas that once had established root systems becoming barren spaces.

Winters often lack snow on the valley floor, though it will snow in the mountains. “White Christmas” was fairly common until the early 2000s. Now winters are typically milder in temperatures and drier. Any rain begins in January and then there is typically no rain again until the start of Spring. The milder temperatures have resulted in certain insects such as mosquitos and wasps coming out of hibernation earlier in the year. These insects would normally die off during the cold winter but now they persist.

Figure 9. Alpine Lake within the Eastern Sierras, at the Palisades (west of Big Pine and part of the Big Pine watershed)

Source: L'eaux Stewart

Impacts on physical systems

Petroglyphs and pictoglyphs in the area have been affected by climate change due to erosion of the rock faces due to the increased frequencies of dust storms, and moisture from rain and dew accumulating under the surface of rock panels which causes them to fall and damage other panels below them. The pigments in the pictoglyphs are becoming lost due to the wind erosion.

Areas north of the town of Big Pine and to the east accumulate water during the wet seasons, forming temporary lakes; the water leaches alkaline soil to the surface which causes a thin crust to form when the water eventually evaporates. The alkaline dust then gets caught in wind and blows south into the town, affecting everyone’s breathing. Due to less and less precipitation each year, the alkaline dust caught in the air becomes greater overtime. Currently the tribe tracks air particulate matter through their Air Quality program to document the increase in particles trapped in the air that is causing breathing issues. The Tribe has seen an increase in dust and is working with outside officials to mitigate the problem.

Wetland areas have nearly disappeared due to the water table dropping and the lack of sustained rainy seasons. The Big Pine People’s ancestral territories included many freshwater springs that have now disappeared or remain mostly dormant; these areas were the sites of traditional stories and often were markers of certain family boundaries. The loss of these areas is due to a drop in the water table, likely a combination of LADWP pumping activities and the lack of rainfall to replenish the aquifers.

Snowpack has been reduced for years and has impacted the amount of water runoff into the valley, which leads to further issues such as reduction of native plants in the spring and summer, causing animals to have to move to different areas in order to find resources.

Access to traditional pine nut harvesting areas has been greatly impacted by soil erosion; root networks in the soil have disappeared in many areas due to a lack of water and as a result, many roads and paths have been washed out due to rainstorms that cannot be absorbed into the soil and create mini mud/rock slides. This requires hiking into areas, which can be perilous as the disturbed roads and trails might not be stable and the hiker risks the possibility that the rocks they're walking on might slide out from under them.

Impacts on vegetation

The abundance of plant species has reduced by a significant amount in the Big Pine area: plants typically associated with basket making such as willow and devil's claw are often so difficult to source that they must be found outside of the traditional land boundaries (often by Bishop or Mono Lake). Food such as Taboose (*Cyperus esculentus*), a plant that grows a small nut-like tuber, was once so prevalent that a person could walk through miles of plants within arms distance; Taboose is now only found in spaces in the backcountry around Big Pine and can no longer serve as a supplementary food to an adult's diet without depleting the plant population severely. Acorns were another primary source of protein for the Big Pine peoples. Now to harvest acorns, one would have to travel south to Fort Independence, which does not produce acorns regularly enough to support an adult through the winter season. Previously, acorns could be gathered in such large quantities that it was common to bury a large cache in a riverbank over the year so that the running water could leach the tannins out of the nut meat. The taste of the local acorns has purportedly changed so that the tannins are stronger and require more time being leached.

Pine nut harvests are commonly less successful. This is not due to an overharvest or loss of land, but due to climate change. Pine nuts grow on a seven-year cycle and it is common to rotate traditional pine nut harvesting sites every year. Families select their own harvesting site and often keep the information private; it is not an easy task, and most people aren't knowledgeable about pine nuts. There is little evidence that the lack of pine nuts from year to year has to do with interference by anything but the climate changes our area experiences. Pine nuts are no longer the primary source of winter foods due to convenience of modern foods, but they are still a very welcomed food in the Paiute and non-Native community of the Owens Valley. We have also noticed that the size of the pine nuts has gotten smaller.

Tule and cattail are no longer harvested in abundance for food or housing material due to the development of the lands that they grew on. Wetlands have dried up and houses or other development have replaced the tule beds. There is also high concern about the quality and safety of eating them due to chemicals that are sprayed on them for mosquito control and in the water that they grow around.

Wildfires in the area have become increasingly dangerous due to the drier plants in the wildland areas around Big Pine; certain plants have a difficult time regrowing after the area has been burned such as blackbrush, while others invade the area, such as foxtails and cheatgrass.

The coyote potato has been difficult to find, and it is unknown if this is due to the destruction of the land by development that would have typically served as its habitat or due to loss of water in the area overall.

Wild tobacco grows in recently burned areas, so there has been an increase in wild tobacco growth around the town of Big Pine in areas where wildfires burned; however, there is a lack of native plant growth in those same areas afterwards. Instead, those places have become covered by cheatgrass and tumbleweeds, which do nothing to save the soil during windstorms, or create a root network to help establish soil stability. This also means that looking for traditional plants that might grow after the tobacco has repaired the soil is becoming difficult.

Impacts on wildlife

There has been a noticeable decrease of Jackrabbits and Cottontail Rabbits in the valley due to a combination of predators moving down into the areas where we would hunt for rabbits and due to a lack of vegetation for the rabbits to eat. Our area was known for the rabbit drives (a hunting activity) that occurred the fall, where it was common to kill between 70 and 100 rabbits in a day. That is no longer a sustainable activity and tribal members no longer rely on rabbits as a main source of food.

The insects that were once harvested for food are now no longer easily found; the landscapes where insects such as cicadas once lived have changed so drastically due to lack of water and vegetation in the past thirty years that the insects have either migrated or died out.

Larger predatory animals such as mountain lions and bears, as well as smaller predatory animals such as coyotes and bobcats have begun to appear more frequently on the reservation lands; there have been numerous incidents of pets and livestock being killed or maimed, trashcans being disturbed, or prowling on Tribal Member assignments (plots of land held by the Tribe but assigned to Tribal members) in the past fifteen years. Some of the animals have been captured and relocated by California Fish and Wildlife, while other animals have been killed by cars or shot by townsfolk within Big Pine for the danger they pose. This is likely because their typical hunting areas have been deeply affected by their prey migrating to different areas closer to town to access water and vegetation.

Birds of prey are slowly returning to the area due to conservation efforts, however many lack the areas they would typically use for nesting and hunting. The food upon which these avian predators rely, such as rabbits and mice, are impacted by a lack of vegetation. The trees in which the birds of prey would typically live are dying due to lack of water. Owls have been able to adapt by living in abandoned or isolated human-built structures such as silos. They are now seen often in residential areas; owls are considered an omen of bad luck, so many Tribal Members are uncomfortable with their frequent presence.

Native fish species are on the endangered species list due to introduction of other fish species, destruction of habitat, and lack of water, the impacts of which are exacerbated by climate change. Fish can be very delicate to care for, as even small fluctuations in temperature and sunlight can negatively affect their health. Reestablishing the native fish populations has been a struggle due to the change in the landscape and the lowering of the water table throughout the valley. If more is not done to protect them, there is a likelihood that species such as the Tui Chub and Owens Valley Pupfish will go extinct in the next decade. The Big Pine Peoples have focused all their attention to preserving the native fish and no longer fish for them.

Figure 10. Bighorn Sheep

Source CDFW, 2021

Bighorn Sheep have been impacted by drought and are no longer in the area, though are slowly returning with the assistance of the California Fish and Wildlife Bighorn Sheep Reintroduction Program. They were once a staple of the Owens Valley Paiute life, but can no longer be hunted even for cultural purposes; to hunt Bighorn Sheep in the White Mountains, one must acquire one of the six hunt tags through a lottery offered by the state. The Big Pine Peoples have been incredibly supportive of areawide conservation efforts to restore the original herd sizes to the valley.

Impacts on human health and well-being

While the spring is becoming milder. Summers are hotter. As our people no longer travel to the mountains to live during the hotter summer months, they are routinely exposed to higher temperatures in the summer; summer is typically dry and windy, with exposure to smog from tourist vehicles and smoke from California wildfires. During the 2020 fire season, residents of the Owens Valley were forced to remain indoors for many months straight. It should be noted that during this time there was little wind, which allowed the smoke to settle over the town of Big Pine; many people commented about how unusual it was. Not all households own air conditioners or swamp coolers, so many people are left in houses that are too hot to safely occupy.

Droughts have become commonplace in the area. The dry soil leads to dust, which often affects the breathing of all community members; there are a number of elders with lung issues and a growing number of cases of children with asthma and other breathing issues. The soil is alkaline and causes dust clouds that are very irritating to the eyes and throat/lungs.

Hunting isn't as readily accessible due to game having left the immediate area. Smaller game such as doves and quail are easy to find around the south and eastern border of the reservation, but rabbits and deer must be sought out. The death and/or lack of plants has also led to a huge change in diet for the people and has spanned over multiple generations.

Summary

Overall, climate change and the lack of water within the Big Pine area have become of great concern. Climate change has led to soil erosion, loss of wetlands and springs, loss of plants, animal migration, changes in traditional trail systems, and changes in diets and cultural practices; these impacts are tied to water, heat, wind, and fire hazards. Without a return of water to the area, the Tribe is looking at scenarios where the land will not recover and thusly lose out on many of the practices that make up our culture. As a result, the Big Pine Paiute Tribe has become involved in water rights, and activism surrounding the politics and usage of water in our community. It has led to the Tribe working hard to manage water and educate our Tribal Members how to best use the water we are able to obtain.

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IMPACTS OF CLIMATE CHANGE ON THE BIG VALLEY BAND OF POMO INDIANS

Warming air temperatures, variable precipitation, drought, wildfire, warming lake temperatures, harmful algal blooms, reduction of fish, bird and animals, as well as other stressors are impacting Tribal livelihood, culture, and traditions.

Background

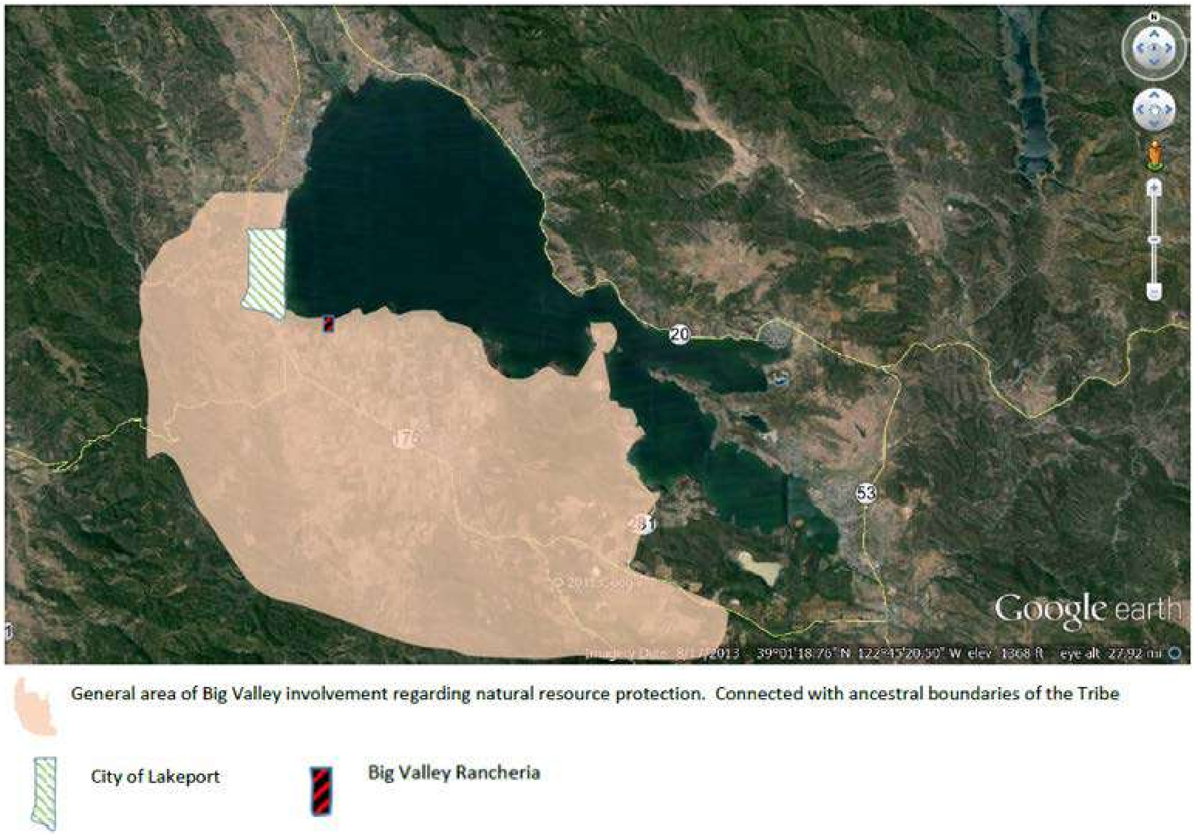
The Big Valley Band of Pomo Indians of the Big Valley Rancheria of California is a self-governing, federally recognized Tribe of Pomo Indians residing on the shores of Clear Lake in Lake County, California (Figures 1 and 2). Their ancestors, the Xa-Ben-Na-Po Band of Pomo Indians, inhabited the Clear Lake area for over 11,800 years (BVR, 2022). In 1851, a treaty was agreed upon with the office of the U.S. President which established a reservation of approximately 72 square miles with extensive lake front property, including much of the Clear Lake basin including Mt. Konocti. However, the U.S. Senate refused to ratify this treaty, along with 17 others. Largely because of the opposition of the Legislature and the Senators from California, the United States Senate refused to ratify the treaties, on July 8, 1852. The United States Senate placed the treaties under an injunction of secrecy which was not removed for over 50 years (Flushman and Barbier 1986). Instead, Congress passed the Land Claims Act of 1851 requiring claims to California lands be presented within two years (Patrick, 2008). Tribes were intentionally never told of this new requirement. Like all Tribes, the Big Valley Band of Pomo leaders failed to meet the statutory deadline, and their Tribe and others became landless. After the US Government took Indian homelands, they gave loans to settlers to buy Indian land (Montez, 2022).

Figure 1. Clear Lake basin looking from what is now called Soda Bay

Photo: L Monserrat, OEHHA

Big Valley, along with other bands of Pomo, were granted small rancherias years later. In 1914, the U.S. Department of the Interior purchased land for the Big Valley Rancheria. In 1936, under the Indian Reorganization Act of 1935, the Tribe became federally recognized, formed its government, and ratified its constitution. Then in 1963 the Tribe was illegally terminated under the California Rancheria Act of 1959. The Tribe was subsequently re-established by court order as a federally recognized Tribal entity in 1983. During that 20-year period approximately half of the original Rancheria land, including Mt. Konocti, had been seized and sold to non-Indians. In 1986 the Big Valley Tribe began the process of reconstituting their rights of self-determination by re-forming their government through the guidance of their 1936 Constitution. The Tribe is also in the process of buying back their homelands (BVR, 2022a).

Figure 2. Map showing location of Big Valley Rancheria (red and green area), the City of Lakeport (green-striped area), and the general area in which the Tribe engages in natural resource protection (tan area). The tan area is also closely tied to the Tribe's ancestral boundaries.



Source: BV EPA, 2014

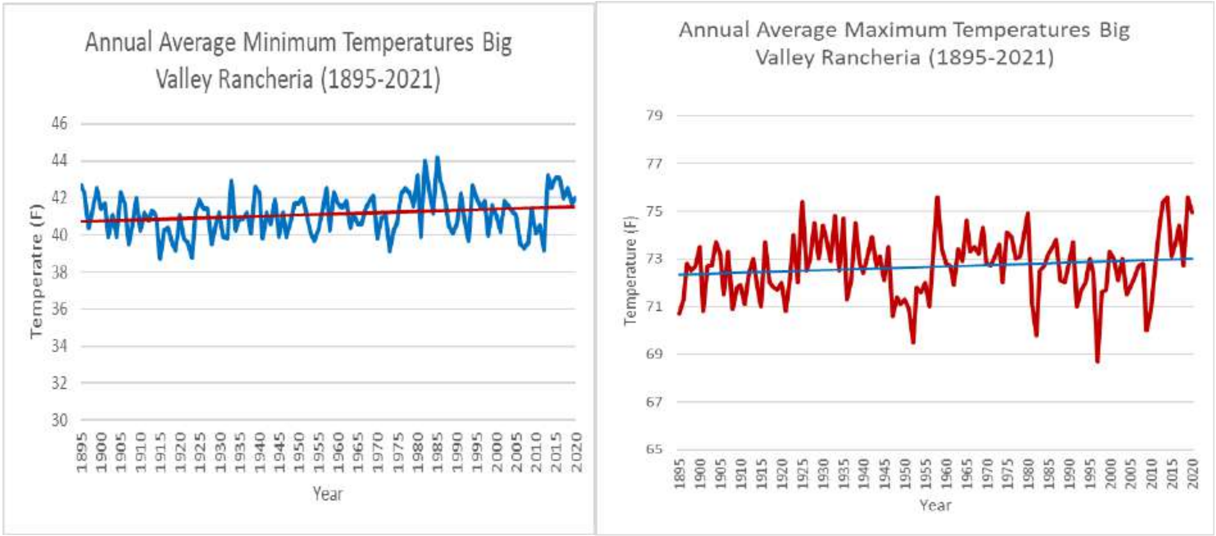
Current Big Valley Tribal membership is approximately 1,300 people. Though the Rancheria sits on 350 acres today, traditional Tribal lands extend much farther. Additionally, Tribal members live all around the lake, and throughout California. Figure 2 shows the Rancheria territory, the City of Lakeport, and the much larger general area in which Big Valley is involved in natural resource protection. This map helps illustrate that the lands the Tribe uses and cares for extend beyond Rancheria borders. Big Valley Pomo rely heavily on Clear Lake and the resources surrounding it for subsistence and livelihood, as well as for important cultural and spiritual practices.

The waters of Clear Lake itself are of cultural importance to the Big Valley Tribe. The Tribe conducts their Tule Boat Festival and other important cultural and spiritual events on Clear Lake. The Tule Boat Festival is a three-day festival showcasing traditional Pomo boat-making skills. The boats, constructed primarily using materials gathered from shoreline tule plants, are raced by Tribal members. The festival draws Tribes from around the North Coast region and beyond and provides an opportunity for sharing traditional foods. (BVBPI and MRPI, 2021).

Air Temperatures

Figure 3 shows that over the past century, maximum temperatures (daytime) and minimum temperatures have increased at the Big Valley Rancheria. However, minimum temperatures, which reflect temperatures at night, are increasing at about 1.2 times the rate of maximum temperatures (0.06°F/decade and 0.05°F/decade, respectively).

Figure 3. Annual average daily maximum temperatures (left) and annual average daily minimum temperatures (right) at Big Valley Rancheria.



Source: PRISM, 2022

Warming air temperatures are linked to numerous impacts on human health and livelihood, as well as ecosystem health and function. Warmer air temperatures change precipitation and runoff patterns, which impact the availability of freshwater. Warming air temperatures lead to changes in species distribution and abundance and the timing of life-cycle events, all of which alter the ecosystem as a whole. Rising temperatures also strain energy demand and infrastructure, increasing the number and length of the Public Safety Power Shutoffs (PSPS) the Tribe has seen. To protect Elders during these PSPS events the Tribe has purchased generators. Increasing air temperatures promote ozone formation leading to adverse health effects such as lung irritation, inflammation, worsening of asthma, and increasing mortality (USEPA, 2021a).

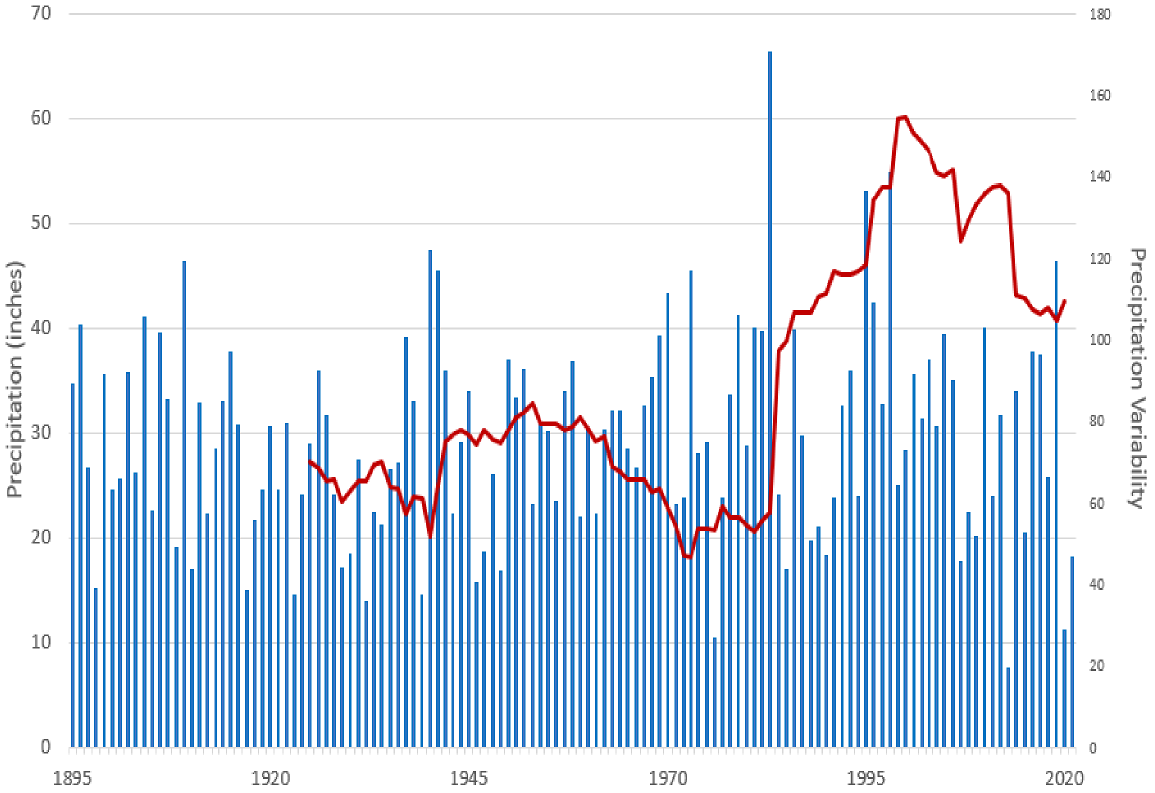
Warmer air temperatures along with a lack of rainfall over time stresses vegetation, creating susceptibility to pests, disease, and death. The increase in dead vegetation then increases wildfire risk for the Tribe. The effects on vegetation also reduce the availability of materials and resources important to the Tribe for various cultural and spiritual uses, such as tules.

Warming temperatures and changing precipitation patterns are associated with increased harmful algal blooms (HABs) in Clear Lake. Additionally, warmer winter temperatures have allowed the invasive water primrose to flourish year-round, leading to further tule loss along the shoreline due to competition (BV EPA, 2014).

Precipitation

As shown in Figure 4, there is considerable year-to-year variability in the amount of rain at the Big Valley Rancheria, particularly in the last thirty years. Average annual precipitation dropped to its lowest around 2013/2014 and during a period when Lake County experienced extreme drought (Lake County, 2021). The Rancheria has experienced years of extremely high and extremely low rainfall, as well as increasingly unpredictable precipitation patterns throughout the year. High rainfall events cause a sharp increase of surface water flow into Clear Lake, leading to sedimentation and erosion, particularly in shoreline areas where vegetation has been lost. Sediment deposition into the lake impacts water quality (USDA, 1995). Sediments carry contaminants such as trace metals and organic and inorganic compounds which are toxic to plants and animals (BV EPA, 2017a). Sediments are often nutrient-rich, and these excess nutrients cause HABs.

Figure 4. Total yearly precipitation at Big Valley Rancheria, 1895-2021



Source: PRISM, 2022

Heavy rains affect infrastructure at Big Valley. The Rancheria needs a better drainage system to prevent flooding which also damages homes. Many Tribal members live in mobile homes, which are particularly susceptible to flooding and seepage. Several members have had to build their own weirs to access their homes during high rainfall. The Tribe has identified increased mold growth after heavy rain events as an impact of climate change (BVBPI and MRPI, 2021). The marina at the Rancheria has been replanted with vegetation previously lost along the shoreline to combat erosion, but during periods of heavy rain, large sections of shorelines wash away.

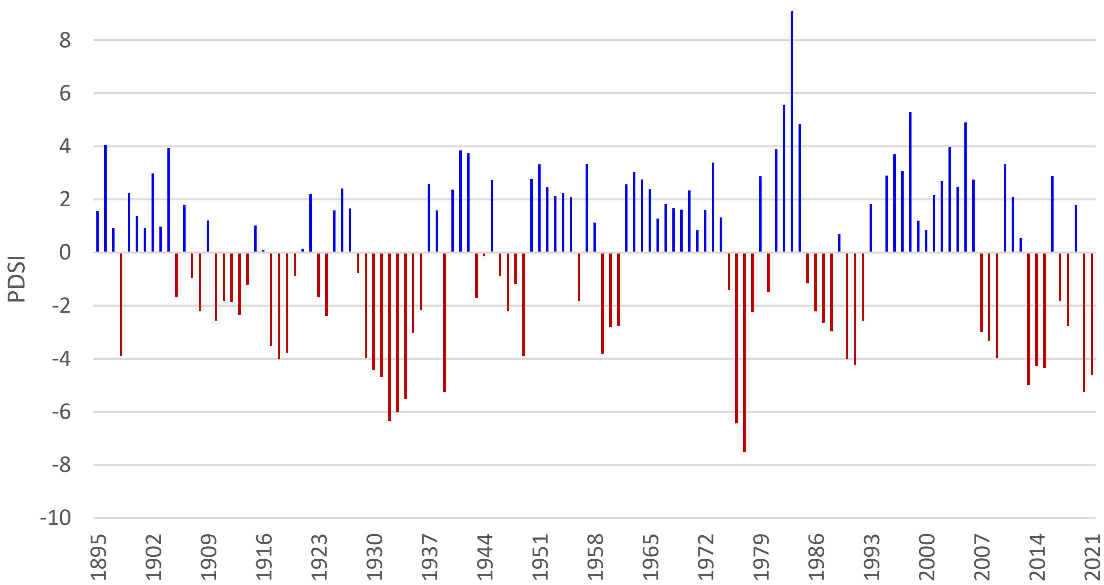
Big Valley's Integrated Solid Waste Management Plan addresses climate change impacts such as flooding and resulting landslides the Tribe is seeing as a result of extreme rain events. The Tribe has experienced landslides that blocked roads and damaged Tribal buildings and lands following heavy rainfalls in recent past and the Tribe is working to protect its facilities from future impacts (BV ISWMP, 2015).

Drought

Figure 5 shows a commonly used measure of drought, the Palmer Drought Severity Index (PDSI), which combines both temperature and precipitation data to provide a measure of relative dryness (drought) on a scale from +10 (wet) to -10 (dry). The lower the number the drier the conditions. In the 80 years between 1895 and 1975 the Big

Valley Tribe experienced extreme drought (-4 or below) 7 times, including the state-wide drought that impacted California from 1928-1934 (USGS, 2022). During the 47 years since then Big Valley has experienced extreme drought 9 times. The most recent two years 2020 and 2021 were -5.25 and -4.62 respectively (Abatzoglou et al., 2022).

Figure 5. Palmer Drought Severity Index, Big Valley Rancheria (1895-2021)



Source: Abatzoglou et al., 2022

Drought has impacted Clear Lake resources, lake water quality, and consequently, the people and other species that rely on the lake. Additionally, drought has caused stress to vegetation throughout the Lake County area, notably to native pine trees, making them more susceptible to pests such as the Pine Bark beetle. Dead trees and other vegetation increase fuel for wildfires. Water scarcity impacts local agriculture, stressing crops such as pears, walnuts, and grapes. Increased reliance on groundwater to support agriculture in areas near the Rancheria reduces the volume of surface water entering streams where Clear Lake Hitch, an endemic and culturally significant fish, spawn (see Lake water temperature section). Many streams and creeks surrounding Clear Lake have dried up during periods of drought (BVBPI and MRPI, 2021).

The Pine bark beetle has killed large areas of Pinon pine trees which are a food source for the Tribe. Government policies have prevented traditional cultural burning, leading to an increase in large-scale wildfires as well as an increase in invasive species and pests. For example, invasive star thistle and other non-native plants have taken hold, increasing the use of herbicides which also poison native species, further exacerbating the issue. This increases the pesticide/herbicide exposure from dust and runoff from nearby agricultural operations that impact the health of Tribal members.

Figure 6. Children playing in a tule boat

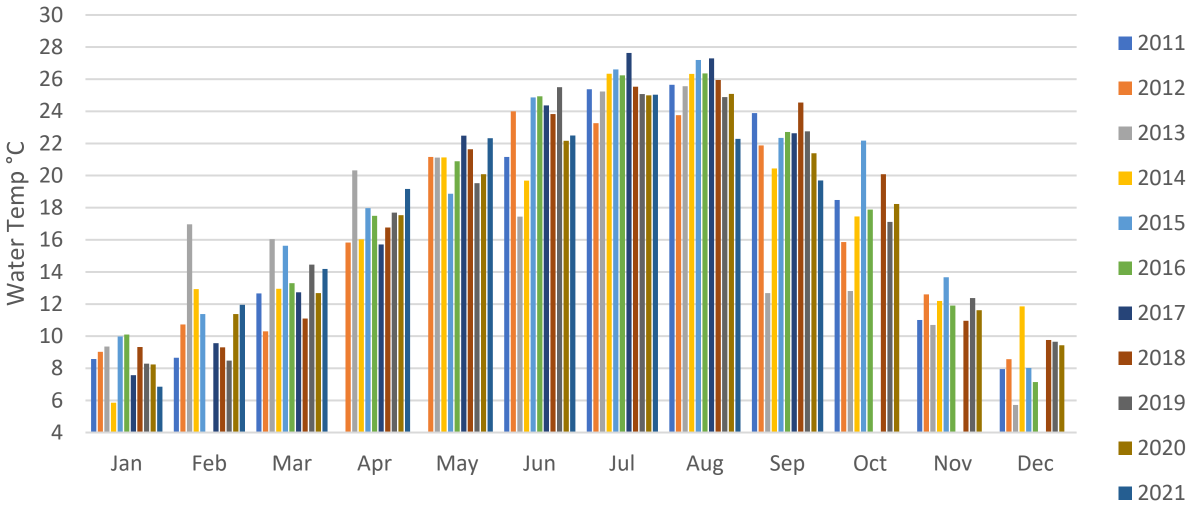
During periods of drought, decreased stream flows into Clear Lake reduce dilution, thus concentrating pollutants, leading to increases in microbes and pathogens in the lake, which in turn affects public health. Additionally, drinking water sources are impaired and with 18 water purveyors pulling water from the lake, the increased cost is passed to the Tribal consumer. Partnering with Tracking California, which compiles and analyzes data about public health and the environment, Big Valley tested private drinking water systems on Clear Lake for cyanotoxins, nitrates, coliform bacteria and herbicides, all contaminants of concern for private drinking water systems (BV EPA, 2017b). During the most recent testing between June and October 2021, twenty of the thirty-six homes tested had detectable cyanotoxins and 13 were above the USEPA health advisory level of 0.3 µg/L (micrograms per liter). The highest level sampled was 3.85 µg/L. In November 2021 forty-one homes were tested and cyanotoxins were found in 22 samples; of those 10 were above the USEPA health advisory (Cal-WATCH, 2022). The Tribe is also developing a program to measure groundwater in local wells to have a better understanding of the variations in groundwater storage to ensure sustainability.

Declining lake water levels in Clear Lake due to drought have exposed cultural resources, such as arrowheads. This has exacerbated the problem of non-natives actively searching for these resources to sell. These items are Tribal property and taking them is disrespectful and disturbs the Tribe as a whole. Artifacts found need to be honored and left in place or returned to the Tribes (BVBPI and MRPI, 2021).

Lake water temperature

Figure 7 presents annual average lake surface water temperature between 2011 and 2021 at a sampling site (BVCL6), an area of Clear Lake of particular importance to the Tribe. Six total sites offshore of Big Valley Rancheria were selected for analysis (shown circled in yellow in Figure 8). All six sites showed similar results, so only data from BVCL6 is displayed. This site has seen monthly average water temperatures that are highly variable across years, marked by exceptionally warm temperatures in certain years: for example, notably warm temperatures were observed from February to April in 2013, in December 2014, and in October 2015.

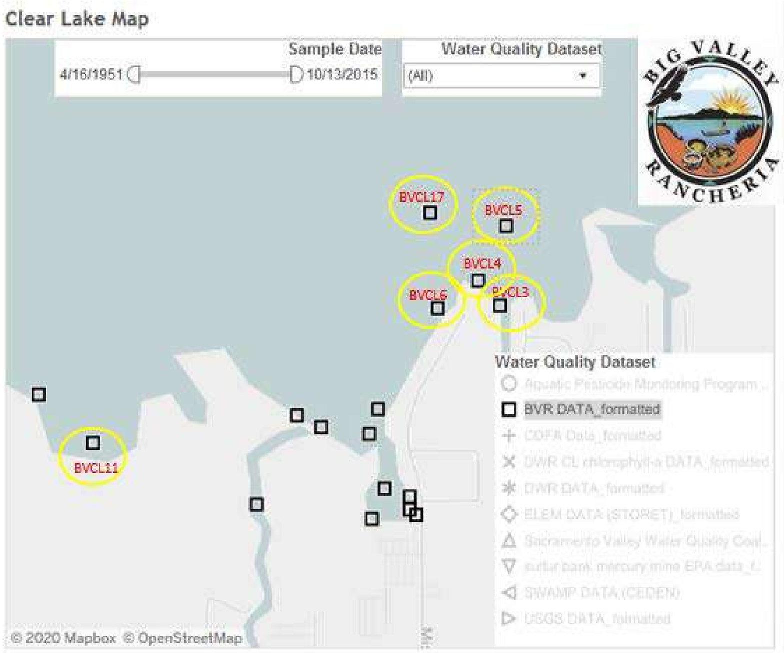
Figure 7. Monthly average lake surface water temperature by year at sampling site BVCL6 in Clear Lake (2011-2021)



Note: No sampling Oct-Dec, 2021 due to low lake levels

Source: BV EPA, 2022b

Figure 8. Location of Big Valley offshore monitoring sites



Source: BV EPA, 2022

Even seemingly small increases in water temperature can significantly affect key physical and biological processes in lakes. As the lake is impacted, so is the Tribe. Fish and other aquatic species often do best within a certain range of water temperatures. As water temperatures rise, native populations of fish and other species which are important to the Tribe might not thrive, while introduced species that previously would not survive in the lake are absent their natural predators. Balance is key for a healthy lake.

Figure 9. Map showing concerns relating to some creeks that drain into Clear Lake

Source: BVBPI and MRPI, 2021

Changing lake temperatures affects the habitat and distribution of fish. Figure 9 shows creeks feeding into Clear Lake in the Big Valley area (BVBPI and MRPI, 2021). Clear Lake Hitch, a threatened species of "immeasurable ecological and cultural value" (CDFW, 2014) migrate from Clear Lake into tributary streams such as Kelsey Creek and Adobe Creek (indicated with yellow stars on the map) for spawning (Feyrer et al., 2019). In 2014 Hitch were only observed spawning in these two streams.

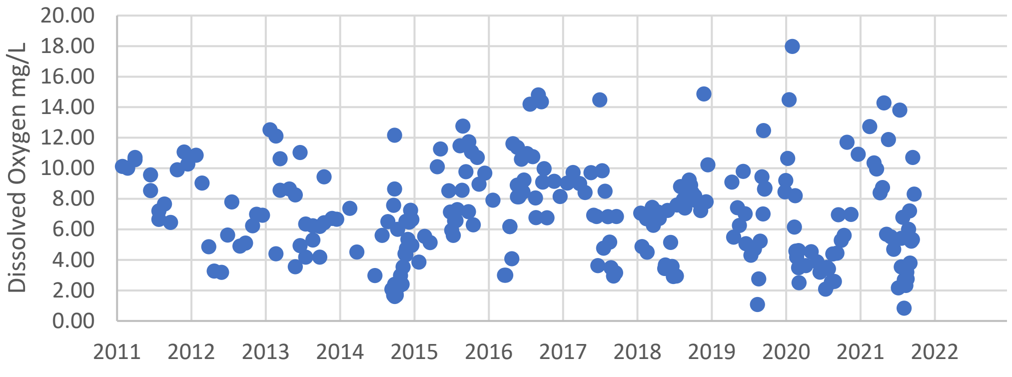
While there is no water quality standard for cool water temperature ranges in Clear Lake, there is a standard that the lake has no more than a 5˚F difference from receiving stream temperatures (BV EPA, 2017b). A temperature differential greater than 5˚F leads to negative impacts on fish which are important to the Tribal diet. Warming waters are associated with lower levels of dissolved oxygen (DO) in the water, which poses risks to aquatic species. Precipitation also impacts the level of DO in the waters of Clear Lake. DO is the most important health indicator of a water body and its capacity to support a balanced aquatic ecosystem of plants and animals. Oxygen from the atmosphere and photosynthesis dissolves into the upper level of all bodies of water.

The amount of DO in a water body decreases with depth, rising water temperatures, and the oxidation of organic matter and pollutants. Erosion and sedimentation caused by high precipitation events carry organic, oxygen-consuming pollutants into Clear Lake leading to a reduction in DO. Sediments also carry nutrients that promote HABs. Low levels of precipitation, and lower surface flow into Clear Lake reduce dilution and increase the concentration of organic pollutants in Clear Lake, also leading to a decrease in DO.

Data collected by multiple agencies over the last several years on Clear Lake show extended periods of time throughout the lake where DO was suppressed, leading to fish kills that have been investigated by California Department of Fish and Wildlife who have confirmed that low DO was the cause (BV EPA, 2017a). The Upper Arm of Clear Lake, where the Tribe and monitoring station BVCL6 is located has shown lower DO and increasing frequencies of hypoxia since 2000 (UCD, 2010).

Big Valley Rancheria has developed a set of water quality objectives that for DO are outlined by three beneficial uses: (1) warm freshwater habitat - uses of water that support warm water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish or wildlife, including invertebrates; (2) cold freshwater habitat - uses of water that support cold water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish or wildlife, including invertebrates; and (3) warm spawning, reproduction and/or early development – uses of water that support high quality aquatic habitats for reproduction and early development of fish (BV EPA, 2017a). These water quality objectives dictate that DO concentrations in Clear Lake should not fall below 5.0 mg/L for warm habitat and 7.0 mg/L for both cold habitat and warm spawning habitat. Figure 10 shows DO levels at site BVCL6 over the past 10 years. During that time DO dropped to extremely low levels (below 2.0 mg/L) 6 times, below 5.0 mg/L 71 times, and to below 7.0 mg/L 128 times.

Figure 10. Dissolved Oxygen (DO) mg/L at Clear Lake Sampling Site BVCL6, 2011-2021



Source: BV EPA, 2022b

Culturally important species

Climate change has impacted species of cultural significance to the Big Valley Band of Pomo Indians. The Tribe is seeing fewer, quail, otters, turtles and other animals that are important to the Tribe. These species have diminished due to the cascading impacts of climate change on their habitat (BV EPA, 2022a). Additionally, the Tribe has observed fewer flicker and red-wing blackbird species. These are important birds because the Tribe uses the feathers in regalia and other important cultural activities. With the loss of these birds, the passing on of skills, vocabulary, and ceremony to younger generations is impacted. This constitutes a larger loss than just having to change which feathers the Tribe uses for regalia; it constitutes a loss of culture and an important part of Tribal identity and long-standing traditions (BVBPI and MRPI, 2021). Twenty eight percent of the native aquatic fish species in Clear Lake have become extinct in the last century (UCDNAR, 2022).

The Asian clam (*Corbicula fluminea*) was historically invasive to this area but over time became a staple food source for the Tribe and others living around Clear Lake. Tribal members have observed changes in the size and availability of Asian clams in Clear Lake. Asian clams are short-lived filter feeders, consuming large quantities of phytoplankton (Sousa *et al.*, 2008). As such they are susceptible to contaminants such as mercury and cyanotoxins, which pose serious health risks to people who consume Asian clams.

Figure 11. Clear Lake Hitch

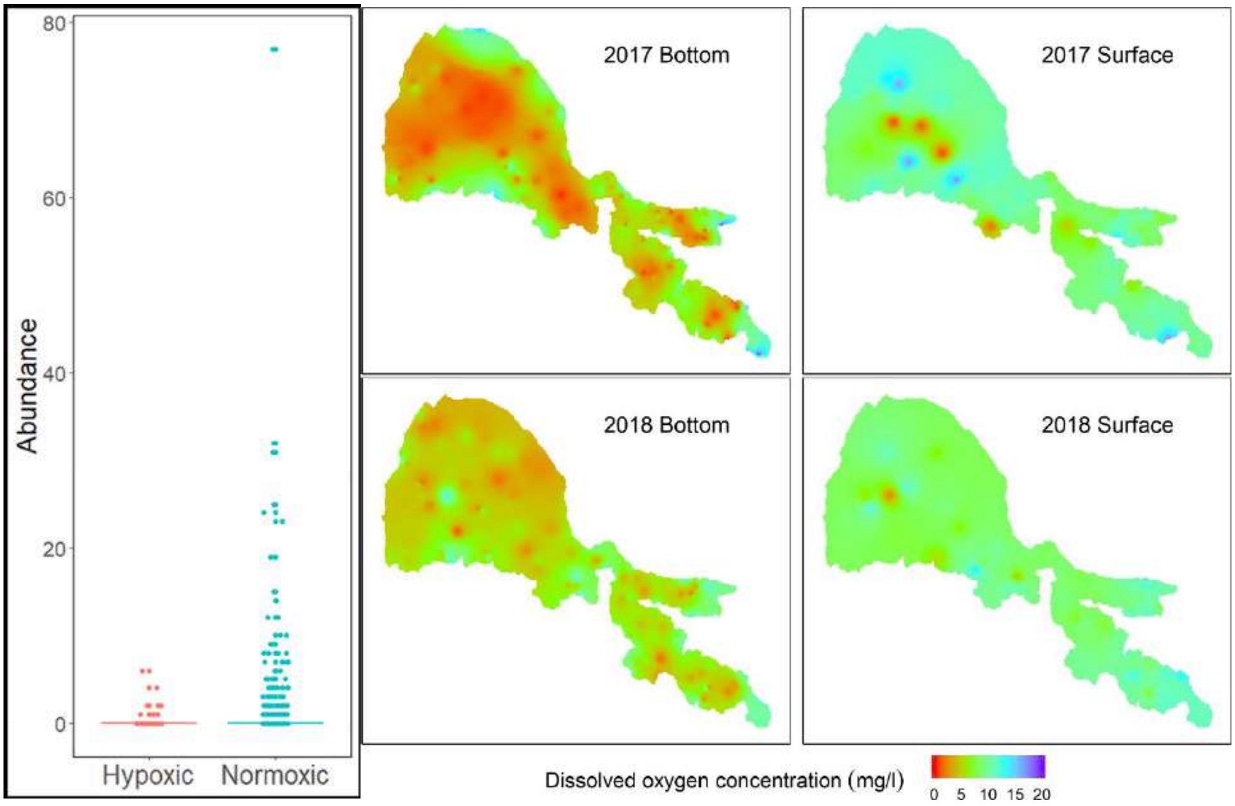
Photo by Richard Macedo

One native species of concern is the Clear Lake Hitch (pictured below), a large minnow, 14-16 inches long found only in Clear Lake and its tributaries. Hitch typically live 6-7 years. Unlike salmon that die after spawning, Hitch normally return to Clear Lake at the end of their spawning season. Hitch were formally listed as a threatened species under California's state Endangered Species Act in 2014 due to significant decline in numbers of Hitch, and the fish's disappearance from most former spawning streams. Clear Lake Hitch have been impacted by reduced stream flows from drought and decreased precipitation, loss and degradation of spawning habitat, water pumping, barriers to fish migration (such as dams), pollution, and competition from invasive fish (Center for Biological Diversity, 2017; Feyrer, 2022).

Elders of the Big Valley Tribe have seen Hitch numbers decline in their lifetime. In the 1960s and 1970s, Hitch were so numerous that they made the water appear to boil in area creeks and streams (BVBPI and MRPI, 2021). Hitch now spawn regularly in only two streams, Adobe Creek and Kelsey Creek. One Big Valley Elder reported that while Hitch used to be plentiful in Kelsey Creek, which runs behind his home, he has not seen Hitch in the creek since 2010. He also noticed that the spawning season has shortened. Traditionally Hitch would spawn for about 6 weeks and now the spawning season seems to be about three weeks. Another Elder explained that the Hitch were dried and kept for use throughout the winter and was a valuable trade item with Coastal Pomo Tribes for resources such as seaweed, clam shells and abalone. Hitch were also a major food source for ceremonies (BVR, 2013). The Clear Lake Hitch are a culturally and biologically important fish. The loss of this fish impacts the community, the history, and the culture of the Pomo people. Restoring their habitat and numbers will also improve the health of Clear Lake overall as they are also an important food source for numerous birds, fish and other wildlife.

Clear Lake Hitch avoid areas with low levels of DO. A survey done by the USGS in 2017 and 2018 identified abundance-habitat relationships for juvenile and adult Hitch. Results of this study showed that DO concentration was the most important habitat feature measured. The figure below, right, shows DO concentrations in Clear Lake in 2017 and 2018. The graph on the left shows the number of Hitch detected and if they were found in low DO (hypoxic) or normal DO (normoxic) areas.

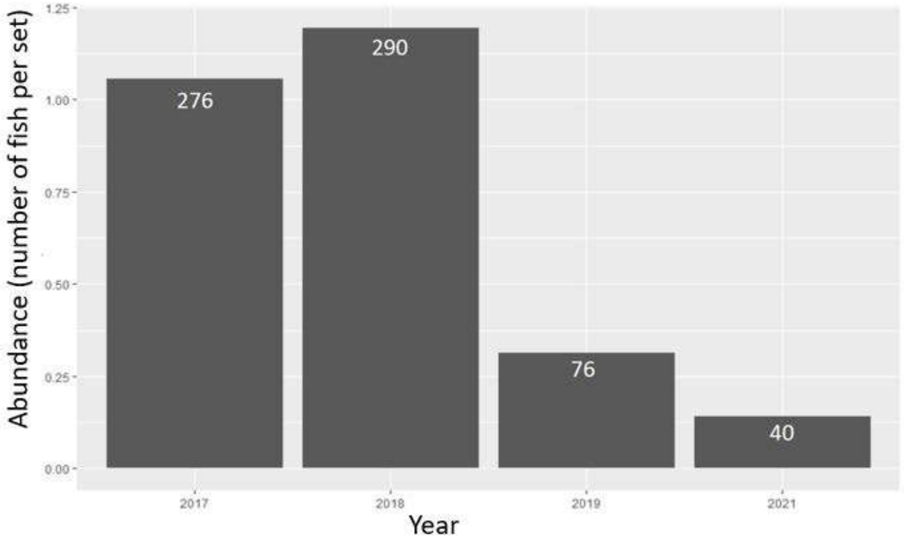
Figure 12. Abundance of Clear Lake Hitch in normal and low DO areas in Clear Lake 2017-2018 (left panel); the spatial distribution of DO concentrations in waters at the surface and lake bottom in 2017 and 2018 (maps on the right)



Source: Feyrer et al, 2020

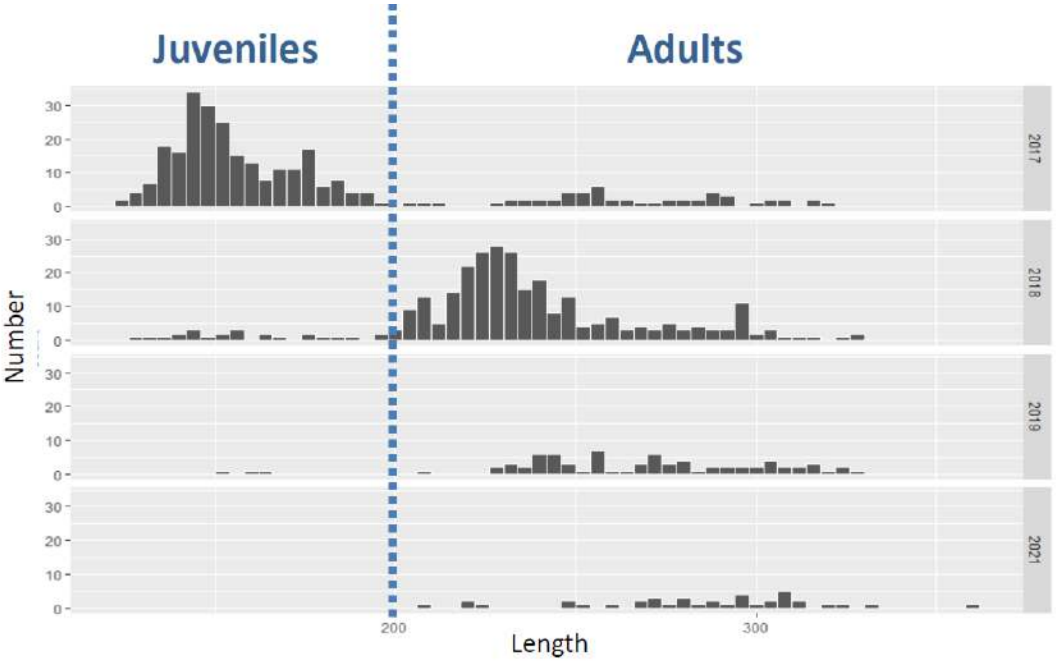
Monitoring of the Hitch in Clear Lake, (Figures 13 and 14) shows a troubling pattern, not only are fewer Hitch in Clear Lake, but the number of juveniles, are declining.

Figure 13. Hitch abundance in Clear Lake 2017-2021



Source: Feyrer, 2022

Figure 14. Numbers of adult and juvenile Hitch in Clear Lake 2017-2021



Source: Feyrer, 2022

Clear Lake Hitch have been forced to adapt to a very brief period of suitable stream conditions for their annual spawning run, as water diversions and a changing climate have caused streams to prematurely dry. Hitch typically spawn in the Spring during periods when creek and groundwater levels are now lower as a result of drought, agricultural irrigation, and the use of pumped water for frost protection. These low water levels are also impacting overall Hitch numbers. Increased drought and rapid climate change due to warming temperatures will likely accelerate this trend, causing further spawning failures. The spawning runs from 2013 to 2015 had an annual average of fewer than 1,000 spawning fish in the entire Clear Lake basin. Since 2013 the average number of spawning fish in the last two tributaries, Kelsey Creek and Adobe Creek, has been under 1,700 fish annually (Center for Biological Diversity, 2021). Spawning, the process of releasing the eggs and milt, is only part of the success or failure of the Hitch to thrive. The fry must also hatch and survive long enough to travel back to Clear Lake and then live long enough to reproduce for the fish numbers to begin to rebound (Feyrer, 2022).

Figure 15. Hitch spawning at Bell Hill Road Crossing on Adobe Creek

Photo by Richard Macedo
CA Department of Fish and Game

Figure 16. Clear Lake Hitch rescue by Tribal staff and CDFW

Source: BPBP and MRPII, 2021

Big Valley, the nearby Robinson Rancheria and Habematolel Pomo of Upper Lake have been working together to study and protect Clear Lake Hitch since 2005. In 2015 Big Valley Rancheria received an award from the Bureau of Indian Affairs (BIA) to conduct a Water Resource Climate Adaptation Plan on Adobe Creek for the Recovery of Hitch (*Lavinia exilicauda*) in Clear Lake (Bureau of Indian Affairs, 2015). Clear Lake area Tribes are also working with non-tribal agencies to help with Hitch recovery efforts, but to date these efforts have no regulatory authority, and as a result may not effectively restore Hitch populations.

Fish consumption by Big Valley Tribal members is often higher than among recreational anglers. A person who eats fish occasionally from sport fishing or commercial fish sources will also consume fish from multiple sources, thereby limiting exposure to contaminants found in a specific location. Tribal members eat large quantities of fish from Clear Lake during ceremonies or as a regular food source. Additionally, the Tribe consumes fish caught in different areas of the lake than recreational anglers.

Tribal Elders have observed a large reduction in the abundance of other native fish species which Tribal members eat, such as blackfish, sculpin, and sunfish.

Tules, an important plant for the Tribe, are used to build boats, for weaving, in traditional ceremonies, as a food source, and for various household uses, are also at risk from a changing climate and area development. Roughly 85% of the shoreline tules have been lost already (BVBPI and MRPI, 2021).

Tules have been impacted by drought and warming temperatures which stresses tules, making them more likely to be impacted by pests, disease, and invasive species. One such invasive species is water primrose, which has taken over where many tules used to grow along Clear Lake's shoreline. Tules help buffer against wind and water, allowing the establishment of other types of plants and reducing erosion. Tules have roots at or under the waterline and play an important filtration role in Clear Lake's ecosystem. These tule wetlands filter out much of the nutrient load and other chemicals found in storm water runoff before they enter the lake. Tules also provide habitat, food, and nesting materials for terrestrial and aquatic species.

> *"The Tule is part of our Traditional Tribal history, it was used for ceremony inside the Roundhouse as a ground cover and mat for the people to sit upon, The Big Head Dancers wore skirts made of Tule for our regalia, clothing for our women were made of Tule, Tule Mats were used as sleeping mats in our Hut made of a willow frame and a covering with Tules, men made a Tule Shirt worn in colder weather, we ate the Tule Roots for food, The health of the Tribe and the health of the Tules are interrelated. It is important to bring notice to and make others aware of the problems we are seeing in the quality of our lake waters and how it is affecting our cultural practices, our subsistence fishing, birds and loss of plant life (Tules) on the shores of our rancheria."*
> *~Ron Montez, Tribal Elder and Tribal Historic Preservation Officer*

The use of plants such as tule, sedge, dogbane, and willow does not just benefit the user, but the ecosystem as a whole. Stands of plants are tended and groomed to make them more useful for basketry and other uses and that grooming helps strengthen riverbanks and reduces soil erosion. The plant bases go from short and knotty, to straight, long and strong. This grooming also promotes access for riparian animals who can more easily access the water in well-tended areas (Pearce, 2022).

Manzanita, a culturally important plant, produces berries that are eaten raw, used to sweeten other foods, or ground for flour; its bark and flowers are used to make a medicinal tea (Pearce, 2021). Manzanita is now seen as a fire risk by some and has been cleared by non-tribal members for fire mitigation and to clear land for vineyards. Removal of manzanita constitutes a loss of traditional food and medicine, as well as a loss of habitat and food for other species.

Angelica root is another culturally important medicinal plant that has been impacted by drought and erosion from flooding. The Tribe has tried to harvest Angelica from areas where it may no longer thrive and propagate it in areas where it grows better or is more accessible to the Tribe. Basketry materials such as willow, redbud, and dogbane have also been impacted by the changing climate. Traditional gathering areas have been reduced due to vegetation changes, wildfire, and the privatization of lands (BVBPI and MRPI, 2021). As the Tribe has seen a reduction in culturally important plants, they have seen a rise in invasives such as star thistle, Scotch, French and Spanish broom (BVBPI and MRPI, 2021).

Harmful Algal Blooms

Harmful algal blooms (HABs) are colonies of algae and/or cyanobacteria that grow out of control, threatening fisheries, aquatic ecosystems, public health and economies. HABs produce toxins that contaminate waterbodies used for recreation or drinking water sources, and the shellfish, fish and wildlife living within them. Even without producing toxins, HABs damage aquatic environments by suffocating fish, blocking sunlight, or depleting oxygen in the water (COST, 2016; WHO, 1999).

Climate change affects the factors that drive HAB formation (US EPA, 2017a). Warmer water temperatures, drought conditions, increased carbon dioxide and alternating periods of storms and drought are all known to promote HAB formation (Lehman et al., 2017; Power et al., 2015). Anthropogenic inputs of nutrients like phosphorus and nitrogen also promote HAB formation.

Tribal members and locals around Clear Lake report that HABs have become much more prevalent over the last few decades. HABs are regularly observed in Clear Lake; these blooms damage the environment and produce levels of cyanotoxins that are harmful to humans. The main cyanotoxin produced in Clear Lake is microcystin, which has been known to kill pets and other animals, and cause skin, gastrointestinal and liver impacts in humans. Tribal members are exposed to microcystin through interactions with the water such as swimming, cultural ceremonies, the consumption of aquatic organisms, and drinking water.

HABs on Clear Lake produce very high levels of microcystin and the lake is often posted with recreational advisories from April through October. The California Cyanobacteria Harmful Algal Bloom (CCHAB) Network has adopted tiered cyanotoxin trigger levels for posting recreational waters. For microcystin these advisory levels are 0.8 micrograms per liter (µg/L) (Caution - keep away from visible algae), 6 µg/L (Warning – no swimming) and 20 µg/L (Danger – do not contact the water or eat aquatic organisms). All advisory levels warn people to keep their pets and small children away from the water and shoreline and to avoid shellfish and wash fish filets before cooking them. The Big Valley Band of Pomo Indians and the Elem Indian Colony have been actively involved in sampling and monitoring their waters. Results of the monitoring for 2014-2021 are shown in Table 1 below.

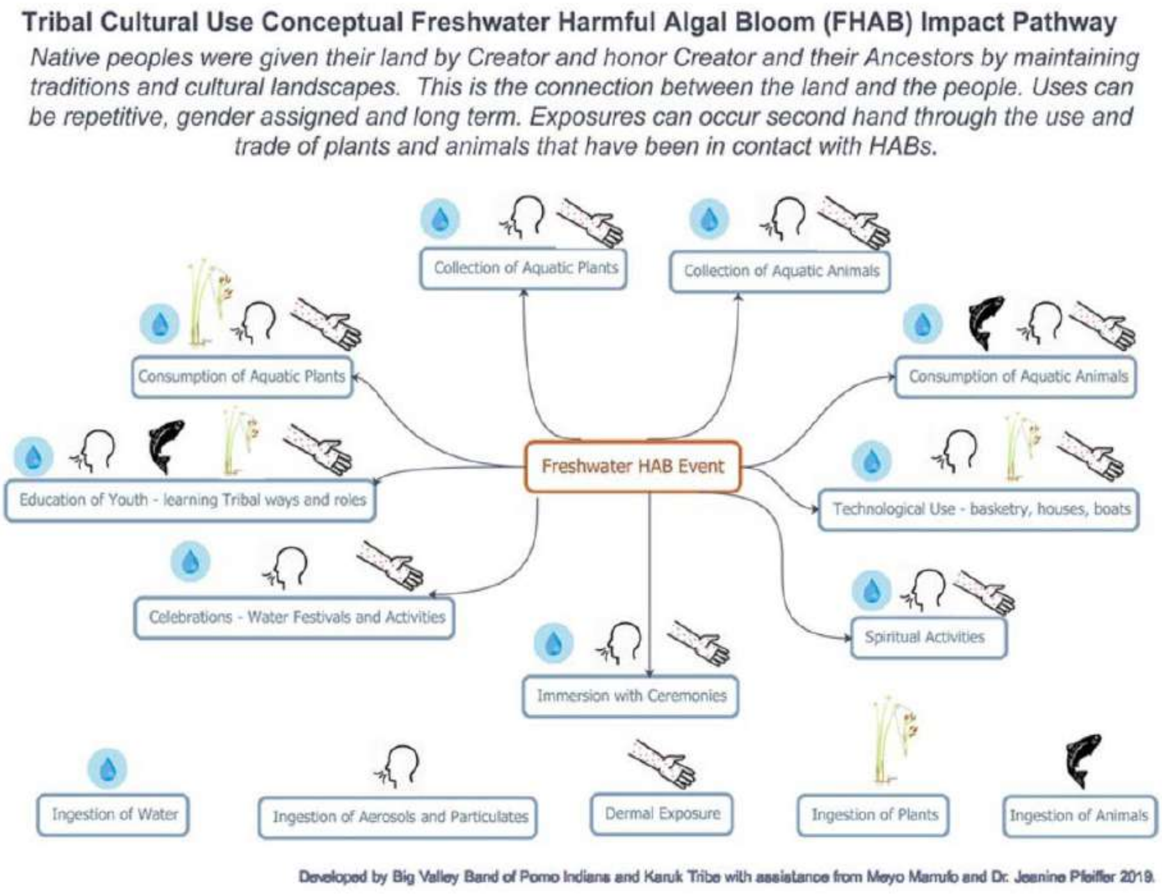
Table 1. Highest Concentrations of Microcystins in Clear Lake Waters

Arm of Clear Lake	Highest Level of Microcystins (µg/L)							
	2014	2015	2016	2017	2018	2019	2020	2021
Upper Arm	878***	Trace	0.3	4*	13**	0.3	1,146***	5,910***
Oaks Arm	16,920***	278***	0.7	46***	4,800***	0.9*	79***	1,449***
Lower Arm	769***	10,162***	0.3	1*	230***	150***	902***	160,377***

Source: BV EPA, 2022b

Notes:
**Above CCHAB Caution Trigger Level of 0.8 µg/L*
***Above CCHAB Warning Trigger Level of 6 µg/L*
****Above CCHAB Danger Trigger Level of 20 µg/L*

Figure 17. Tribal Cultural Use Conceptual Freshwater Harmful Algal Bloom (FHAB) Impact Pathway



When advisories are posted at Clear Lake, Tribal Members can't safely participate in Tribal activities that require them to be in the lake. Important Tribal activities that are prevented by trigger level advisories include spiritual activities, water immersion for ceremonies, using plants for ceremonies and basketry, and the collection and consumption of fish and other aquatic organisms. Tribal members are also be prevented from swimming or playing in the water, which is important for heat relief. In 2021, cyanotoxin was monitored from April through December. During that time there was never a period in which the whole lake was safe for contact (BV EPA, 2022b). Figure 17 illustrates the potential routes of exposure to HABs based on Tribal uses and practices involving Clear Lake.

HABs create sludge that clogs drinking water intakes in Clear Lake (Figure 18). This leads to higher operating and electrical costs due to filters needing to be flushed more frequently. It also increases the cost due to the need for sludge disposal. When microcystin is present in raw water, water treatment plants must make sure this toxin is kept out of the finished drinking water. In Clear Lake more carbon filters have been required to remove the cyanobacteria and toxins, which also increases costs.

Figure 18. HABs at Clear Lake, September 2021

Photo credit: Justin Sullivan / Getty Images

A 2015 CalEPA Environmental Justice grant funded the Big Valley Rancheria to measure microcystin in Tribally important fish from Clear Lake. Fish and shellfish from ten species were collected over several years. Analysis of 91 fish tissue and 32 fish liver samples found detectable amounts of microcystin. Summaries of the average microcystin toxin levels per fish species are shown in Table 2.

Table 2. Microcystin (MC) concentrations in fish from Clear Lake (2010 – 2018).

Species	Tissue MC ng/g Avg (Count)	Liver MC ng/g Avg (Count)
Black crappie	4 (8)	19 (5)
Blackfish	7 (1)	83 (1)
Blue gill	ND (2)	7 (2)
Carp	14 (2)	34 (2)
Catfish	2 (6)	10 (6)
Hitch	10 (8)	16 (7)
Largemouth bass	2 (7)	6 (2)
Tule perch	6 (10)	35 (8)
Crayfish	4 (23)	
Mussel	10 (26)	

Source: WRCB, 2022

Concentration is at or above OEHHA’s state-wide Action Level for microcystin in fish consumed by humans (10 ng/g).

The Action Level for fish consumption recommended by CalEPA’s Office of Environmental Health Hazard Assessment (OEHHA) based on total microcystin in fish and shellfish is 10 nanograms per gram (ng/g) and is calculated for a 70 kg person eating at the sport fish and shellfish consumption rate of one 8-ounce meal per week (Butler et al, 2012). Many Tribal members eat fish and shellfish at a higher weekly consumption rate. Based on a higher consumption rate and a similar risk level, the recommended maximum level for total microcystin would be lower than 10 ng/g. OEHHA is working with the Big Valley Band of Pomo Indians’ Environmental Protection Department to calculate Action Levels for Tribal members.

The occurrence of HABs causes great economic losses. A study from 25 years ago estimated that HABs resulted in $7 – 10 million in lost tourist revenue annually in Lake County (Goldstein and Tolsdorf, 1994). Clear Lake is a large-mouth bass fishing destination and other water activities, such as water skiing, jet skiing, and swimming are popular at the lake. Economic loses today are likely much greater.

To mitigate HABs and fish kills on Clear Lake, Big Valley Environmental Protection Department, with the assistance of a Bay Area Council California Resilience Challenge grant, has acquired and installed two Tribally-managed water quality data loggers. This monitoring program for HABs and fish kills creates a real-time, open-access Clear Lake water quality data monitoring portal, to analyze and address aquatic species die-offs impacting Tribal beneficial uses (BV EPA, 2021).

Additionally, the Big Valley Band of Pomo Indians is partnering with Tracking California to carry out the California Water: Assessment of Toxins for Community Health Project, or Cal-WATCH. The project is working to increase the ability to reliably track and prevent harmful algal bloom illness statewide, with a special emphasis on Clear Lake.

Alongside the climate change impacts causing HABs at Clear Lake, is the closed Sulphur Bank Mine, a flooded open pit mercury mine 23 acres long and 90 feet deep located 750 feet from Clear Lake. The site is filled with a combination of contaminated mine waste and natural geothermal water that seeps mercury into the lake. While the mine closed in 1957 it was not declared a Superfund site until 1991 (USEPA, 2017b). OEHHA has established fish advisories for Clear Lake based on high levels of mercury in fish (OEHHA 2018).

In 2015, Big Valley's EPA measured the mercury levels in several species of fish in different locations around the lake. Mercury levels measured in certain fish in 2015 were found to exceed fish tissue goals established by the Water Board (WRCB, 2015).

In February of 2021, the USEPA updated the local community on the Sulphur Bank Mine's Superfund Site's status. The USEPA estimated that they were within four years of beginning the main clean-up project, which will be broken up into two phases: consolidation and capping. Initially, the plan involves moving smaller piles of mining waste onto large piles to shrink the area that needs to be removed before installing a heavy cap to act as a barrier over the site. The cap will then be covered with clean soil so that plants begin to grow and rehabilitate the area (USEPA, 2021b).

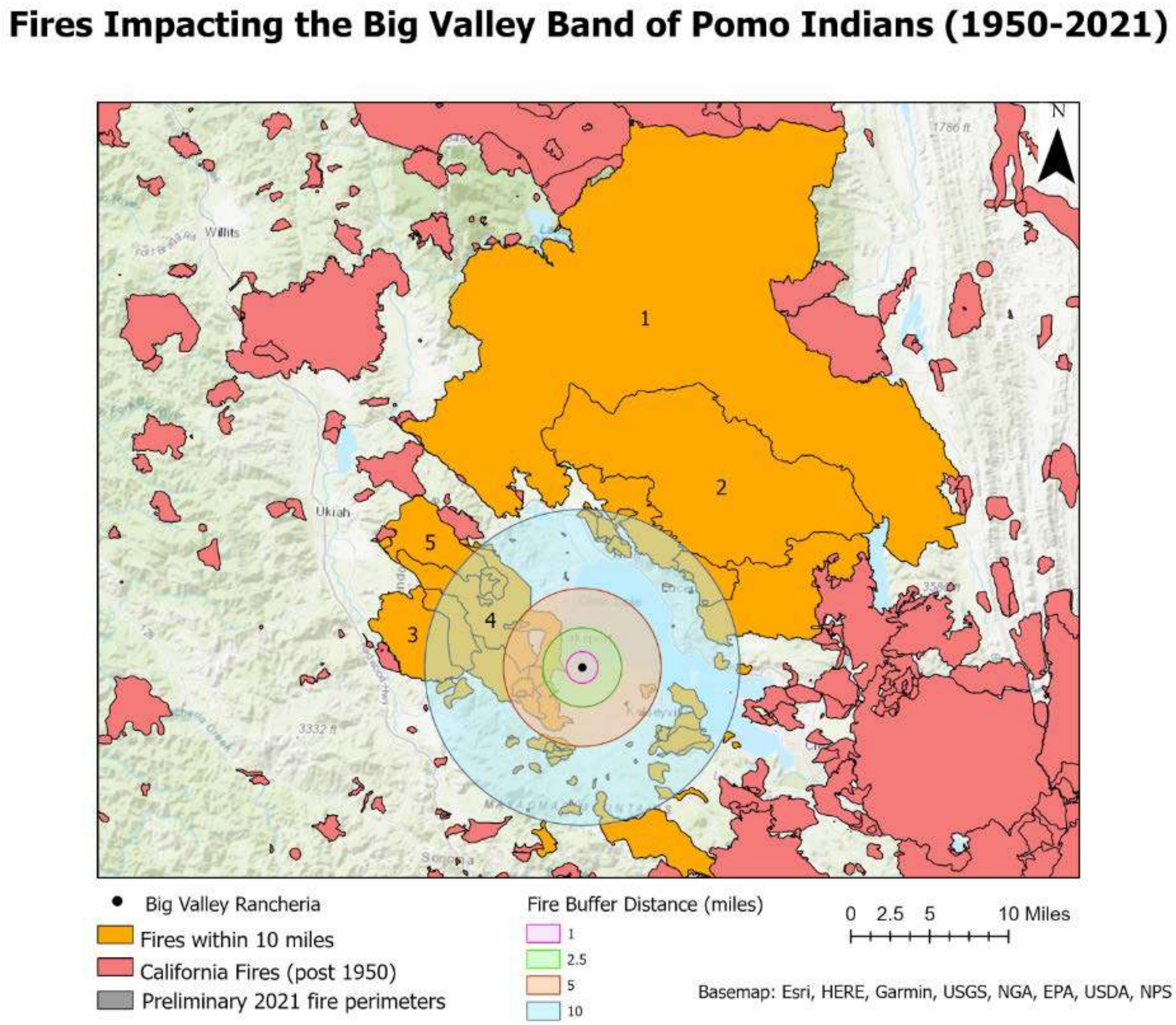
Wildfires

Figure 19 shows California wildfires around the Big Valley Rancheria from 1950 through 2021. In 2018 the Ranch and River fires began during the Tribe's annual Tule Boat Festival, and eventually merged into the 459,123-acre Mendocino Complex Fire (#1 on the map), California's largest wildfire on record at the time.

The Big Valley EPA Director recounted *"People were having trouble breathing on the rancheria. We have a lot of people with asthma and respiratory illnesses. We went to the local stores and tried to get some air purifiers, but everybody was sold out. A neighboring Tribe, the Middletown Rancheria of Pomo Indians, helped Big Valley acquire seventy air purifiers."*

Wildfires are a natural function of California's ecosystems and are important for shaping ecosystem structure. Human influences and policies, however, have worked to prevent natural wildfires and cultural burning practices. Combined with drought, this has led to an increase in the intensity, duration, and frequency of large-scale wildfires which destroy habitat, human infrastructure and livelihood, and harm human health.

Figure 19. Fires within 10 miles of the Big Valley Rancheria.



Source: CAL FIRE, 2022

Historically the Pomo would have conducted cultural burns, low intensity burns on designated parcels which, under the right conditions, reduce the risk of wildfire by consuming dead wood and other fire fuels on forest floors (Miller et al., 2020).

While cultural burning is gaining respect and use, current levels of agency-prescribed burns and tribal cultural burns are too low to make a significant impact on millions of acres left untended for a century and a half. As a result, Tribal members today encounter a surge of catastrophic wildfires their great-grandparents never experienced. Wildfires pose unique and heightened challenges to Tribes, given their relationships to the land. Further, non-Native government officials often the lack an understanding of tribal customs and priorities (Pfeiffer, 2021).

Figure 20. Mount Konocti in clouds.

Photo: L Monserrat, OEHHA

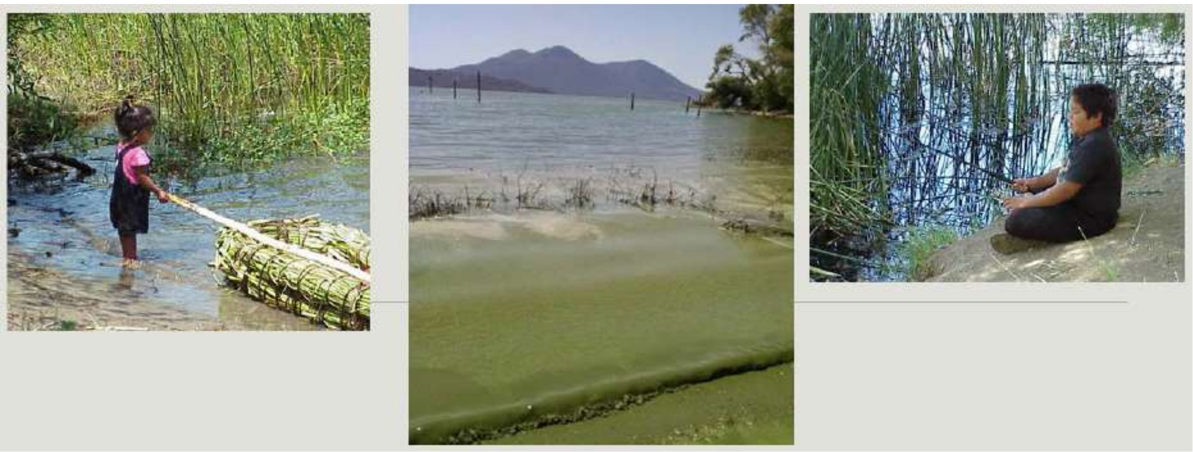
Climate change has created shifting conditions for species and created new opportunities for invasive species in what were previously unfavorable climatic regions. Human activities are responsible for habitat and biodiversity loss, land use changes, anthropogenic climate change, forest management and the loss of cultural burning. The resulting droughts, fires, flooding, increases in HABs and other climate threats are impacting our Tribe.

Human Health

The health of the Big Valley Band of Pomo Indians cannot be separated from the health of their environment. Increasing temperatures, increasingly variable rainfall, wildfires and exposure to smoke, pesticides, mold, the loss of important plant and animal species, and exposure to mine waste from the nearby Sulphur Bank Mine Superfund site all impact the health of the Tribe. Exposure to cyanotoxins is a human health concern for the Big Valley Tribe. Tribal members have always used the lake for food, drinking water, ceremony, and recreation (Figure 21). Thus, potential exposures to HABs that produce cyanotoxins include unique pathways that do not apply to non-tribal individuals (Figure 17). Cultural activities that require the use of the lake have had to be postponed or moved due to a lack of tule and other ceremonial material and poor lake water quality. Poor water quality limits Tribal members' access to the lake, an important cultural resource as well as threatens access to safe and clean drinking water.

Climate change has exacerbated food insecurity and the nutrition of the Tribe. There are fewer native wildlife species on which the Tribe has relied on for food such as Indian potato, clover, acorn, pine nuts, edible mushrooms such as chicken of the woods (*Laetiporus sulphureus*), Clear Lake Hitch, clams, prickly sculpin, crayfish, and tules.

Figure 21. Scenes from Big Valley.
Left, child at Tule Boat Festival. Center, HABs impacts at Clear Lake. Right, a child fishing in the tules



Source: Big Valley EPA

Summary

The Big Valley Band of Pomo Indians has been living alongside Clear Lake and managing their ecosystem since time immemorial. Big Valley Tribal members, like other Tribes have similar challenges as non-tribal members. Temperatures are warming, rain is less predictable, the environment is stressed. The Tribe is working to restore the balance in their environment. Pomo Tribal members have historically been careful about the balance of consumption and restoration of the environment. The Big Valley Tribe is working both internally and with outside agencies to help to restore a balance and provide a more sustainable and certain environment for future generations.

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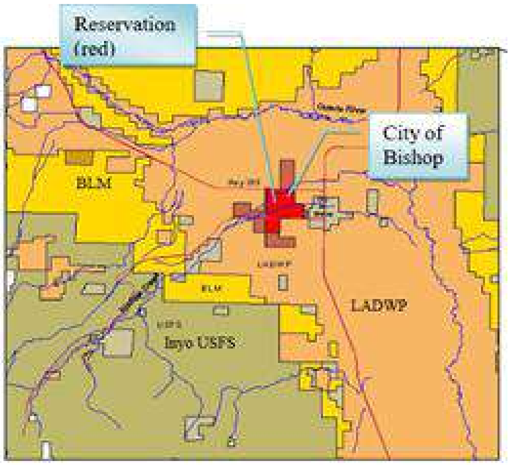
IMPACTS OF CLIMATE CHANGE ON THE BISHOP PAIUTE TRIBE

Rising temperatures and drought compounded by over pumping of groundwater are impacting the physical, cultural, and spiritual health of the Tribe, its habitats, and ecosystems.

Background

The Bishop Paiute Tribe is a federally recognized tribe living in Inyo County at the foot of the Eastern Sierra Nevada mountains, in the Owens Valley, just west of the city of Bishop. They are the fifth largest tribe in California with ~2,000 enrolled members and have one of the smallest land bases (879 acres) (BPT, 2018). Payahuunadü, or land of flowing water, is the Paiute word for the Owens Valley and Eastern Sierra region of California.

Figure 1. Bishop Paiute Reservation (red) within the city of Bishop (brown)



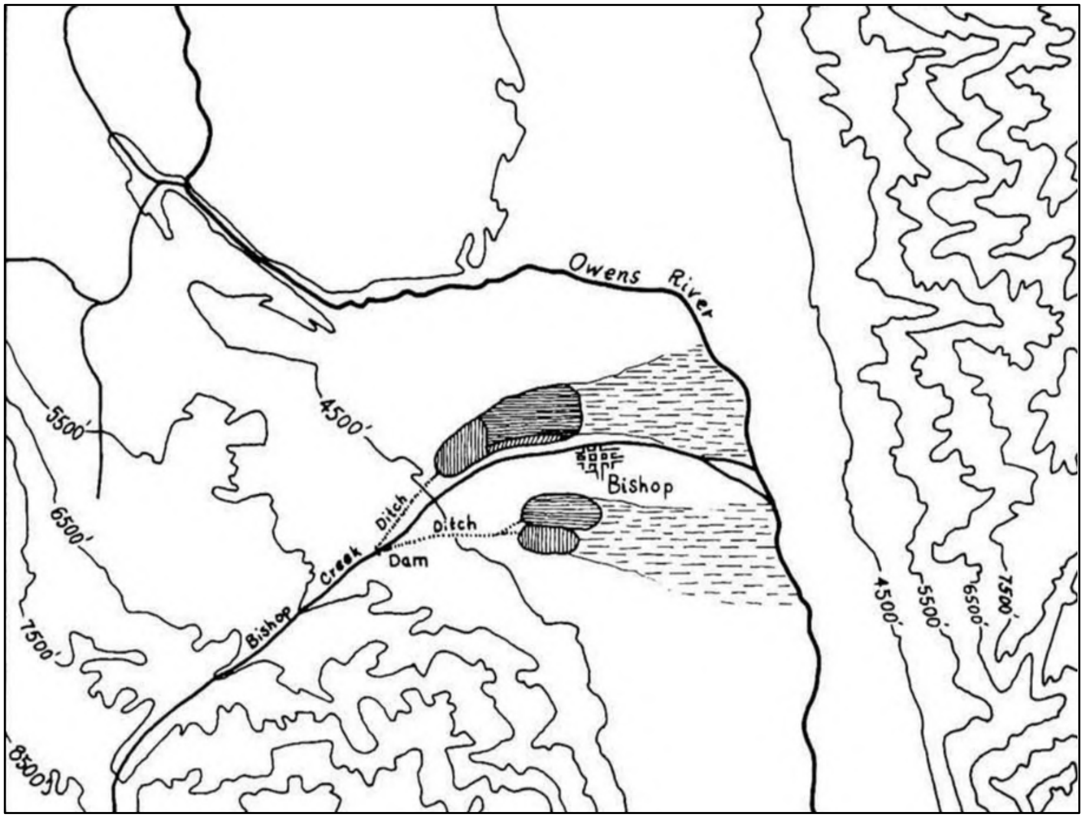
Source: BPTEO, 2018

The people of the Bishop Paiute Tribe are descendants of the “Nüü-Mü,” the original people of the Owens Valley who have lived in the area since time immemorial and whose ancestral lands encompassed over 2 million acres of the greater Owens Valley (BPT, 2018). In 1912 under pressure by the US Government, the Bishop Paiute people entered into a treaty in which the US Government reserved 67,120 acres of land in the Owens Valley named the Casa Diablo Indian Reservation for Indians of the area. However, the Paiute were never allowed to move to this Reservation. This treaty was broken in 1933 when President Roosevelt revoked the agreement (Executive Order 6206) and the lands were placed in watershed protection for the City of Los Angeles (OVIWC, 2021). In 1936, the City of Los Angeles and the federal government “traded” the 67,120-acre Casa Diablo lands for the 879 acres that now comprise the Bishop Paiute Reservation (BPT, 2021a).

Historically, the Paiute dug irrigation ditches that routed runoff from melting Sierra Nevada snow into the Payahuunadü. But unlike modern irrigation practices, the Paiutes did not channel the water onto farms or specific plots of land. Bishop Paiute Tribal Elder and water protector Harry Williams explained “We looked at everything as a garden. The natives made this place bloom like a rose. The water was used to irrigate ’wild’ seed plants” (Williams, 2016).

Water was so important to the tribe that they had an elected position called the Tuvaiju who oversaw irrigation. The Tuvaiju would use an irrigating tool known as a "pavado" to direct water into the ditch network in the Payahuunadü.

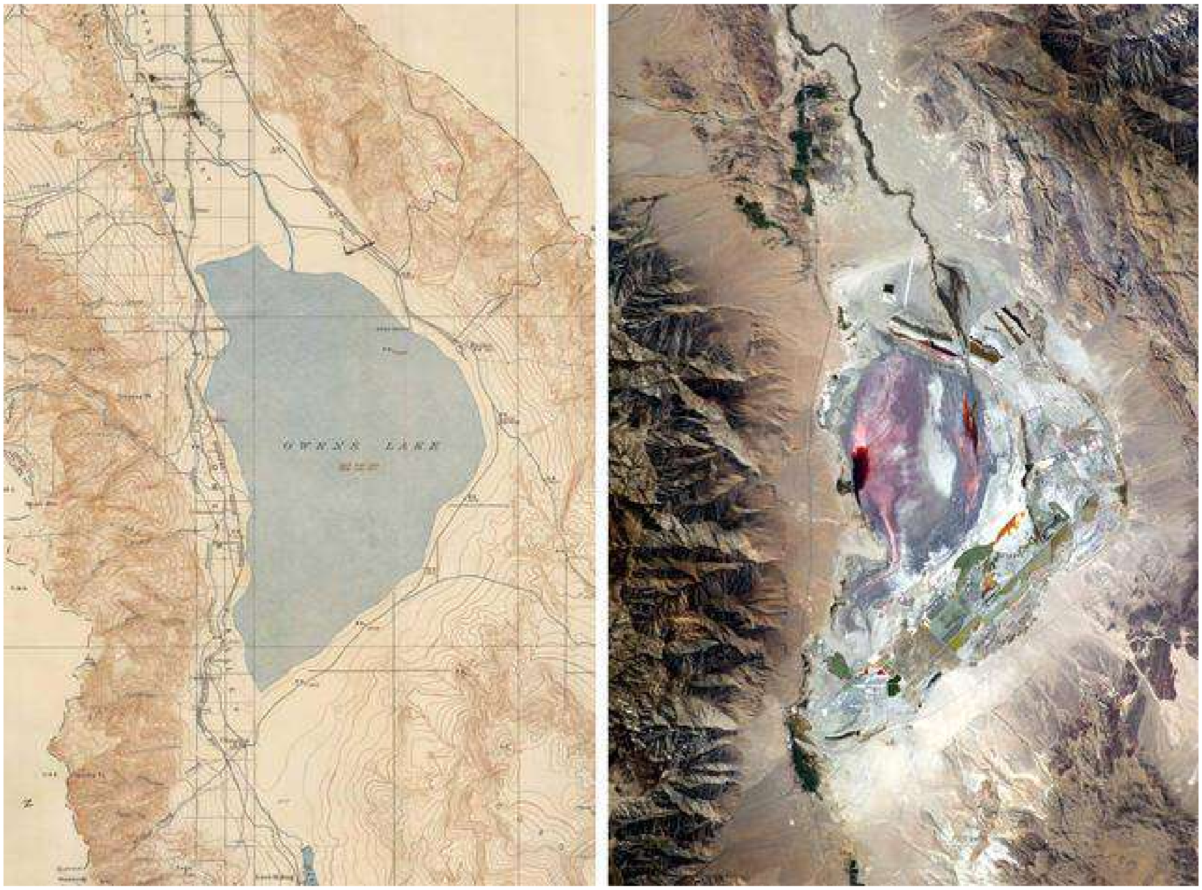
Figure 2. Drawing of traditional Paiute irrigation system at Pitana Patii, near present-day Bishop, Owens Valley, California.



Source: Lawton et al., 1976

The Paiutes' valley was divided by the Bishop Creek into northern and southern plots. As is shown in Figure 2 above the Tribe created a dam system designed so that only one of the areas would receive water each year; the plots were purposefully alternated to conserve soil fertility. The irrigation helped the growth of grass nuts and tubers that made up a significant part of the native diet. The ditches also funneled native fish into areas where they were easy to catch. The irrigation canals distributed the water across the Payahuunadü (Wei, 2016).

Figure 3. Owens Lake and Vicinity between 1905-1911 and as seen from space in 2011



Sources: USGS, 1939 and NASA, 2011

Owens Lake had held water continuously, and at times overflowed to the south, for at least the 800,000 years prior to 1913 (Smith et al., 1993). In 1913 the Los Angeles Department of Water and Power (LADWP) began pumping Owens Lake, which at the time spanned 108 square miles (~1/3 the size of Lake Tahoe), to provide water to Los Angeles. By 1926 the lake was dry (Reheis et al., 1995). In 1970, a second aqueduct that mainly pumps groundwater from the Owens Valley for use in Los Angeles was added. This ongoing water export has intensified the effects of precipitation changes and drought caused by climate change in the Eastern Sierra. (BPT, 2020).

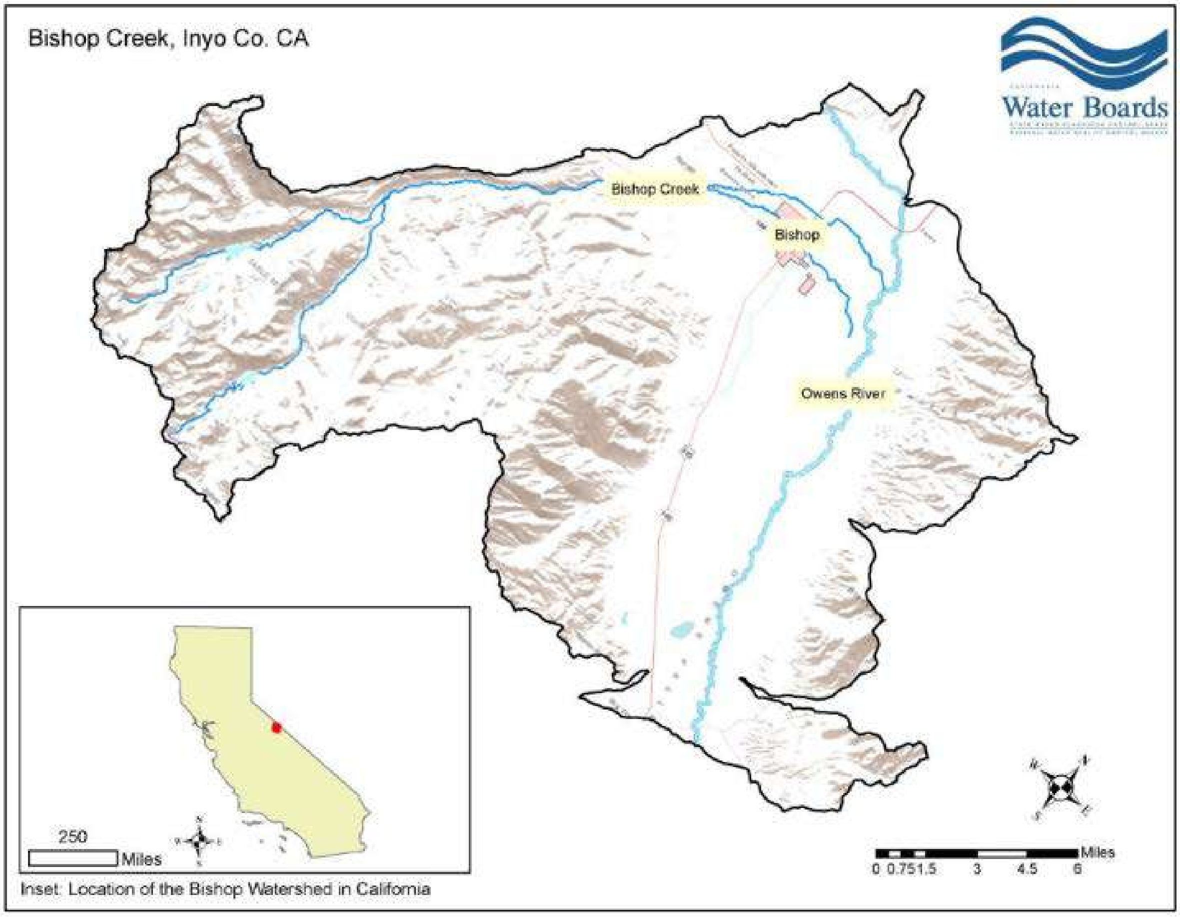
Figure 4. Dry winds blow sand across what used to be the north shore of Owens Lake

Photo credit: David McNew

This change to the Owens Valley climate has also caused a troubling rise in the level of PM10, inhalable particles with diameters that are generally 10 micrometers and smaller. Owens (dry) Lake is currently the largest source of PM10 in the United States, thirty tons of which is arsenic and nine tons of which is cadmium. USEPA estimates that 94% of the PM10 in the Owens Valley comes from the now dry Owens Lake (USEPA, 2017). Research has linked exposures to relatively low concentrations of particulate matter with premature death. At greatest risk are Tribal Elders and those with pre-existing respiratory or heart disease, lung disease, asthma or chronic obstructive pulmonary disease (USEPA, 2017).

The current Reservation ecosystem is over the Bishop Cone, an area characterized by a shallow water table with depths ranging from 1 to 10 feet below ground level. This substantially enhances vegetation coverage including a variety of pasture grasses and several types of deciduous tree species. As shown in Figure 5, both North and South Forks of Bishop Creek traverse the Reservation. With the exception of relatively recent increases in bacterial levels in South Fork stream water quality is excellent and supports a 5-mile-long riparian forest corridor providing a rich habitat for a variety of flora and fauna (BPT, 2018). Additionally, there is a wetland in the southeast corner of the Reservation within the Conservation Open Space Area (COSA).

Figure 5. Bishop Creek and surrounding Watershed, Inyo County, CA



Source: LRWQCB, 2020

Figure 6. Petroglyphs at the Volcanic Tablelands

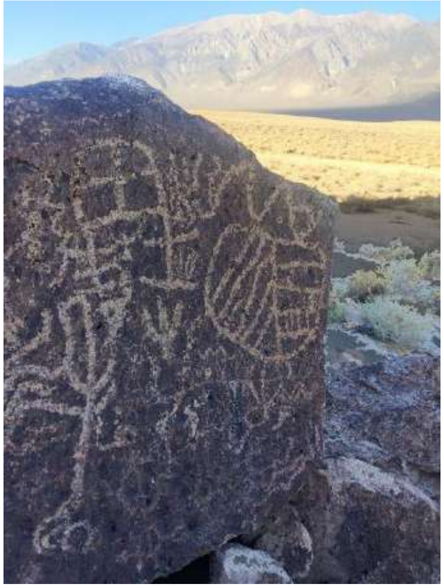


Photo credit: Sarah Rea

In 1988 the Bishop Paiute Tribe established the COSA which serves as important habitat for native plants and animals. Furthermore, the COSA is currently being utilized to increase populations of threatened and endangered plants and animals, such as the Owens Valley Checkerbloom and the Inyo County Mariposa Lily. The Tribe has been working to introduce the Owens pupfish to the COSA via a Federal Safe Harbor Agreement, which would provide these culturally important fish with another refuge.

Because the impacts of climate change do not start and stop at the Reservation borders, and because the culture of the Bishop Paiute Tribe is tied to all their traditional lands, this report covers both the changes seen on the Reservation lands as well as on traditional lands of the Bishop Paiute such as Volcanic Tablelands and Fish Slough. Petroglyphs within the Volcanic Tablelands are shown in Figure 6.

Cultural and Spiritual Health

As the climate changes the cultural and spiritual health of the Bishop Paiute Tribe are impacted. You cannot separate the health of the earth from the health of the Bishop Paiute Tribe. The Tribe has seen a loss of gathering areas and ceremonial locations, a reduction in traditional medicines and foods, impacts on culturally important fish species, and a loss of the Bishop Paiute's traditional waters through both drought and groundwater pumping for export by LADWP. The Tribe has observed pumping is causing local streams and springs to die which has a cascading and compounding impact on the surrounding insects, fish, mammals, and vegetation (BPT, 2020).

The Bishop Paiute Tribe has created a web of interconnected efforts aimed at responding to the complexities of climate change. They are protecting their natural resources with a combination of mitigation efforts, such as installing rooftop solar panels, increasing food sovereignty, and invasive plant removal, as well as adaptation strategies such as protecting Tribal waters, providing cooling for elders, and educating Tribal members (Kapp, 2019).

CLIMATE CHANGE IMPACTS

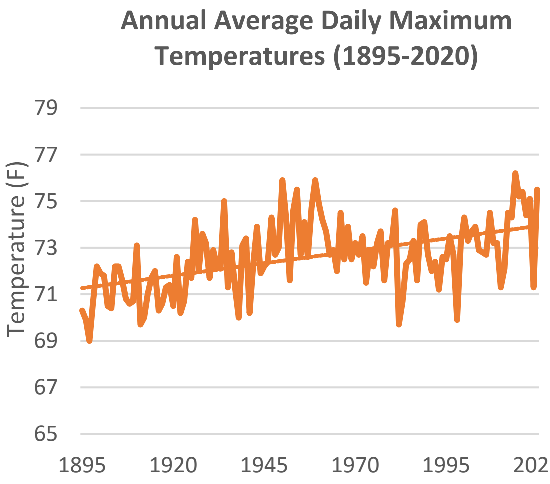
Climate change in the Bishop Tribal lands in the Eastern Sierra has impacted wildlife, native vegetation, and culturally important foods such as pine nuts, acorns, fish, and wild game. Drought in the area, along with beetle infestations, have caused an increase in tree mortality. The build-up of dead trees in the National Forest area at Indiana Summit and the increase of perennial weeds, shrubs, and other flashy fuels have increased the fire danger over time. Sporadic heavy rains in the winter and spring increase the growth of vegetation which then dry and become fuel in the hot summers (BPT, 2020).

Elevated Temperatures

Temperatures have been increasing in Bishop. Elevated temperatures affect human health, mental health, cultural and spiritual health, socio-economic health, as well as the plants and animals that are part of the Bishop Paiute's ecosystem. Elders, children, outdoor workers, and those with existing medical conditions are particularly susceptible to these impacts.

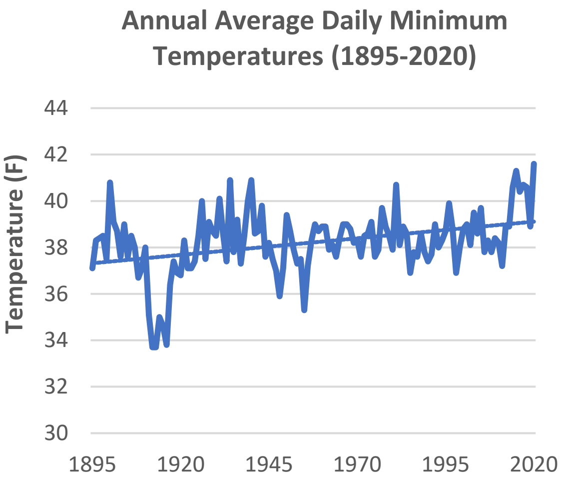
As shown in Figures 7 and 8 both the annual average daily maximum (daytime) temperatures and the annual average daily minimum (nighttime) temperatures are rising at Bishop, with the daytime temperatures rising faster.

Figure 7. Daytime temperatures at Bishop



Source: PRISM, 2021

Figure 8. Nighttime temperatures at Bishop



Source: PRISM, 2021

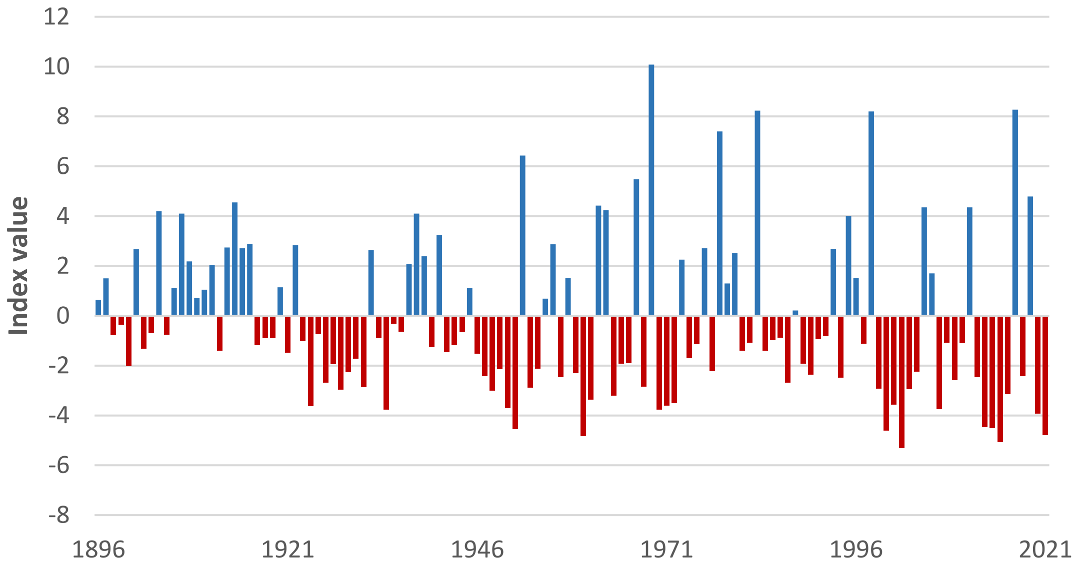
Warming temperatures are considered a high-risk exposure for the Bishop Paiute Tribe. As is evident from the increasing minimum temperatures, the cooling nights that the Bishop Paiute community has been accustomed to are warming over time. The combination of warmer daytime and nighttime temperatures is impacting both the human and the plant communities. As temperatures have increased, the Bishop Paiute Environmental Department has observed declining areas of important habitats including native grasslands, wetlands, riparian, and upland habitats and increasing levels of non-native grasses and shrubs (BPT, 2020). The conditions caused by drought and the over pumping of groundwater also allow invasive species to take hold (e.g., invasive weeds such as Pepperweed, Cheatgrass, Non-native Asters, and Tumbleweed).

Drought

The impacts of drought are intensified in the Owens Valley due to ground and surface water pumping by LADWP to supply water to Los Angeles (ICWD, 2021a). No matter how much snow or rain falls in the Eastern Sierra, the water needs of Los Angeles remain and will increase as populations increase, further burdening the Bishop Paiute community.

As is shown in Figure 9, Bishop is having more frequent, and more intense, dry years. The graph shows a commonly used measure of drought, the Palmer Drought Severity Index (PDSI), which combines both temperature and precipitation data to provide a measure of relative dryness (drought) on a scale from +10 (wet) to -10 (dry). The lower the number the drier the conditions. Prior to 1958, dry years (with PDSI values below zero) occurred 37 times, only one of which was classified as extreme drought (PDSI at or below -4). From 1959 to 2021 Bishop experienced 43 dry years, including 7 years of extreme drought (Abatzoglou et al., 2022).

Figure 9. Palmer Drought Severity Index at Bishop for the years 1895-2021



Source: Abatzoglou et al., 2022

As detailed in the history of the Bishop Paiute, water holds a strong cultural significance for the Paiute people. A lack of water impacts the survival of plants and animals, which hold cultural importance to the tribe.

Impacts to Vegetation

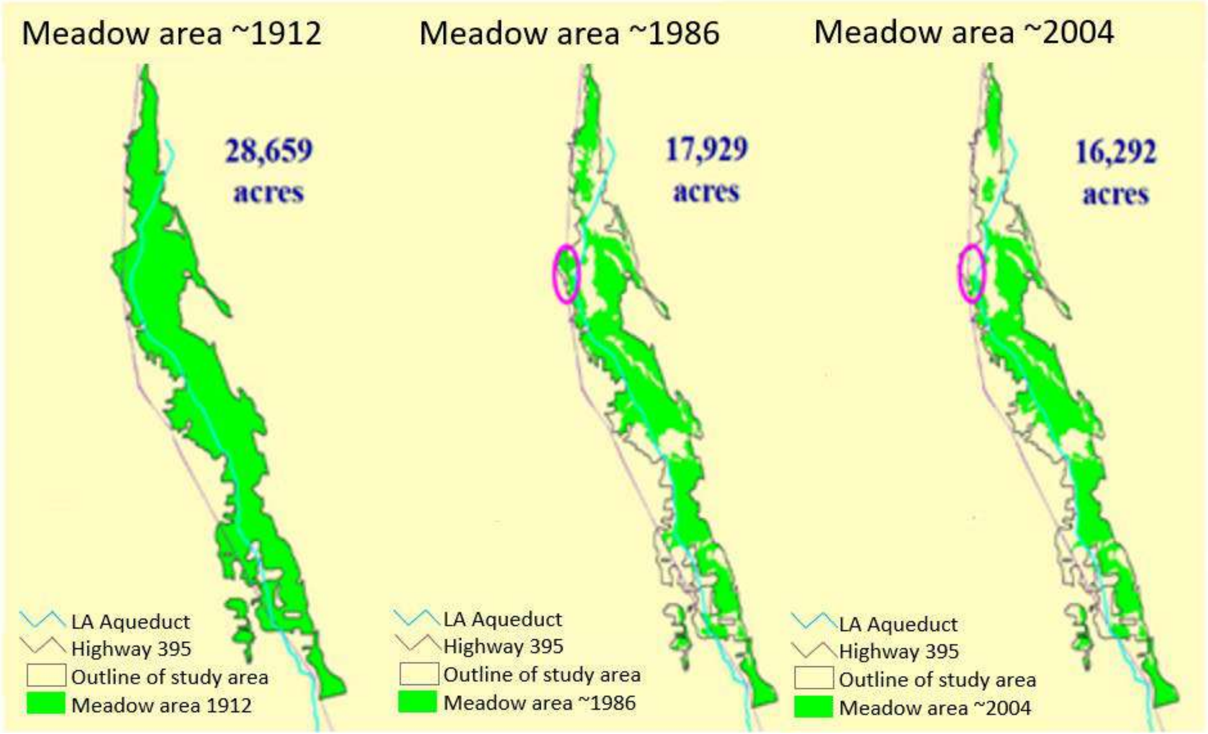
Climate change in the Bishop Tribal lands in the Eastern Sierra has negatively affected native vegetation, including culturally important medicines and foods such as pine nuts and acorns. Drought in the Eastern Sierra, along with beetle infestations by the mountain pine beetle (*Dendroctonus ponderosae*), have caused an increase in tree mortality. As trees become stressed by drought, their vigor and defense mechanisms weaken, making them more vulnerable to attack. High temperatures exacerbate already stressed conditions for tree survival. (BPT, 2020).

In addition to the decreased availability of acorns, the Bishop Paiute Tribe and other Eastern Sierra Tribes reported a change in the taste of the flour made with local acorns. With the decrease in water and increase in temperatures in the Eastern Sierra, the Tribe has seen the local vegetation change from water-loving plants to shrubs. As these plants change, the animals that rely on them must necessarily change too (BPT, 2020).

Bishop Paiute's ecosystems have suffered from water deficits during years of low precipitation, exacerbated by the anthropogenic drought caused by pumping of the Owens Valley groundwater for use in Los Angeles. The entire region experienced a 6-year drought (1987–92), during which annual precipitation was below the 50-year median of 7.12 inches (USGS, 1998). Elmore et al. conducted a 16-year study which documented an increase in the depth to the groundwater table—associated with increased groundwater pumping—and analyzed changes in vegetative cover. The study found plant cover to be correlated with groundwater depth, indicating that pumping exacerbates drought impacts to vegetation in the Owens Valley (Elmore et al., 2006).

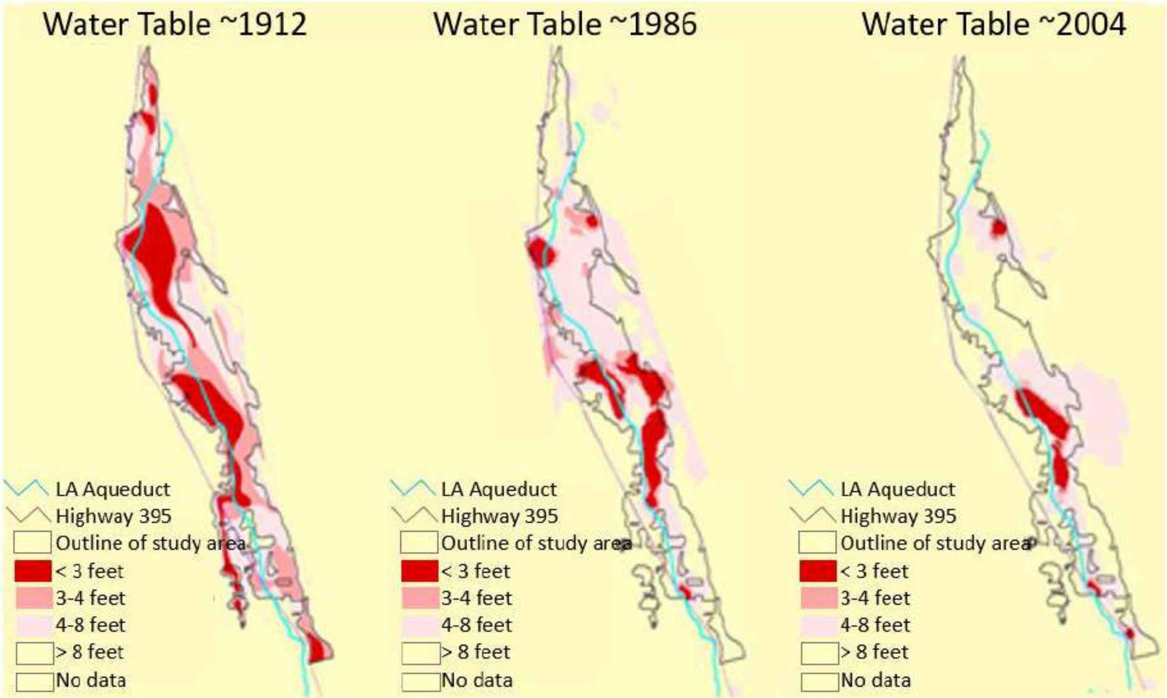
As the Owens Valley climate continues to change, becoming warmer and dryer, the Valley meadows are disappearing, and the Tribe is seeing a desertification of the area. The Tribe knows that with sufficient water in the area, the meadows and grasses would thrive again (Bengochia, 2021). As shown in Figures 10 and 11, reductions in meadow vegetative cover have occurred with dropping water table levels. In 1912 a former United States Geological Survey (USGS) hydraulic engineer created maps showing ground water depths and vegetation types (Lee, 1912). Digitized versions of these maps are used here to compare ground water and meadow ecosystems. The maps in Figure 10 allow a comparison of the area occupied by meadows in 1912, 1986, and 2004. The 1912 map shows the baseline of the grasslands. The 1986 and 2004 maps, based on monitoring by LADWP, show substantial grassland loss with the area known as Blackrock 94 (see photograph, Figure 12) highlighted in pink. Figure 11 shows the water table levels in the same area. Due to groundwater pumping, water tables have gotten deeper and areas with shallow groundwater (less than 3 feet) have decreased substantially. The lack of groundwater corresponds to the lack of meadow in the same area.

Figure 10. Maps showing areas occupied by meadows (shown in green) in the Owens Valley in 1912, and reductions in 1986 and 2004. Blackrock 94 is highlighted in pink.



Source: Manning, 2012; digitized maps from Lee, 1912

Figure 11. Maps showing depth of water table in the Owens Valley



Source: Manning, 2012; digitized maps from Lee, 1912

The photographs in Figure 12 show the Blackrock 94 area in June of 1988 (top) and June of 2007 (bottom). In 1988 the area had 33% vegetation coverage, dominated by green grass with 4% shrubs. By 2007 vegetation coverage was reduced to 15% in the same area, consisting of ~11% shrubs and ~3% grass.

Maps more recent than 2004 showing data that can be compared to Figures 10 and 11 are not currently available. This is partly due to changes in the methods of data collection. It is noteworthy to mention that some groundwater data recently collected from County of Inyo Water Department suggests that comparing years 2021 and 2022 the average basin groundwater table was reduced by an average of approximately two (2) feet

Figure 12. Comparison of Blackrock 94 area June 1988 (top image) and 2007 (bottom)

Source: Manning, 2021

(ICWD, 2021b). The Owens Valley is a closed basin that has been drained over the past 100 years and the continuation of pumping is leading to a reduction of vegetation diversity including culturally important plants in the Payahuunadü.

Though it is generally rare in California, alkali meadow is a major vegetation type in Owens Valley, and on the Bishop Paiute Reservation. The Owens Valley has 67% of the alkali meadow in California. In the 1980s, LADWP biologists mapped at least 70,000 acres of Valley floor as dominated by California native grasses, supported by Owens Valley's naturally shallow groundwater (Davis *et al,* 1998). These meadows are home to species of cultural importance and conservation concern, both plants such as the Owens Valley checkerbloom and the Inyo County star tulip, and animals such as Owens Valley vole, northern harrier and red shouldered hawk (Elmore *et al,* 2006).

Meadows are a biodiverse habitat that sustain common as well as rare species. Owens Valley meadows are dominated by one or both native perennial grass species: saltgrass (*Distichlis spicata*) and alkali sacaton (*Sporobolus airoides*). Both are hardy species, with roots growing to approximately 2 meters. Other common grasses in meadows include Beardless wildrye (*Leymus triticoides*), Baltic rush (*Juncus balticus*), scratchgrass (*Muhlenbergia asperifolia*), basin wildrye (*Leymus cinereus*), and, to a lesser extent, alkali cordgrass (*Spartina gracilis*). Irises, lilies, and broad-leaved herbaceous plants intermingle with the grasses.

Other meadow species include:

- Alkali mallow (*Malvella leprosa*)
- Fish Slough milk vetch (*Astragalus lentiginosus ssp. Piscinensis*)
- Hall's meadow hawksbeard (*Crepis runcinata ssp. Hallii*)
- Inyo County star-tulip (*Calochortus excavatus*)
- Nevada blue-eyed grass (*Sisyrinchium halophilum*)
- Owens Valley checkerbloom (*Sidalcea covillei*)
- Saltmarsh bird's-beak (*Cordylanthus maritimus* Nutt. ex Benth.)
- Stinkweed (*Cleomella*)
- Wild licorice (*Glycyrrhiza lepidota Pursh*)
- Yerba mansa (*Anemopsis californica*)

Native shrubs include:

- Rabbitbrush (*Chrysothamnus nauseosus*)
- Nevada saltbush (*Atriplex lentiformis ssp. torreyi*)
- Greasewood (*Sarcobatus vermiculatus*)
- Sagebrush (*Artemisia tridentata*)

Of these species, the annual species *Malvella*, *Cleomella*, *Cordylanthus* are less tolerant of changes to water and are more likely to be lost as meadows are deprived of water. The Tribe has translocated many of these species to the COSA to attempt to preserve them.

Wetlands provide some of the richest habitat on the Bishop Reservation, supporting many species of plants and animals. There are approximately 25 acres of federally designated wetlands located in the eastern section of the Reservation (BPT, 2021b). One observable way the area has changed in the last 20 years is that much of the alkali meadow portion of the wetlands has been invaded by perennial pepperweed (*Lepidium latifolium*). This plant, not native to Owens Valley, has proved extraordinarily difficult to control. It propagates by seed and has very deep roots (BPT, 2021b).

The Bishop Paiute Tribe has long been attuned to seasonal variations related to planting and stewardship of plants. Jen Schlaich, Food Sovereignty Program Specialist for the Tribe, reported “Several Elders have noted changes in harvest times for traditional foods. Community members have also mentioned changes in seasons such as out of the ordinary weather patterns, warmer fall weather and colder spring weather” (Kapp, 2019).

In addition to the overall decline in the quality and abundance of native vegetation due to climate changes, the Bishop Paiute have seen a decrease in culturally important food species such as “wai” (Indian Ricegrass), tule, acorn and pine nut (BPT, 2020).

Impacts to Wildlife

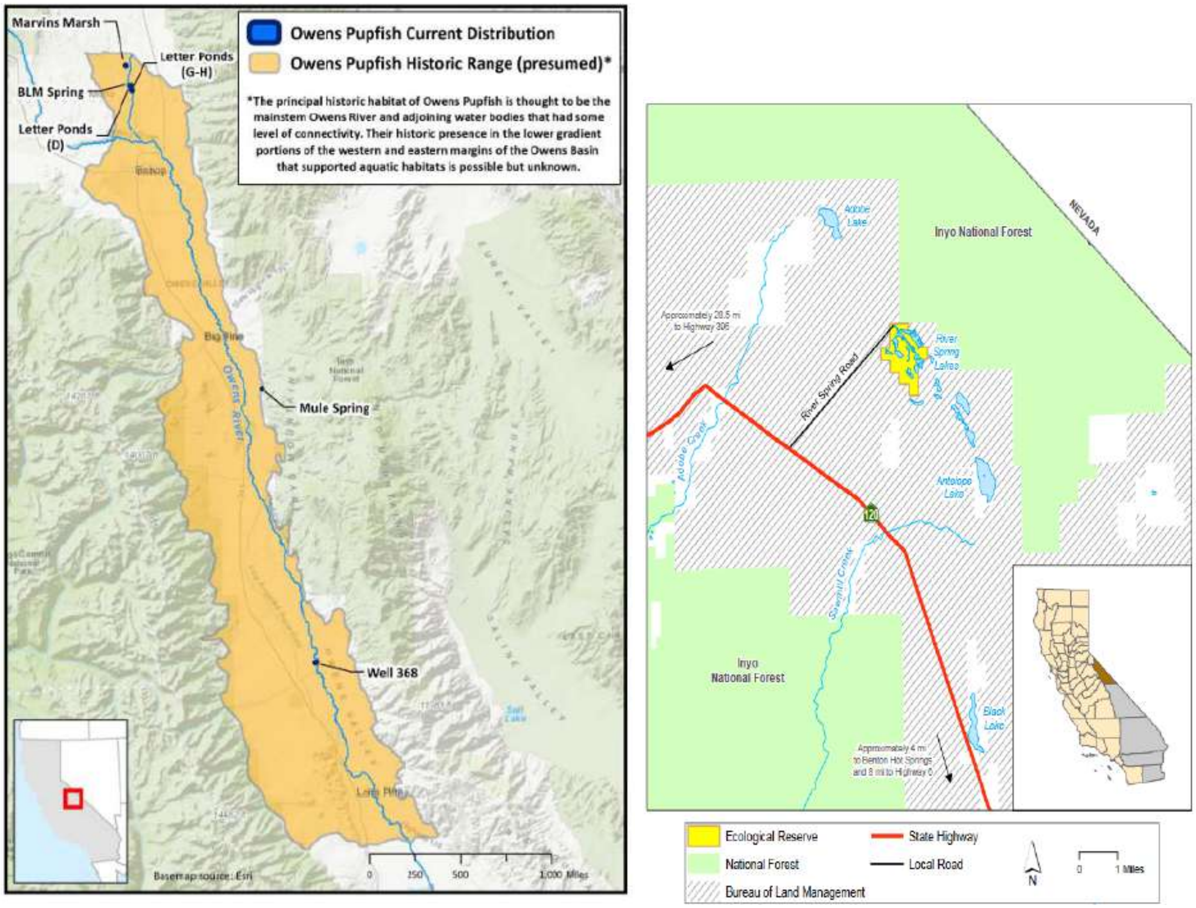
Impacts from climate change threaten the Bishop Paiute’s access to traditional foods such as fish, game, and wild and cultivated crops. These resources have provided sustenance as well as cultural, economic, and community health for generations.

Figure 13. Owens Valley pupfish

Source: UCD, 2021
Phot credit: Joe Ferreira

The Bishop Paiute have cared for and been nourished by desert fish including the Owens pupfish (Figure 13) since time immemorial. The Owens pupfish (named for its playful nature) is a 2.0 inch long, silver-gray fish that turns a bright, florescent blue during spawning season. Historically, the pupfish was a staple food item for the Paiute people in the Owens Valley, who caught the fish by the hundreds and dried and stored them. The Tribe continues to try to protect and care for these threatened fish but as their habitat shrinks due to climate change, land use practices, and extensive water development, they are now limited to the small areas shown in Figure 14 below (CDFW, 2020a) and a newly designated area called the River Springs Lake Ecological Reserve (CDFW, 2021).

Figure 14. Maps of historic range and current distribution of Owens pupfish in Mono and Inyo counties (left), and of River Spring Lakes Ecological Reserve (right)



Source: CDFW, 2021

Shell mounds of freshwater mussels (*Anodonta nuttalliana*) and surveys on the Bishop Paiute lands including the creeks and Owens Lake indicate the historic use of mussels as a food source. Mussels are no longer found in Owens Lake because it is dry, but they have been found in the Bishop Creek canal, which diverts water from the Owens River for use by LADWP, as recently as 2014 (Blevins et al., 2017), (CDFG, 2015). Freshwater mussels have also been seen in LADWP dredge piles (Klingler, 2021), but due to reduced numbers they are no longer used as a source of food for the Paiute people (Bengochia, 2021).

Figure 15. Freshwater mussels in a canal dredge pile. The different sizes/ages classes indicate they were reproducing in the recent past.

Photo credit: Ceal Klingler

The Owens Tui Chub (*Siphateles bicolor snyderi* or *Gila bicolor snyderi*) is endemic to the Owens Basin, Mono and Inyo Counties. It was a food source for the Bishop Paiute people but is now found in only six sites, including the COSA, all created for the preservation of the species on the Bishop Paiute lands. The COSA Tui Chub are hybridized. The Toikona Tui Chub is the original species and is now only found in isolated conservation areas to prevent hybridization (CDFW, 2020c).

The Owens speckled dace (*Rhinichthys osculus ssp*.) historically occupied most small streams and springs in the Owens Valley. By the 1980's the stream-fed ponds and springs that the Owens speckled dace lived in were depleted or destroyed by the construction of and pumping for the LA aqueducts, and they were extirpated from most of their historic range. The COSA on the Bishop Paiute lands is one of three remaining, isolated habitats left for these culturally important fish (Mussmann, et al. 2020).

The Paiute still hunt both large and small game and have noticed a decline in culturally important species. Rabbits, especially black-tailed jackrabbits and cottontail rabbits, used to be plentiful in the area. The Tribe has seen a decline in both species. As the area has suffered from drought and desertification, food on which the rabbits depend has become less available (Bengochia, 2021).

Mule deer is a culturally important species for the Bishop Paiute Tribe. Mule deer are in decline across the west, their migration patterns and food availability impacted by drought and other aspects of climate change (Aikens et al., 2020). In 2017, 120 mule deer that were migrating to their winter grounds in the Valley ran into persistent snow and ice sheets, not normally found in the area, and slid to their deaths. This type of event has only happened twice before that the Tribe knows of and never on this scale (Brown-Williams, 2017).

In 2020 the Bishop Paiute Tribe entered into an agreement with the California Department of Fish and Wildlife allowing the Tribe to take 16 deer for cultural education purposes. This agreement was the first of its kind and it recognizes the Tribe's authority to protect wildlife resources (CDFW, 2020b).

Some of the other impacts to wildlife the Tribe is experiencing include:

- Declining numbers of native fish such as Owens pupfish, Owens tui chub, Owens speckled dace, Owens sucker and tui kona tui chub
- Increasing stream temperatures
- Increasing bacteria levels (E. coli, cyanobacteria) in surface waters on the Reservation and associated adverse effects on local wildlife
- Decrease in bird species such as yellow-headed black bird, red-winged black bird, eagles, and swallows
- Decline in numbers of bats

The Tribe has also observed increases in non-native species that have the potential to take the place of native species as the climate of the Owens Valley warms and dries, such as:

- Barred Owl
- Black Witch moth (native to Mexico)
- Bullfrogs and mud snails
- Rainbow trout, largemouth bass, catfish, and perch

The Bishop Paiute lands provide habitat for many threatened or endangered species such as Western Meadowlark (*Sturnella neglecta*), Owens Valley vole (*Microtus californicus ssp. vallicola*), a myriad of insects and spiders, and many other animals. The Northern Harrier (*Circus cyaneus*) and Red Shouldered Hawk (*Buteo lineatus*) are year-round residents, breeding in Owens Valley and foraging in meadows. As discussed earlier, the meadows that these species rely upon are threatened by climate change impacts that continue to lower the water table (Manning, 1997).

Wildfire

The incidence of large forest fires in the western United States has increased since the early 1980s (Wehner et al., 2018). Fire season in California is starting earlier and ending later each year (CAL FIRE 2021). Since 2007 there have been 10 fires over 100 acres in size that have impacted the Bishop Paiute. The Reservation is in an area designated as a High Fire Severity zone (BPT, 2018).

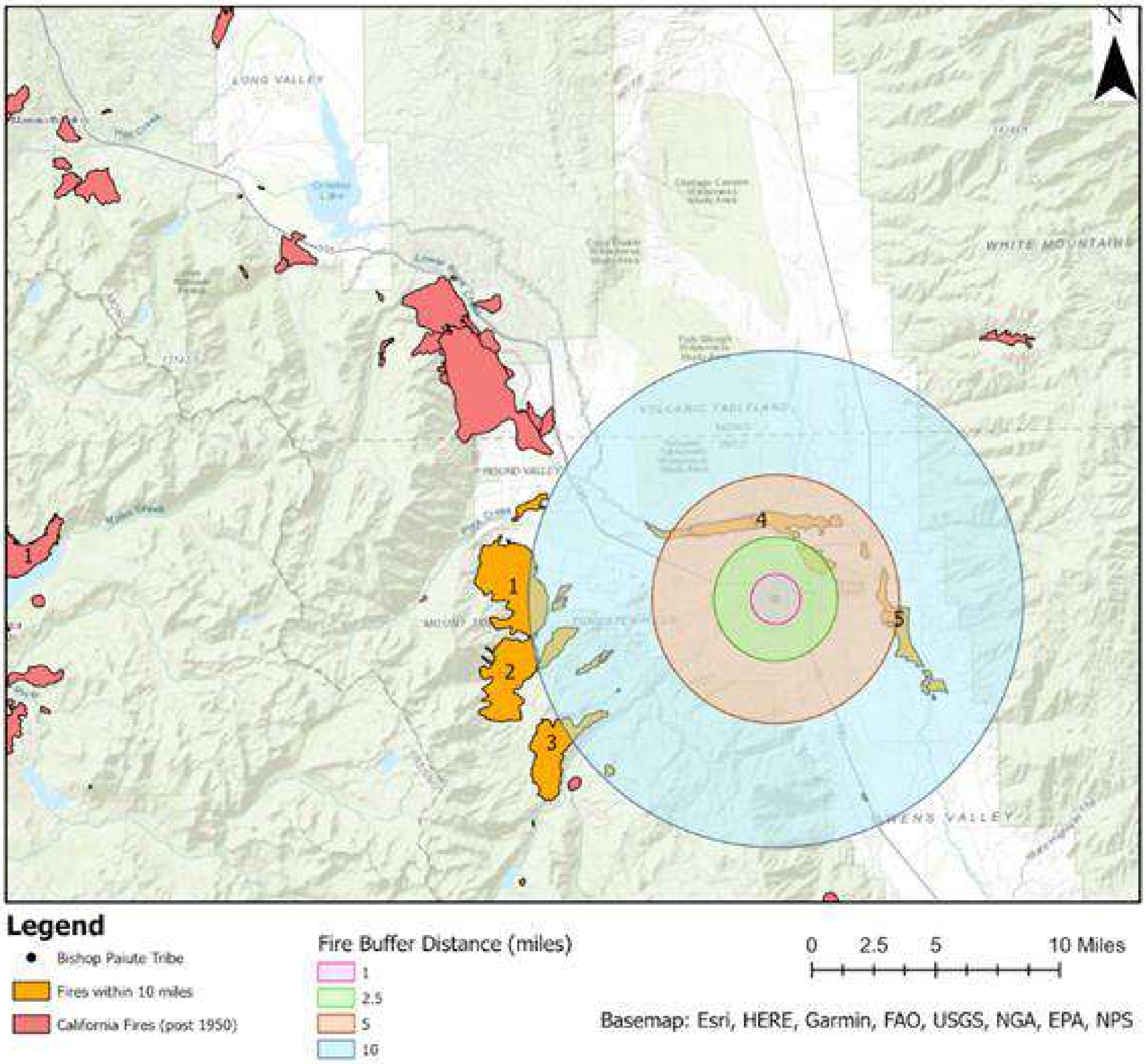
Table 1. Wildfires Impacting the Bishop Paiute Tribe 2007-2020

Year	Fire	Acres
2007	Inyo Complex (#1)	35,000
2009	Fort Fire (#4)	5,000
2009	Forks Fire	3,268
2011	Center Fire	850
2014	Bridges Fire	113
2015	Round Fire (#3)	7,000
2018	Pleasant Fire	2,070
2019	Cow Fire	1,975
2019	Taboose Fire (#2)	10,400
2020	Beach Fire (#5)	4,000

Source: CAL FIRE, 2021

The map in Figure 16 shows fires within 10 miles of the current Bishop Tribal lands that occurred between 1950 and 2020; the five largest fires are numbered. While the Reservation itself has not been burned by large wildfires, there have been impacts to the soils, riparian habitat, air, and water quality (BPT, 2018). Fires increase soil erosion, particularly in denuded watersheds. Wildland fires that eliminate forest areas affect soils, watershed value and habitat. Fires that burn hot and destroy most of the vegetation are also destructive to aquatic habitats.

Figure 16. Fires Impacting the Bishop Paiute Tribe 1950-2021



Source: CAL FIRE, 2021

Years of drought, declining snowpack, over pumping of groundwater, and increasing temperatures, combined with more than a century of fire suppression and attendant changes in forest composition, have significantly increased fire severity, frequency, and size throughout the Eastern Sierra (Dettinger et al., 2018). The Tribe has noted that a build-up of dead trees in the National Forest area at Indiana Summit and the increase of weeds, shrubs, and other flashy fuels have increased the fire danger for the Tribe (BPT, 2020).

During the 2019 fire season, the overlap of smoke from fires such as the Taboose Fire shown in Figure 17, and dust from windstorms caused a build-up of respirable particulate matter (less than 10 micrometers in diameter; PM10) that was documented by the Bishop Air Quality Monitoring Program (BPT, 2020). In 2021 there were 12 wildfires ranging in size from the 25-acre Pine Fire to the 963,306-acre Dixie fire that caused wildfire smoke exposure to the Tribe (BPT, 2021c).

Short-term exposures to PM10 have been associated primarily with worsening of respiratory diseases, including asthma and chronic obstructive pulmonary disease, leading to hospitalization and emergency department visits (CARB, 2021).

Figure 17. The Taboose Fire, 2019

Source: NWCG, 2019

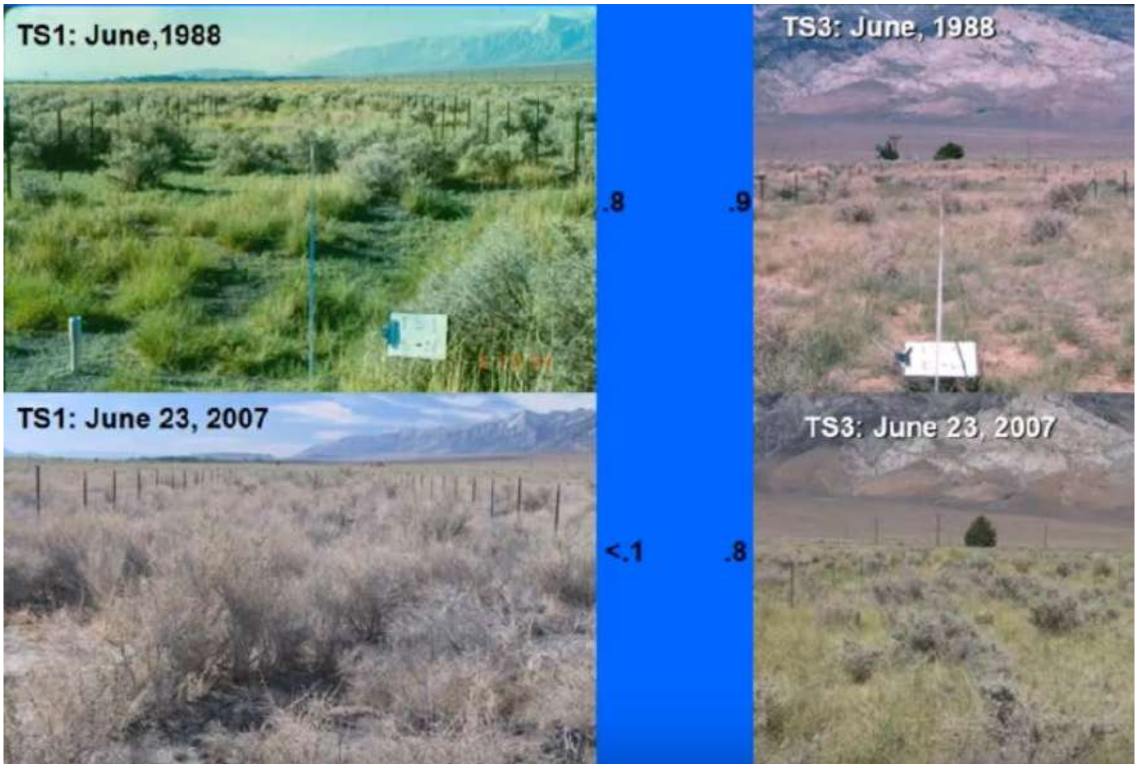
Many mountain meadows below the elevation of 7,500 feet, including the meadows of the Eastern Sierra, are not truly natural but were influenced for millennia by Tribal burning practices. Native people altered the size and composition of meadows through periodic burning. Setting fires in the areas surrounding the meadows discouraged the encroachment of more wet-tolerant vegetation. Periodic burning within the meadow boundaries influenced the species composition, density, and abundance of native plant populations. Certain meadow plants such as deergrass, yampahs (a genus of wild carrot) and clovers were favored and maintained through burning (Anderson, 2005).

Historically, the Paiute conducted cultural burns on their lands. Controlled burns are no longer practiced by the Bishop Paiute. The population of the Bishop area has grown over time and federal land agencies control much of the lands the Tribe used to steward. On the Reservation the reduction of agricultural lands and densification of single-family homes (2000 members live on just 879 acres) have created a matrix of fuels that are unsafe to control with prescribed burns (BPTEO, 2021).

Burning was also used to increase foods such as wild onions and elderberries, and to clear out the underbrush to bring in new growth for the animals. The Owens Valley Indians also grew tobacco and burned the fields where the tobacco grew (Padilla, 2004).

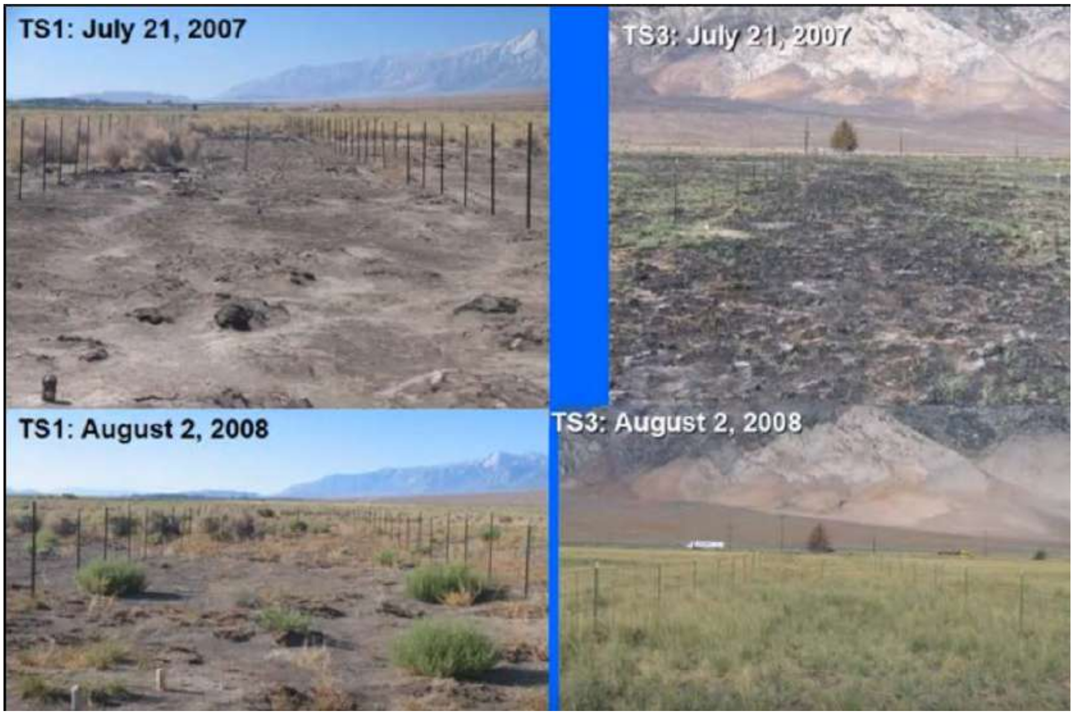
As non-native vegetation dominates, the Valley is less resistant to fire. The roots of meadow grasses have evolved to tap into the historically shallow (8 feet) ground water of the area, while the roots of the encroaching shrubs can burrow deeper for water. In early July 2007, the Inyo Complex fire burned over 35,000 acres including a vegetation study area. Figure 18 shows two sites in the study area (TS1 and TS3) in 1988, when the grass-to-shrub ratios were similar in both locations (0.8 in TS1 and 0.9 in TS3). By 2007 site TS1 had been over pumped, and this anthropogenic climate change impact had promoted the growth of shrubs such as tumbleweed, resulting in a grass-to-shrub ratio of less than 0.1. In site TS3, an area that had been better managed and allowed more water, native grasses were nearly as abundant as they were in 1988. The top photos of Figure 19 below shows both the TS1 and TS3 areas soon after the Inyo Complex burned through the area. A year later (bottom photos) area TS1, which had been populated by non-native shrubs, still looked barren while area TS3, populated by native grasses, had nearly recovered.

Figure 18. Study areas TS1 and TS3 pre fire. The numbers shown in the middle panel next to each photo are the grass-to-shrub ratios: for TS1, 0.8 in 1988, <0.1 in 2007; for TS3, 0.9 in 1988, 0.8 in 2007.



Source: Pritchett and Manning, 2009

Figure 19. Areas TS1 and TS3 after the Inyo Complex Fire



Source: Pritchett and Manning, 2009

Summary

Climate change is impacting the culture, lives, environment, and health of the Bishop Paiute Tribe. These changes are compounded by LADWP's diversion of water from the Payahuunadü.

The Bishop Paiute people continue to work to protect and enhance the natural resources and habitat of the Owens Valley. Because climate change is deeply affecting the environment and altering and disrupting the ecosystems within and around the Owens Valley, the Bishop Paiute community is actively working to understand, adapt to, and mitigate the effects of climate change and other impacts to their lands. Their goal is to continue to manage and protect their traditional lands and limit the impact climate change is having on the Bishop Paiute people's right to hunt, fish, and gather from their land—something that is integral to their culture, well-being and livelihood.

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IMPACTS OF CLIMATE CHANGE ON THE KARUK TRIBE

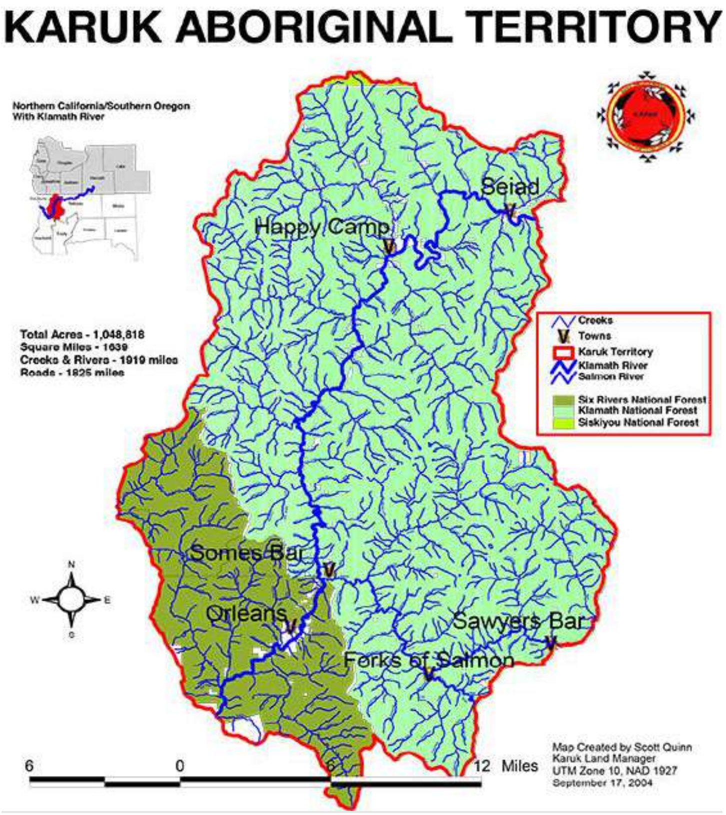
Self-described as "fix the world people," the Karuk Tribe has relied on fire and ceremony to manage their lands since time immemorial. The threats of climate change, acting alongside non-climate factors, are an opportunity for the Tribe to return to traditional management, which includes the use of 22 key cultural indicator species to gauge ecosystem health and to guide appropriate action.

Background

The Karuk Tribe is a federally recognized Tribe comprised of Karuk araráhih (upriver people) located along the Klamath River in the northwestern corner of the state, in Humboldt and Siskiyou Counties. The Karuk Tribe is one of the largest tribes in California with 3,744 members and 5,271 descendants (Karuk Tribe Enrollment Department).

Since time immemorial, the Karuk have lived in the Klamath-Siskiyou Mountains in the mid-Klamath River region of northern California (Figure 1). With an Aboriginal Territory that includes over a million acres, the ancestral Karuk people resided in more than one hundred villages along the Klamath and Salmon Rivers and tributaries. Thriving with a subsistence economy supported by rich natural endowments and a strong culture-based commitment to land stewardship, Karuk environmental management has shaped the region's ecological conditions for millennia. Through carefully observing natural processes, the Karuk have developed traditional management regimes based on a landscape-level ecosystem approach. Self-described as "fix the world people," the Karuk continue ceremonies that restore balance and renew the world.

Figure 1. Map of Karuk Aboriginal Territory



Source: Karuk Tribe
Climate Vulnerability Assessment, 2016

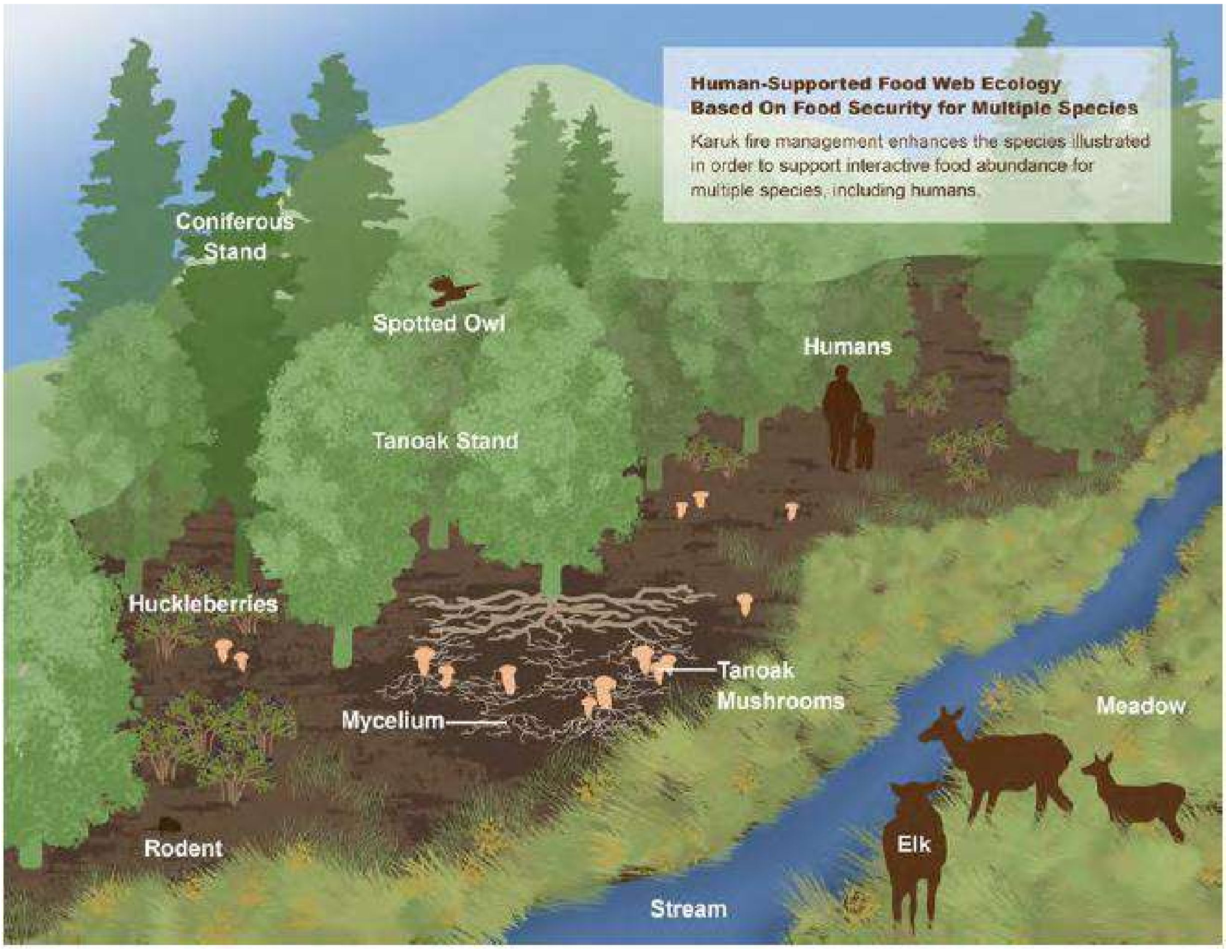
The Karuk People have historically been wealthy from tending of the land. Traditional ecological knowledge provides the Karuk with foods—including acorns, salmon and deer—and fibers such as hazel, willow, and bear grass which they use as materials for their well-known basket-weaving skills. Medicinal plants were also abundant. This rich and diverse cultural landscape was made possible through the use of fire and ceremony.

The mid-Klamath ecosystem has co-evolved with the Karuk people and culture over millennia. Multiple species of importance to the Karuk people play vital roles as cultural indicators for appropriate human actions within the Tribe's system of traditional management. For countless generations, Karuk people have observed the behavior of particular plants and animals to understand ecological dynamics, and have used this as a guide for necessary human management. The return of particular migrating birds signals the timing of the eel run, the appearance of Pleiades in the night sky denotes the time for cultural burning, while the behavior of other species warns of danger. This knowledge gained from attending to the land over generations is inscribed in ceremonies and prayers.

Karuk culture is directly reliant on fire as a tool to manage the environment for cultural sustenance and well-being. Karuk fire management practices include burning at a specific season, frequency, and intensity at a variety of severities. This frequent, low-intensity fire is linked with various fire-adapted vegetation communities and is necessary for the maintenance of cultural resources. Fire is especially critical for restoring grasslands for elk, managing food sources including tanoak and black oak acorns, maintaining quality basketry materials, producing smoke that shades the river for fish, and more. While fire can be incredibly dangerous, it is an inevitable part of natural ecosystems, especially in lightning-prone forested areas such as the mid-Klamath. Forested areas in northern California have become adapted to the frequent occurrence of relatively low intensity fire from human and natural ignitions for more than the past 1,000 years. Karuk's use of fire has been central to the evolution of the flora and fauna of the mid-Klamath (see Figure 2).

Gold mining started on the Klamath and Salmon Rivers around 1850, ushering in Settler Colonialism for the region and its devastating effects to the people and land. The Karuk People have always resisted Settler Colonialism, whether through armed rebellion as with the 1855 Red Cap War, legal action and protests such as the G-O Road Struggle and the Un-Dam the Klamath Campaign. The longstanding human-ecological relationships and practices have been interrupted by European settlement and its consequences: attempted genocide, displacement, resource extraction and the imposition of non-Native land management policies and ways of understanding the world. The policy of fire suppression has been especially significant. While these interruptions have been substantial and have taken place over an extended period of time, cultural and ecological information is retained today in ceremonies, stories, collective memory and the land itself.

Figure 2. Karuk Cultural Burning Produces Species Abundance



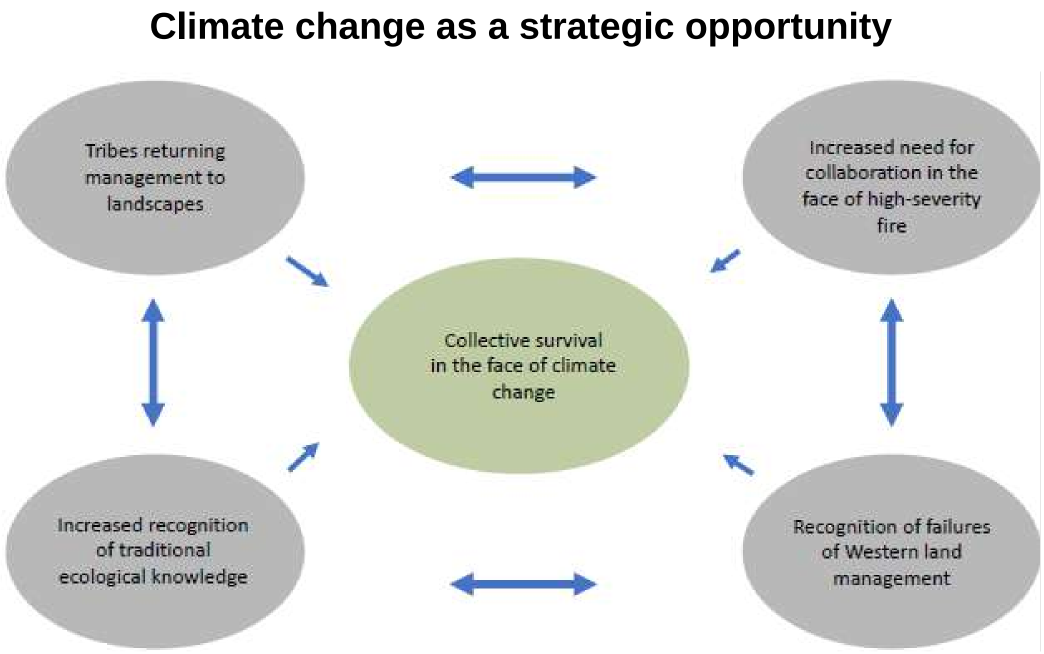
Source: Karuk Climate Adaptation Plan, 2019
(Credit: Figure courtesy of Kirsten Vinyeta)

Karuk Tribe and Climate Change

Within Karuk aboriginal territory, the effects of climate change are immediate and occurring now. Climate change poses a threat not only to the Klamath ecosystem, but also to Karuk culture, which is intimately intertwined with the presence, use and management of cultural use species. The Karuk are fortunate to retain relationships with hundreds of species they consider their relations: foods, medicines and fibers that are embedded within cultural, social, spiritual, economic and political systems, and daily life. Impacts to such culturally significant species in the face of climate change thus have more direct impacts on the Karuk people than on communities that do not have such intimate connections in the natural world. Part of the increased vulnerabilities Karuk people face as the climate changes are a direct result of the strength of these connections. For example, the loss of acorn groves that have been family gathering sites for generations is much more than an economic impact. In addition, the social justice challenges that have impacted the Tribe since European influx are ubiquitous today in the form of low economic opportunity and restricted access to traditional cultural resources, employment, schools, food sources, medical facilities, and emergency evacuation routes in this remote area.

Climate change is viewed by the Karuk as the product of unsustainable Western land management practices and the rise of political and economic systems for which indigenous people hold little to no responsibility. The impacts of the changing climate interact with existing ecological stressors such as water diversions and fire suppression.

Figure 3. Diagram illustrating how Tribes can lead efforts toward collectively addressing climate change



Source: Karuk Climate Adaptation Plan, 2019
(Credit: Sara Worl)

Nevertheless, the crisis posed by climate change presents a strategic opportunity for tribes to retain cultural practices and return traditional management practices to the landscape, and for all land managers to remedy inappropriate ecological actions. There is increasing recognition of the importance of indigenous burning as an ecosystem component and restoration technique. Traditional ecological knowledge, the need for collaboration in addressing high severity wildfire, and a recognition of the failures of Western land management, have combined to create an exciting political moment in which tribes are uniquely positioned to lead the way toward collective survival in the face of climate change (see Figure 3). In the mid-Klamath region specifically, many goals in the Forest Service’s own management plan can be best achieved through restoring Karuk tribal management.

The Karuk people have long been part of the ecosystem. Adapting to climate change is about restoring human responsibilities and appropriate relationships with species and ecosystem processes. Karuk tribal knowledge regarding the use of fire can be utilized to manage cultural resources, promote biodiversity, and mitigate catastrophic wildfires, thereby protecting public as well as tribal trust resources. The Karuk Tribe's work on restoring traditional fire regimes holds the potential to inform both climate adaptation and mitigation efforts, given that wildfires themselves generate carbon emissions, and a reduction in high severity fires could result in a reduction in forest emissions.

The Tribe's adaptation approach to climate change centers around the revitalization of Karuk cultural management, the restoration of traditional fire regimes, the reduction of impacts from intervening factors, the expansion of Karuk tribal management authority and capacity, community engagement and public education, increased interjurisdictional coordination, and expanded research and monitoring. Utilizing Karuk Traditional Ecological Knowledge alongside western science, climate adaptation will center on the revitalization of 22 focal species as cultural indicators for human responsibilities and necessary human management actions. "These species have stories to tell, lessons in terms of how to get back to traditional management. They serve as indicators of relationships, responsibilities and of when and where to burn" (Bill Tripp, Deputy Director of Eco-Cultural Revitalization).

Climate Change and Its Impacts

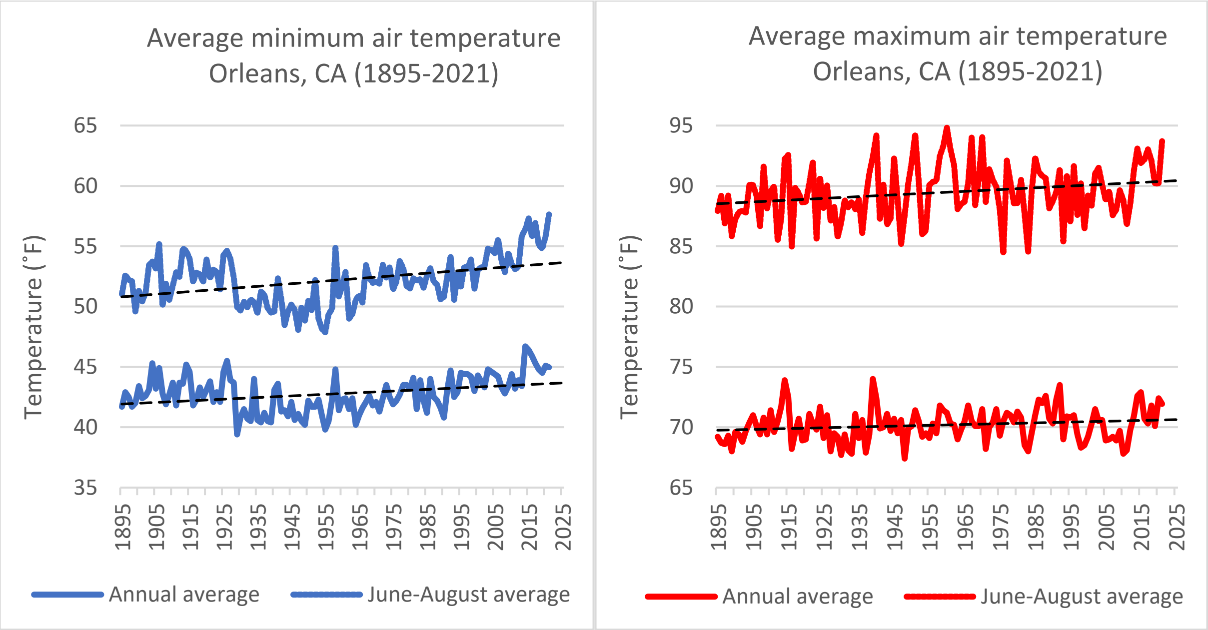
Trends in the Pacific Northwest Region of the United States include rising air temperatures, changing patterns of precipitation, and associated changes in snowpack, soil moisture, length of growing season, fire behavior and more. Similarly, the mid-Klamath region of California has experienced warming, changes in precipitation patterns, increased droughts, increased frequency and severity of wildfires, and disease and pest outbreaks in forests. Observed changes and impacts are summarized below. Unless otherwise stated, the Karuk Climate Adaptation Plan is the basis for the information presented (Karuk Tribe, 2019).

Changing Temperature Patterns

Air temperatures have been increasing in California over the past century (see Air Temperature indicator). Common measures of air temperature include annual average air temperatures, nighttime summer and winter minimum temperatures, number of days per year that exceed 86 degrees Fahrenheit, number of frost-free days (a measure of the length of growing seasons), and measures of extreme heat events. Both across California and in the North Coast region specifically, these temperature increases have been greatest in the summer months. Minimum nighttime temperatures have been increasing faster than either maximum daytime highs or average temperatures. Not only are there overall increases in air temperatures across these measures, but more variable temperature patterns are observed. Future projections in temperature-related metrics are presented in the Adaptation Plan.

Temperature data for Orleans, California are presented in Figure 4. Warming trends are evident. Notably, minimum temperatures, which occur at night, have risen at more than twice the rate of maximum temperatures. Temperatures during the warmer months rose at a faster rate compared to yearly rates: maximum temperatures for the months June through August warmed almost 2.2 times faster than maximum temperatures averaged over the year, and minimum temperatures for June through August warmed more than 1.6 times faster (PRISM 2021).

Figure 4. Average Temperatures at Orleans, CA.


Average minimum air temperature Orleans, CA (1895-2021)

Average maximum air temperature Orleans, CA (1895-2021)

Source: PRISM, 2022

The Adaptation Plan reported the total number of days above 86°F as 49.8 days for 1971-2000, and the number of days without freezing temperatures as 282.5 days. For the period between 1991 and 2020, these have increased to an average of 99 days/year above 86°F and 340 days/year above freezing (32°F) (PRISM, 2021).

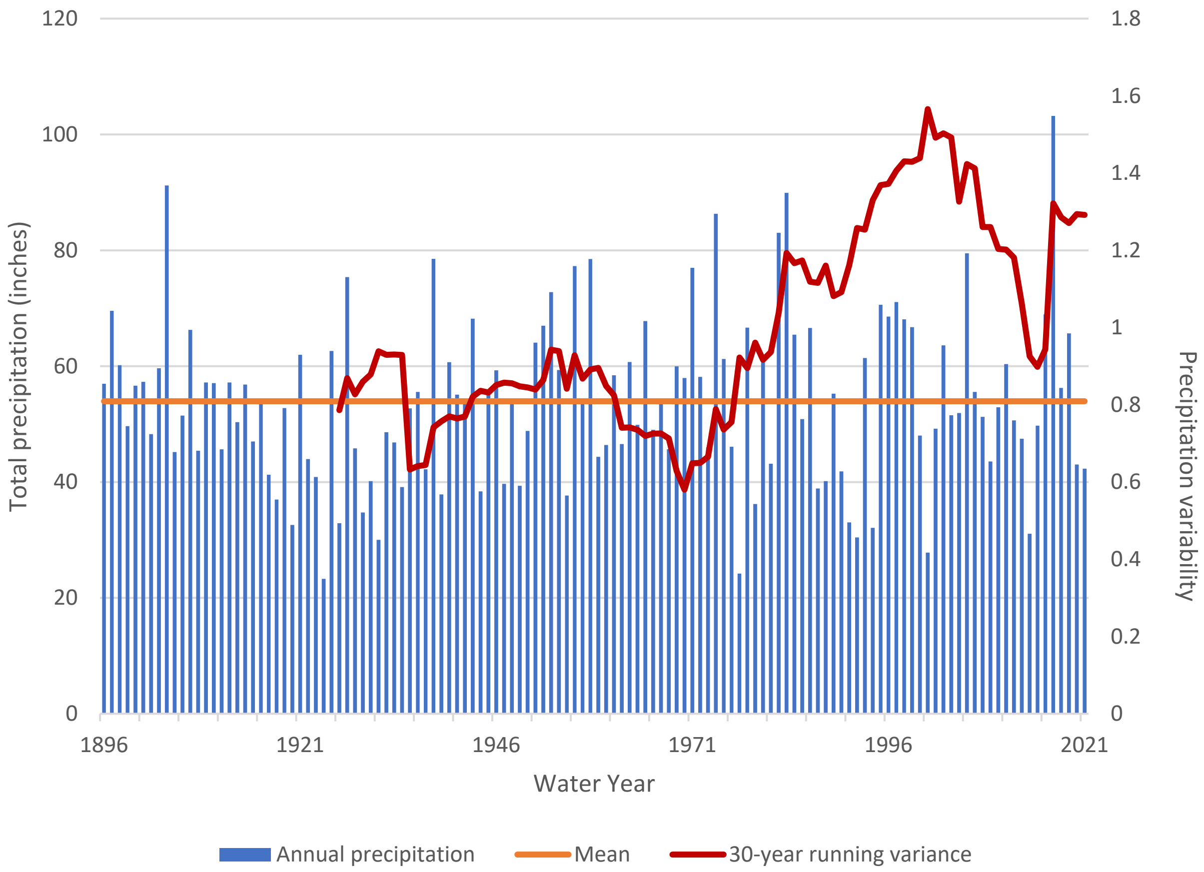
Warmer temperatures have been associated with changes in hydrology, including decreased snowpack (particularly at low elevation sites), earlier snow melt and spring runoff, decline in total runoff occurring in the spring, rising river and stream temperatures, and increased variability in streamflow. These changes have occurred in conjunction with changing precipitation patterns, discussed in the next section.

In addition, warmer temperatures may increase the spread of tree diseases (such as sudden oak death) and pest infestations (such as bark beetles); delay autumn migrations of certain species such as black-tailed deer; increase fire risk as vegetation dries with reduced soil moisture and increased evapo-transpiration. Rising temperatures also pose health concerns, including heat stress and heat-related deaths, respiratory effects from increased pollution and pollen, and from food and water contamination, particularly from toxic algae.

Changing precipitation patterns and drought

Precipitation patterns are changing in the Klamath basin and across the Pacific Northwest. Key measures of precipitation include total annual precipitation, timing of winter and summer precipitation, and the total amount of precipitation in individual storm events. Annual precipitation measured by water year in Orleans, California, is presented in Figure 5. Year-to-year precipitation is highly variable, while showing no trend in the annual amount over time.

Figure 5. Annual precipitation at Orleans, CA

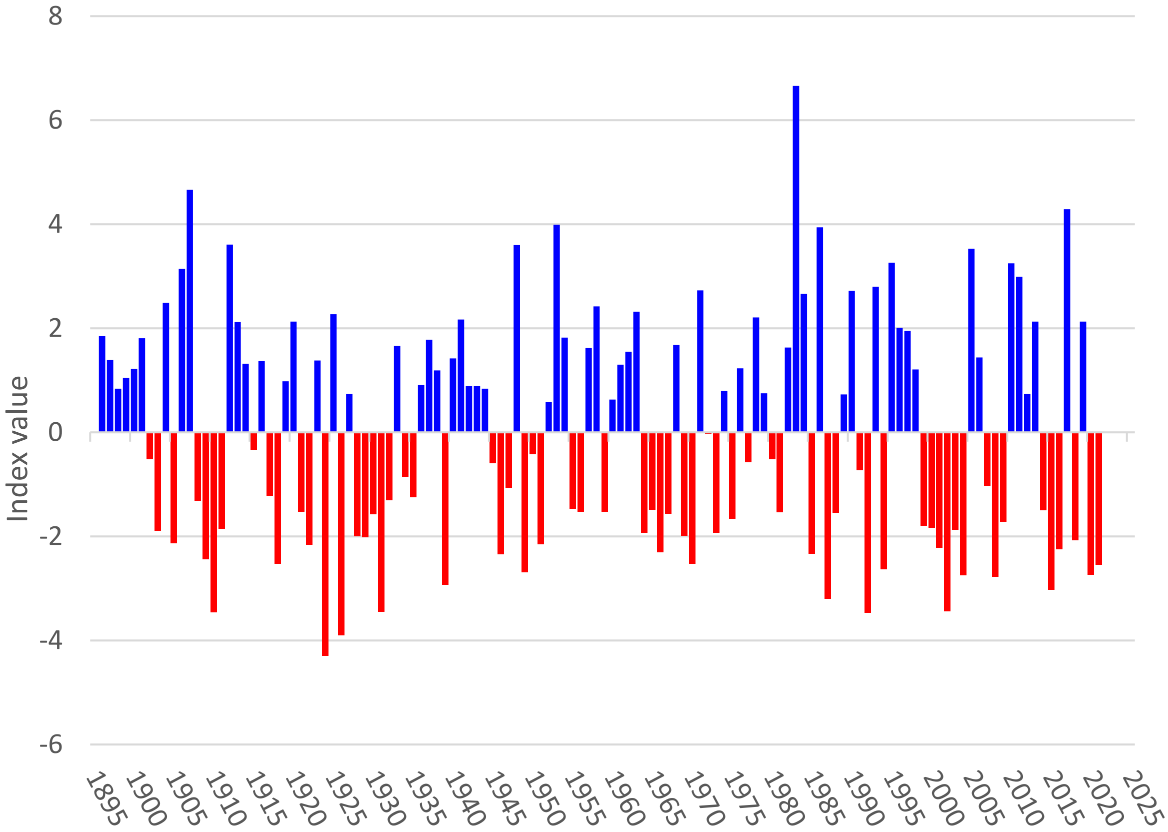


Source: PRISM, 2022

Warmer winter temperatures result in more precipitation falling as rain instead of snow. For the North Coast as a whole, the average spatial extent of snow on April 1st has declined from 60 to 50 percent at elevations above 3,000 feet between 1951-1980 and 1981-2010, with the greatest loss of snow occurring in the Klamath-Siskiyou Mountains. In Karuk Aboriginal Territory, the average snow water equivalent (a measure of snowpack) on April 1st between 1971-2000 was 10.3 inches. This is predicted to decline significantly by the end of the century.

Figure 6 presents a commonly used metric to track drought, the Palmer Drought Severity Index. The index reflects relative dryness based on readily available temperature, precipitation and soil water content data. Positive values (blue bars) denote wet years; negative values (red bars), dry years. Values below -3 represent severe to extreme drought. Twelve of the last twenty years were dry, with two severely dry years in 2002 and 2015.

Figure 6. The Palmer-Drought Severity Index showing drought patterns at Orleans, CA (1895-2021)



Source: WRCC, 2022

Changing patterns of precipitation, along with warming, translate into decreasing flows and increasing stream temperatures. Prolonged drought will generally reduce stream flows, and may cause permanent streams to become intermittent. Flows in the Salmon and Klamath Rivers are projected to decline, while stream temperatures are projected to increase, affecting habitat for aquatic species such as salmon. Low summer base flows exacerbate toxic algae bloom conditions, and increase the likelihood of tribal members' exposures to the toxin microcystin through contact with contaminated water or consumption of food and water.

Less precipitation – particularly in the form of snowpack – can lead to vegetative stress, for example weakening sugar pine. Drought will lead to more severe wildfires and their cascading impacts on habitats in the region. There is concern that less predictable and reduced precipitation may constrain windows to apply fire.

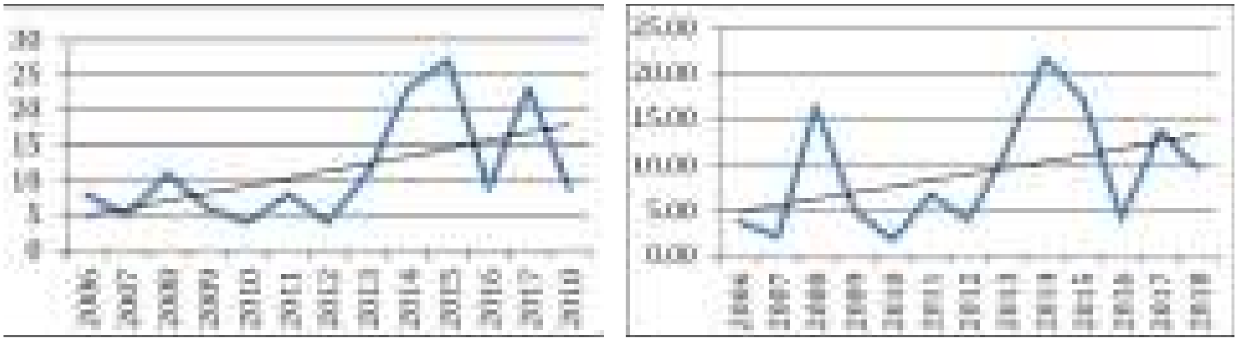
Changing patterns of fire behavior

The Klamath Basin has experienced increasingly frequent, large-scale, intense fires in recent years as a result of both climate change and increased fuel loads resulting from federal land management practices and the cessation of indigenous burning. Invasive species such as scotch broom, star thistle, Himalayan blackberry, non-native grasses and many others are well established within Karuk Aboriginal Territory, adding to the fuel load. Many of these invasive plant species exacerbate fire behavior through the production of long flame lengths.

Changing patterns of fire behavior are among the most pressing of the local dimensions of climate change within Karuk Aboriginal Territory. As shown in Figure 7, the number and length of time of fire weather watches or “red flag warnings” between 2006 and 2018 in the two fire zones that make up the Territory have increased. A Red Flag Warning is issued for weather events which may result in extreme fire behavior that will occur within 24 hours

The increasing frequency of high severity fire threatens individual species, alters the habitat, and disrupts ecosystem dynamics. Fires cause direct mortality to plant and animal species, reducing the availability of food sources; they consume snags and logs used by woodpeckers for nesting, roosting, and foraging. Fires during the flowering and fruiting season may affect harvest and plant reproduction. Trees stressed by fire injury are susceptible to bark beetle and other insect infestations which, in turn, can increase future fire severity.

Figure 7. The [a] number and [b} duration of fire weather watches/warnings, Fire Zones 204 and 280.



[a] Number

[b] Length of Time (days)

Source: Karuk Tribe, 2019

Fire suppression actions have produced adverse impacts. The firefighting tactic of “burning out” along the fire lines creates areas of very high severity fire. Timber fallers often intentionally cut chinquapin and black oaks preemptively because they may have cavities in which fire can smolder; these cavities are important habitat for Pacific fisher. In the immediate aftermath of high severity fires, activities such as salvage logging and associated road building can impact forest stands.

High severity fires in the Klamath region pose immediate health implications during emergency situations, as well as impacts on physical and mental health from smoke exposure. Exposure to smoke is strongly associated with increasing respiratory symptoms which tend to occur during the fires; the deterioration of existing respiratory diseases, hospital admissions, and deaths from respiratory causes impact the Tribal community.

Fires also impact critical tribal infrastructure including the electrical grid, transportation systems, water supply, communication systems, and emergency services.

Impacts on human health and well-being

The Klamath River and its tributaries, forests, grasslands and high country are essential for the cultural, spiritual, economic and physical health of Karuk people. Among the physical health impacts of warming temperatures are: heat stress (many homes do not have air conditioning systems, and those that do are at risk of power outages); increasing rates of asthma and allergies due to increased particulate matter and pollen; and food and water contamination from toxic blue-green algae. Increased residence time of water in the Copco and Iron Gate Reservoirs in the mid-Klamath basin due to drought and low summer flows create ideal growing conditions for the algae (Microcystis aeruginosa) that produces microcystin, a liver toxin. Exposures to the toxin can occur through consuming contaminated water and traditional foods, recreation, bathing or cleansing, and ceremonial activities. The World Renewal Ceremonies in which the medicine man traditionally bathes and drinks Klamath River water overlaps annually with the highest levels of microcystin.

There are serious negative health consequences of smoke inhalation. Large-scale, high severity fires burn much longer than traditional cultural burns, leading to more significant health impacts. In addition to smoke exposures, other potential health concerns include disrupted access to emergency vehicles and to medical care. Poor visibility during periods of thick smoke creates hazardous conditions for air craft operations for firefighting as well as for emergency medical transport. Additional damage to important gathering sites can occur from firefighting tactics. Wildfires are in and of themselves disturbing events in which people may lose or fear the loss of their homes and important sites in the landscape, and normal home and work routines as well as cultural and subsistence activities are disrupted. Irritability or “cabin fever” can set in when people need to stay indoors for prolonged periods.

Biophysical changes across the landscape – including those related to climate change – have affected access to many important food, fiber and medicinal resources. Salmon, acorn, elk, deer, berries and teas are among the traditional foods that are vitally important to the Karuk people, and their consumption prevents diet-related diseases such as diabetes and heart disease. About 50 percent of tribal members in Karuk Aboriginal Territory secure food by hunting, fishing or gathering; 40 percent reported climate and availability as barriers to acquiring sufficient healthy quantities.

Access to an intact natural environment and participation in one's culture are widely recognized as vital for psychological well-being. Cultivating, harvesting, processing, preserving and consuming traditional foods and medicines provide the framework for the Karuk eco-cultural socialization process and religious belief. These practices perpetuate Karuk traditional ecological knowledge and confirm Karuk occupancy on the land. Sharing food is a social obligation, and food related activities strengthen intergenerational relationships within families and the community. Such activities include the Pikyávish ("Fix the World") Ceremonies which are carried out to ensure abundant harvests and restore social and personal balance, and the First Salmon Ceremony, which invokes the spring salmon run.

Not only are ties to the natural world particularly strong for many Native people, but there are extensive disruptions of social, cultural and spiritual systems from ecological change and denied access to management. Karuk Tribal members have expressed grief, shame, stress and powerlessness from the loss of species, and from their inability to manage the ecosystem in accordance with their cultural practices and spiritual responsibilities. The cultural impacts of climate change are just the latest in a long thread of stressors affecting the mental and emotional health of the Karuk araráhih. Indigenous people in the U.S. already contend with the daunting task of processing centuries of historical trauma resulting from colonialism, a fact that has led to high rates of substance abuse, suicide, and violence within indigenous communities (Karuk Tribe, 2019). Many tribes and tribal organizations are turning to traditional healing practices to restore mental health and spiritual well-being to their communities.

Impacts on vegetation and wildlife

As described above, climate change is altering habitat conditions in Karuk territory. As a result, the biodiversity of ecosystems is threatened. The impacts of climate change are compounding those resulting from non-climate related stressors such as dams, fire suppression, and timber harvesting.

Karuk land management reflects a culture-centric perspective on vegetation zones, organized by elevation bands with different timing and purpose in relation to fire management: low elevation forest below the zone of smoke inversions; middle elevation forest within the zone of smoke inversions; and high elevation forest above the elevational gradients in which smoke inversions occur. Additional habitat zones are riverine, riparian, grasslands and wet meadows. These seven habitat zones are experiencing climate change related impacts that include: changing patterns of precipitation, increasing temperatures, decreasing winter snow pack, changing fire behavior, increasing frequency of high severity fires, drought, and species invasions.

While different habitat zones face distinct threats in light of the changing climate, it is important to recognize their connections to one another. For example, wet meadows supply water to lower elevations where tanoak stands are critical winter foraging habitat for elk who are in turn needed to sustain wolf populations. Each habitat zone is influenced by fire regimes, which have been altered by fire exclusion practices. Fire regimes impact the tanoak stand dynamics of low elevation forests which help shape riparian and riverine habitats. Fire management has shaped the structure and composition of middle elevation forest zones, and has been used to lower stream temperatures.

This section summarizes the impacts of climate change on vegetation and wildlife in the seven habitat zones, as described in the Karuk Adaptation Plan. Certain plant and animal species of importance to the Tribe play vital roles as cultural indicators to guide appropriate human actions. Many species occur across multiple zones, or move across zones seasonally. These 22 cultural indicator species are mentioned in the relevant habitat zone discussion in this section. The Appendix describes each species, organized by habitat zone. More details can be found in the Karuk Adaptation Plan.

Low elevation forests

The low elevation forest habitat lies below the elevational zone (roughly 500-3,000 feet) in which smoke inversions form within Karuk ancestral territory and homelands. This habitat zone is characterized by the presence of tanoak trees (xunyê’ep), and contains an abundance of other species of direct importance for Karuk food, fiber and medicine. Species in this zone are also important for their use as clothing, regalia, and implements, as well as for their role in shaping ecosystems and in informing where and when to burn. The cultural indicator species in this elevation zone are tanoak (xunyêep), tanoak mushrooms (xáyviish), elk (íshyuux), huckleberry (púrith), pileated woodpecker (iktakatákaheen), and wolf (ikxâavnamich). The presence of these cultural indicator species – particularly plentiful tanoak mushrooms and abundant tanoak acorns – is an indicator of balanced ecosystem process and function.

Tanoak forests face primary climate threats from increasing temperatures, decreasing precipitation, lower soil moisture, increased frequency of high severity fires, and expanding forest pathogens such as Phytophthora ramorum, which causes sudden oak death (SOD). The SOD pathogen – which has destroyed millions of oak and other trees and caused twig and foliar diseases in other plant species across California since the 1990s – and other lethal invasive forest pathogens can increase fire danger in coming years.

The composition and overall stand structure of low elevation tanoak forests are the direct result of their long-term intensive management by Karuk people through the use of fire. Frequent fires have traditionally been used to limit the encroachment of competing shrubs and conifer species, providing the open structure that is important for many other species including madrone, white oak, princess pine, pileated woodpeckers and elk. Today, these low elevation forests have been significantly impacted by conifer encroachment, targeted herbicide treatment to reduce competition with conifer plantations, and the past 100 years of fire exclusion. In these stands, meadows are non-existent, conifers such as Douglas fir encroach upon oaks, huckleberries are highly dense but without berries, and elk are not present. Other non-climate stressors to tanoak forests include firefighting activities that can damage the tanoak's mycelium net, as well as salvage logging and associated road building following high severity fires.

In addition to the direct importance of this habitat zone to particular species, the stand dynamics and fire regimes of low elevation tanoak forests significantly shape riparian and riverine health.

Middle elevation forest

The middle elevation forest zone is characterized by the elevational band (roughly 2,500 to 4,500 feet) in which smoke inversions form. Species occurring within this cultural management zone are important for Karuk people as a food source and for use in regalia. Pine roots and needles are used in basket making and are represented in ceremony as the tree of life. The cultural indicator species in this habitat zone are chinquapin (sunyíthih), black oak (xánthiip), pacific fisher (tatkunuhpíithvar), porcupine (kaschiip), and black tailed deer (púufich).

Middle elevation forests with black and other oaks, chinquapin, Douglas fir, hazel, and gooseberry would traditionally be burned every five to seven years. Federal fire management over the past century has led to declines in black oaks and other fire-dependent species and facilitated the growth of conifers, leading to the alteration of the structure and composition of this forest zone and making it vulnerable to high severity fires. A century of fire exclusion and a changing climate has impacted the practice of setting fires on Offield Mountain with the full moon in August as part of the World Renewal Ceremonies. This practice reduced the potential for high severity, high impact events, protecting the village sites below. August fires also cooled riverine systems at the peak of summer temperatures, triggering upstream salmonid migration and cooling the system for fish runs already in the river.

Changing patterns of precipitation and temperature, increased frequency of high severity fire, and species invasions, especially from forest pathogens such as the sudden oak death pathogen (*Phytophthora ramorum*), are climate-related threats for this habitat zone. Forest pest dynamics that appear to be driven or enhanced by climate change in the Klamath Region include the fir engraver beetles that are associated with Shasta Red Fir mortality and *Phytophthora ramorum*.

When it comes to restoration of cultural fire regimes, sites with the combination of huckleberry, chinquapin, and black oak are key sites for management. While sugar pine is often seen at higher elevations, it can occur in middle elevation zones. Sugar pine in this zone is a key indicator of cultural vegetation characteristics, denoting places for management. In ancestral practice, sugar pines were the most prized ignition source, especially because of their yield of pitch and needles. The presence of pines in specific landscapes shows human management. In many cases these remnant pine stands are located in areas central to landscape/resource specific ignition patterns (Tripp, Watts-Tobin and Dyer 2017).

High elevation forest

High elevation forests occupy the zone above which smoke inversions form. It is also defined as forests above the chinquapin band and extending into the high country (defined elsewhere as montane and into the subalpine zone). Processes within this habitat zone are critically important to the health of other parts of the ecosystem. Like their lower elevation counterparts, the high elevation forests within Karuk ancestral territory and homelands are biologically rich and incredibly species diverse. Key Karuk foods and cultural use species in this zone include the sugar pine, gooseberry and beargrass (which especially occurs towards the coast where fog is present). The shrub form of chinquapin may be found at these elevations. Karuk cultural burning enhances species in the high elevation forest zone, making nutrients available in soils, releasing the seeds from sugar pine cones, stimulating growth and flowering of beargrass, and minimizing fuel loads to protect from high severity fires. Cultural burning at roughly five- to ten-year intervals across the landscape creates multiple gathering areas for beargrass.

The high country is key for Karuk cultural and spiritual activity. Especially during summer, families and individuals journey from lower elevation zones to harvest and process foods, materials and medicines, to hunt, fish, and pray. Karuk people have traditionally used fire to tend this habitat zone. Burning in these areas often occurs along trail networks, targeting meadow areas and patches of particular food and cultural use species such as huckleberry. Some foods, fibers and medicines of particular importance in this zone are wild onion, beargrass, huckleberry, princess pine, Oregon grape, and sugar pine. Much of Karuk high country is under wilderness designation, with fire suppression as a primary intervening stressor; logging is also a stressor.

High elevations forests are being impacted by changing patterns of precipitation and temperature, and the resulting changes in snowpack, soil moisture levels, and fire frequency and seasonality. While this forest zone benefits from regular low severity fire, high severity fires can, in the long term, convert the forest to brush fields. Species invasions and forest pathogens including White Pine Blister Rust and Port Orford Cedar Root Rot are also of concern. Using fire in high elevation forests is critical for getting back to historic fire regimes and an overall manageable, fire-safe system, particularly in light of the increasing pressures from decreased snowpack, drought, and fungal pathogens.

Ironically many of the most culturally and spiritually important places throughout Karuk Territory have been the site of particularly intense alteration as a result of fire suppression. One example is the construction and operation of observation stations or “lookouts” to detect and report fires beginning in the 1920s. Some of these were constructed on tribal sacred sites used as prayer seats, thus affecting tribal land use practices, especially traditional setting of fires at culturally significant habitats. In other instances, the use of bulldozers to create fire lines has destroyed not only physical tribal artifacts, but also the vegetation mosaic of the ridge system which had served as an archive of land stewardship and part of cultural knowledge. The Tribe has lost the ability to learn from the ancestors and the land.

Wet meadows

Karuk ancestral territory and homelands contain a number of wet meadow systems scattered throughout the higher elevation forest and high country. The cultural indicator species for this zone is the leopard lily (Mahtáyiith).

Climate related drivers including changing patterns of precipitation, temperature, fire and species invasions are the dominant threats to these systems. Wet meadows are a highly threatened ecosystem with a severely reduced range due in particular to fire exclusion. In the absence of fire, the encroachment of conifers into wet meadows leads to a cycle in which the water table drops, the meadow dries up, and the drier soils become more conducive to Douglas fir and other hardwood trees that were formerly excluded by high soil moisture. Numerous wet meadows within Karuk ancestral territory and homelands are being lost through this process, especially at the middle to high elevations. Non-climate stressors to wet meadows include channelization from grazing, as well as the introduction of invasive species from grazers.

Wet meadows not only provide critical habitat for many species of importance – including bear, trailing blackberry, Mariposa and Panther lilies, wild turnip, and multiple kinds of Indian potatoes (e.g. Brodiaea coronaria) – they are critical for hydrologic, ecological and fire dynamics across the landscape, especially in lower elevations. Wet meadows supply water and provide higher summer base flows and cold water to lower elevation riverine and riparian systems; for example, the Haypress meadow complex supplies cold water to the Wooley, Ti, Irving, Stanshaw, and Sandy Bar watersheds.

Riverine systems

Karuk ancestral territory and homelands encompass several hundred miles of riverine habitat along the middle portion of the Klamath River, the lower portion of the main stem Salmon River, and many key tributaries. Species from riverine systems hold significant cultural or spiritual significance and provide over fifty percent of the calories and protein of traditional Karuk diets. They are also important for food, culture and ceremonies. The cultural indicator species for the riverine zone are spring Chinook salmon (Ishyá’at) and Pacific lamprey (akraah).

Riverine systems are especially at risk due to changing patterns of precipitation, increasing temperatures, and decreasing winter snow pack. These changes directly impact stream flow and water temperatures. Elevated stream temperatures can cause fish mortality, support fish pathogens and diseases, and enhance the suitability of the habitat for non-native fishes.

Non-climate stressors that threaten riverine systems result from non-Tribal management actions, including: dams (such as Iron Gate) that trap sediment, block access to cold water habitats, and stop processes that shape habitat and cool water downstream; fire suppression, which has removed the cooling effect of smoke on river waters during critical periods for Chinook fall migration and spawning; and water quality impairments from agricultural inputs, fire retardants, logging activity and others

Riparian systems

Riparian areas – lands along water courses and water bodies – are key sites for many food, fiber and medicinal species of importance to Karuk people.

Species from riparian systems serve as indicators of healthy systems; they signal when management steps, including burning, need to be taken. The riparian zone cultural indicators are the Pacific giant salamander (púfpuuf), aquatic garter snake (asápsuun), beaver (sahpihnîich), and yellow-breasted chat.

Riparian habitat is threatened by changing patterns of temperature, precipitation, fire behavior and species invasions. Prolonged drought, which reduce stream flows, may cause permanent streams to become intermittent; increasing temperatures may dry forest floors, thus reducing the area of moist refugia in the terrestrial riparian zone; more severe winter or spring rains may cause flooding events that increase siltation and alter aquatic riparian habitat structures; and warmer climates may increase the spread of diseases and increase the susceptibility of amphibians and other species to diseases. Aside from climate stressors, riparian systems are already threatened in the mid-Klamath area by dams, water diversions, species invasions, logging, roads and fire suppression. The health of riparian habitat zones is important for the functioning of riverine and forest systems.

Grasslands

Grasslands, also known as prairies or glades, historically occurred in mid to upper montane areas on ridges, in both large and small patches. Until about 1850, grasslands were so extensive they covered nearly one-fifth of California. Today a majority of the grasslands that once existed within Karuk Aboriginal Territory have disappeared due to lack of fire. Frequent burning is required to maintain the open prairie structure. Burning prevents conifer encroachment and enhances conditions for key food species, such as many of the species known as Indian potatoes (tayiith). The presence of Indian potatoes indicates where the Tribe traditionally burned and managed grasslands. Traditional Karuk knowledge about grasslands is still being recovered.

Grasslands have been historically significant for many species of broad-leaved herbs, native annual and perennial grasses, insects, birds, mammals, reptiles, and amphibians. Among these are important Karuk foods such as elk, as well as iris and other grasses used for twine, and Indian potatoes. Indian potato and bumblebees are the two cultural indicators for this habitat type.

With the changing climate, drought and species invasions are a particular concern in this habitat type. Probably the main non-climate stressor to grasslands comes from their severely reduced range due to fire exclusion and from the transport and spread of non-Native species. Grazing is another key intervening stressor for grassland systems.

Summary

Karuk araráhih have co-evolved with the mid-Klamath ecosystem and its diverse landscapes since time immemorial using multiple species of importance as cultural indicators for various traditional management practices. The Tribe has managed the landscape with controlled burning for countless generations, however the policy of fire suppression at the state and federal levels interrupted these practices and ultimately led to greater wildfire risk. The effects of fire suppression and other non-climate stressors – notably the construction of dams and logging – along with a changing climate, have altered habitat conditions and disrupted ecosystem process in Tribal territory. The Karuk Tribe and its Natural Resources Department are actively working to understand, adapt to, and mitigate the effects of climate change. As the landscape and cultural indicator species are impacted by the effects of that changing climate, the Karuk people will continue to adapt using the environmental stewardship knowledge collected over countless generations of Karuk araráhih to protect their landscape, resources, culture, and the health of their people.

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Appendix. Karuk Cultural Indicator Species by Habitat Zone

For countless generations, Karuk people have observed the behavior of particular plants and animals to understand ecological dynamics, and as a guide for necessary human management. Cultural and ecological information is retained today in ceremonies, stories, collective memory and the land itself. Today, the Karuk Tribe is centering on the revitalization of 22 focal species, described below, as cultural indicators for human responsibilities and necessary human management actions in the face of climate change. The descriptions and images are taken from the Adaptation Plan.

Low elevation forest

Source: Karuk, 2016

Xunyêep (Tanoak, Lithocarpus densiflorus) is an ecologically, culturally, and economically important species. Tanoak acorns (xuntápan), a staple food for Karuk people, traditionally constituted a high percentage of the calories and protein of their diets. The roots of tanoak trees support the growth of another important food, tanoak mushrooms. Xunyêep is a key cultural indicator for when and where to use fire. There are specific times to burn in a tanoak stand to maximize the quality and abundance of the acorn yield, not only for people but other species including deer, elk and many birds.

The most critical environmental factor determining the fate of tanoaks is fire. Another factor is the spread of the sudden oak death pathogen, which increases in warmer and wetter environments.

Púrith (Evergreen Huckleberry or Vaccinium ovatum) is an important Karuk food source with many nutritional and health benefits. Púrith is a slow-growing, shade-tolerant understory shrub that is most abundant in forests with a higher level of canopy cover. Flower and berry production increases with light and soil moisture where forest gaps have been produced by moderate disturbance related to fire, timber harvest, or thinning. Infections by the sudden oak death pathogen (Phytophthora ramorum), while not lethal, produce lesions that reduce their suitability for tribal use. The infections may also prompt land managers to remove infected plants to protect tanoak stands. Warmer and wetter environments are likely associated with increased spread of the pathogen, and the lack of cultural fire appears to increase púrith’s vulnerability to the disease.

Huckleberry is a cultural indicator for when and where to burn. Burn timing is indicated by the burn timing of tanoak acorn, which is in turn related to insect management. Emerging scientific studies indicate the presence of chinquapin may be a sign as to where one should burn for huckleberry. The Tribe defines púrith as a key cultural indicator of socio-ecological resilience of sustainable harvest and landscape management to ensure food security for both humans and animals that consume huckleberry.

Xáyviish (Tanoak Mushroom, Tricholoma magnivelare) is prized as a traditional food and medicine. It is also highly prized in the global market, making it vulnerable to overharvest by outsiders. In Northern California, xáyviish can be found scattered or growing in groups in well-drained soil or duff under tanoak, golden chinquapin, madrone, or pine trees with which it forms a mycorrhizal, symbiotic relationship. In addition to rainfall, this mushroom requires low temperatures, and a pattern of warming and cooling. Tanoak mushrooms are connected to tanoak trees, elk, huckleberry, deer, wolf and chinquapin and other species in complex ways. The presence of plentiful tanoak mushrooms is an indicator of treatment success from the standpoint of soil impacts and host tree retention.

High-severity fires burn or destroy mycelial mats, preventing them from fruiting into harvestable mushrooms and compromising the survivability of the population. Xáyviish may struggle to repopulate areas if entire stands of host species have been destroyed by high severity fire. Additionally, the moisture and cool temperatures that xáyviish depend on may be less available in forests with repeated high-severity fire.

Xáyviish is threatened by logging machines, which have damaged or severed the mushroom’s mycelium, and harvesting of the mushrooms for economic gain. This species serves as an important indicator of responsible human use. While Karuk tradition emphasizes reproductive success by picking mushrooms with at least 50 percent of the veil open to assure the release of spores, and allowing access by other species before human use, economic gain is maximized when the mushrooms are picked with their veils closed.

Iktakatákaheen (Pileated Woodpecker, Hylatomus pileatus) is seen as an ecosystem engineer that creates cavities that can then be used by up to 20 species of birds and mammals. It also promotes nutrient cycling in the forest through its excavations. The process of harvesting the species for regalia is intricately tied to land management. The largest woodpecker in North America, Iktakatákaheen typically resides in older deciduous or mixed deciduous-coniferous forests. High severity fires consume snags and logs used by pileated woodpeckers for nesting, roosting, and foraging, and reduce insect populations as well as nut and berry sources that are vital to the woodpecker diet.

Íshyuux (Roosevelt Elk or Cervus occidentalis) are important for their use as food, clothing (hides), regalia, and implements, as well as for their role in shaping ecosystems. The management of elk populations, and the protection and restoration of habitats that elk depend on are of vital importance to the Karuk Tribe. The reproductive needs for elk are an important cultural indicator for management. Íshyuux require a mosaic landscape that combines open areas for foraging, and forested areas for cover. Much of the habitat for winter range and calving is now overgrown with mid-mature dense stands and plantations due to fire exclusion. Following a mixed (moderate to high) severity burn in a riparian area in 2015 (in the West Simms unit), elk moved in and started calving in it almost immediately. Differences were significant between the cultural prescribed fire and impacts of an adjacent wildfire.

Ikxâavnamich (Wolf, Canis lupus) once inhabited Karuk territory, but by the 1920's were decimated by Euro-American hunting, trapping and poisoning. It is likely to make a return to California as a result of federal protections. The wolf is important to Karuk tribal spiritual practices and ecosystem stability. Intricate relationships exist between wolves and other species in the low elevation forest zone, including elk, deer, tanoak, huckleberry, chinquapin and tanoak mushroom. Ikxâavnamich habitat tends to be more prey-dependent than land cover-dependent. In the West, wolves are known to follow large ungulate herds from their lowland wintering grounds to their upland pastures. Burns that destroy entire stands may force ungulates to seek new forested areas, straining the herd and thus affecting wolves' diets. Ikxâavnamich creates its own den in meadows near water, rock outcroppings, under tree roots, or even old beaver lodges. Wildfire could kill pups in the den or elsewhere. To succeed as a pack, wolves need large, remote areas free from much human disturbance.

Middle elevation forest

Source: Karuk, 2016

Tatkunuhpíithvar (Pacific Fisher, Pekania pennant) has experienced significant declines in Karuk territory. The fur of tatkunuhpíithvar is traditionally used in Karuk regalia. It is well represented in world renewal ceremonies as the quiver that carries the arrows used to wake up the world. Tatkunuhpíithvar represents the need for balance among dense and open habitats with large fire scarred growth hardwoods. It prefers hardwood forests with significant canopy cover, with large trees and snags where it converts large cavities into a den. The species is currently facing habitat losses due to habitat changes resulting from both climate and non-climate stressors: fire management, high severity fires, insects and pathogens, logging, and rodenticide poisoning from marijuana farms.

Sunyíthih (Chinquapin, Castanopsis chrysophylla) is an evergreen member of the beech family that can grow quite tall and live up to 500 years. Also known as a high elevation species, its presence at other elevations indicates places where one may want to treat for huckleberry. The nuts of sunyíthih are important to the Karuk traditional diet and also provide food to many bird and mammal species. Sunyíthih is particularly competitive in dry, infertile sites. On sites with more moisture and fertile soil conditions, disturbance such as fire is necessary to preserve a chinquapin forest component. Rarely does chinquapin occur in pure stands. Sunyíthih provides important cover for birds and small to medium mammals. Fisher and martens may use them for their natal dens. Diseases and insects have little impact on giant chinquapin, although it is susceptible to heartwood-rotting fungi such as Phellinus igniarius; the filbert worm (Melissopus latiferreanus) may impact reproduction. Chinquapin has recently been identified as a host of sudden oak death pathogen.

Kaschiip (Porcupine, Erethizon dorsatum) are critical food sources for mountain lions and pacific fisher. Kaschiip's quills are used by Karuk people in basketry and regalia.

Ideally the quills are harvested via non-lethal methods, and then the porcupine is re-released. Kaschiip has historically held important ecological roles as a species that maintains oak woodlands and reduces conifer encroachment. The Karuk Tribe aims to restore a healthy local porcupine population, which may in turn assist the recovery of other habitats and species (Karuk DNR 2010). Weavers reported seeing many porcupines in black oak stands while gathering as late as the early 1970’s. Seeing a porcupine in Karuk Territory today is a very rare event. As a result of habitat loss, naturally low reproductive rates, and former Federal and State eradication programs to protect timber harvests, porcupines are now rare in much of California. The porcupine diet consists of herbaceous plants, twigs, and particularly in the winter, coniferous bark and needles. Fires can affect porcupine food sources and habitat, increase the chances of porcupine predation, and kill individuals who are unable to escape.

Xánthiip (Black oak, Quercus kelloggii) occurs in mixed-conifer forests as well as in mixed hardwood forests. In the highly diverse Klamath-Siskiyou area, black oak has many overstory plant associates. While tanoak acorns are the most prized among Karuk people, black oak acorns are also an important traditional food. Having various acorn sources in the forest ensures dietary diversity and resilience in the event of impacts to any one species.

Historically, black oak stands were ignited at a massive scale in February to promote early spring greens and to protect the most susceptible slopes above the villages from excessive fuel accumulation in the summer months. California black oak appear highly adapted and may experience range expansion as a result of predicted increases in temperature and fire activity. High severity fires may destroy acorn bearing stands of black oak that are culturally vital. There is some speculation that increasing temperatures could influence acorn production. Sudden oak death (Phytophthora ramorum) is a major climate stressor for this species and is already impacting black oak in coastal regions.

Púufich (Black Tailed Deer, Odocoileus hemionus) is among the most important traditional Karuk foods and sources of utilitarian and ceremonial items. In 2005, over 65 percent of Karuk households reported hunting púufich for food. The meat, sinew, bones, hide/skin, fur, antler, and hooves have been used extensively for traditional functions. The Deerskin Dance, which is part of Karuk World Renewal Ceremonies, depicts how burning for deer relates to salmon migration and woodpecker habitat and other connections. Deer health and abundance, as well as their movement and habitat selection across the landscape are indicators of appropriate fire management activities. Karuk management of this species includes the use of fire to promote rotational grazing and to draw them away from freshly sprouting basket materials. Tribal management also pays closer attention to allowing for opportunities for reproduction and promoting genetic mixing.

Smaller patches of high severity fire that maintain more open shrub, fern, forb, and grasses promote higher quality forage and dispersal for deer. By contrast, high severity, large-scale fire may burn a significant portion of black-tailed deer's home range and reduce cover from predators. Oak groves burned by such fires can reduce deer diets rich in acorns. Existing stressors include agricultural expansion, habitat loss, disturbance of migration, fire suppression, and barriers (such as fencing, roads and reservoirs). Warming temperatures can affect the availability of food sources and alter patterns of seasonal migration. Delayed autumn migrations may leave púufich at greater risk of sudden winter storms and predation. Warming temperatures and increased humidity may increase spread of parasites and bacteria to which púufich are vulnerable.

High elevation forest

Source: Karuk, 2016

Ússip (Sugar pine, *Pinus lambertiana*) occurs in mixed-conifer forests. In Karuk country, it is of particular value when occurring within or adjacent to tanoak or black oak stands. It reproduces via large, heavy seeds held within cones. It can take sugar pines around 150 years to become good cone producers. The seeds are not highly mobile, and unless moved by animals do not stray far from the parent tree. Sugar pine is often viewed as a high elevation species, but when found at other elevations, it serves as an indicator of specific management actions. It is used by Karuk people for ceremonial and subsistence purposes. The snags possess high quality “black pitch” which is not only a traditional form of money, but is also utilized in the ignition of cultural burns. Sugar pine groves were family owned and managed for nuts (food), pitch (medicine), and roots (basketry).

The presence of sugar pine is a notable indicator of past fire management actions and may be associated with other culturally relevant information or activity. Ússip are often found in strategic places on ridges where they would have been managed to serve as ignition sources. Today it is rare to find an open grown sugar pine tree that is accessible for nut collection. Trees grown in the open develop differently than woodland grown trees, typically developing full crowns and a wide branch structure with large limbs growing from further lower on the trunk. As a future indication of landscape scale fire regime restoration, pine trees with large branches less than 15 feet from the ground and adequate limbs to climb from there will be important.

Decreased snowpack, earlier spring snowmelt and warmer temperatures threaten the health of sugar pines directly, or make them susceptible to beetle infestations and fungal pathogens. High severity fires can not only decimate individuals and stand, but also limit seed dispersal and establishment in burn areas.

Panyúrar (Beargrass, *Xerophyllum tenax*) is a perennial, subalpine herb that inhabits upper slopes, often near or beneath coniferous forests. Beargrass flower stalks are browsed by ungulates such as deer and elk. It is an important plant species for Karuk basket weavers and regalia makers. Blades are considered best for basket weaving the first year after a fire. Panyúrar is traditionally burned every three to seven years, especially in the fall following World Renewal Ceremonies when people bring fire down from the high country. Burning for panyúrar is part of landscape dynamics, and necessary for returning fire intervals across the larger landscape. Along with other important cultural species including hazel, panyúrar grows back particularly strongly after low to medium intensity fire. A combination of frequently burned beargrass and filtered light through a moderately dense canopy maintains an open understory free of brush and other materials typical of fueling large wildfires. The conditions this type of burning maintains can also promote species like salal and saddler oak which are important for gathering and browse for large ungulates. Burning too hot can make basketry materials brittle. High severity fires can burn duff into soil deep enough to destroy beargrass rhizomes; damage to forest duff from very hot fires can delay or prevent the re-establishment of beargrass.

Wet meadows

Source: Karuk, 2016

Mahtáyiith (Leopard Lily, *Lilium pardalinum* ssp. *Wigginsii*) is the cultural indicator for wet meadows. Mahtáyiith is among the most prized bulbs in the Karuk diet. It is dug in the fall and is traditionally cooked in an earth oven like many other bulbs. In the Klamath Mountains, leopard lily is found in high country wet meadows, especially on serpentine soils. This rare and endangered herb grows from bulbs that are small and often clustered, and typically blooms in July. Fire of varying intensities removes competing shrub and tree vegetation which would promote lily flowering.

Riverine systems

Source: Karuk, 2016

Akraah (Pacific lamprey or eel; *Lampetra tridentata*) are related to humans as a food source, related to fire cycles for their well-being, and related to bears and birds upslope by virtue of taking nutrients back up the hill to feed plant life, similar to salmon. They have a long life cycle in which adults live in the ocean and return to freshwater to spawn. The larvae reside and filter feed in silty or sandy substrates for up to seven years before migrating to the ocean. Adult Pacific lamprey follow the scent of pheromones released by juvenile lamprey (ammocetes), not necessarily returning to their natal river systems. This highlights the importance of ammocete habitat in the Klamath, which depends on sediment deposition and fire processes to create favorable conditions. The Scott River, the largest source of fine sediment to the main stem Klamath above the Trinity River, is a snow pack driven river system that is threatened by climate change. Furthermore, Iron Gate Dam has cut off the sediment supply to the upper Klamath River.

Ishyá'at (spring Chinook salmon, *Oncorhynchus tshawytscha*) is a key cultural indicator sensitive to stream temperatures. Their presence is an indicator of both riverine and forest habitat quality. Fresh, cool water temperatures are critical to Ishyá'at, as are spring to early summer high water flows they need to reach summer holding areas, to access spawning grounds, and to reproduce. Climate change and changing weather patterns such as drought cycles and high severity storm events have had direct implications on the species. On the Klamath, "spring creeks" that originate in volcanic terrain are perfect for production of juvenile salmon because of their stable flows and cold water temperatures year-round. However, nearly all spring creeks on both the Klamath and Shasta are locked up behind dams.

Riparian systems

Source: Karuk, 2016

Púfpuuf (Pacific Giant Salamander, *Dicamptodon tenebrosus*), while not a Karuk food source, is central to Karuk culture. They are a keeper of water that is critical to life. In Karuk beliefs, púfpuuf is a spiritual being who transformed into a salamander to monitor spring and creek water quality and quantity. Their presence is indicative of a healthy riparian and aquatic fresh water ecosystem. Púfpuuf is perhaps the most important cultural indicator for identifying the need for emergency management actions. Karuk traditional practitioners report that if púfpuuf is in peril, we are on the verge of system collapse, and the immediate application of fire is recommended to lower acutely high air and water temperatures.

Asápsuun (Aquatic Garter Snake, *Thamnophis atratus*) is a cultural indicator of healthy aquatic and riparian systems. As fire regimes are restored in Orleans and the Black Mountain area, paying attention to this species may become more important. Asápsuun is an aquatic snake that uses water for both foraging and protection. In Karuk territory, people have reported seeing fewer and fewer "water snakes," a fact that they attribute in part to the impact of fire suppression on aquatic systems. With climate change, increased temperatures may dry forest floors and reduce moist refugia for this species in terrestrial habitats.

Sahpihnîich (Beaver, *Castor canadensis*) alters ecosystems in ways that benefit other species. Karuk people value beaver as a teacher of how to intervene in natural processes for the greater good. Sahpihnîich is considered nearly locally extirpated and in need of reintroduction. Habitat destruction and degradation, and a lack of riparian vegetation (their food sources) are climate change-related threats to the species. Restoring historic fire regimes will benefit sahpihnîich by promoting the growth of riparian vegetation, and reducing the threat of high severity fires. Sahpihnîich can play a role in drought mitigation by storing water and maintaining areas of open water. Their dams can moderate stream temperatures, reduce peak flows in flooding events, create complex aquatic habitats for many other species, trap suspended sediment, and restore incised streams to more complex channel and ponds systems.

Yellow-Breasted Chat (*Icteria virens*) is a migratory bird that nests in the spring. In Karuk stories, it is welcomed as the true harbinger of spring. Karuk culture says the chat is tied to the responsibility of humans to realize that something has to be done about fire. The return of the chat and other birds to nest is a signal to stop burning. Chats are numerous in Northwestern California, with the highest densities found along the Klamath and Trinity Rivers. The chat depends on riparian areas, especially sandbars, with willow trees. It nests in dense thickets, and uses larger trees as singing perches. A return of cultural burning at proper intervals will maintain riparian willow and cottonwood habitats. Maintaining riparian floodplain habitat by discouraging channelization of streams will also benefit chat. Chat may also be susceptible to changing wind conditions along migration routes to and from the tropics. The yellow feathers of its breast have traditionally been a part of tribal regalia.

Grasslands

Source: Karuk, 2016

Tayiith refer to a variety of geophytes (including *Brodiaea* spp., *Dichelostemma* spp., *Triteleia* spp., *Calochortus* spp., *Lilium* spp., and *Fritillaria* spp.) commonly called Indian potatoes. The Karuk people harvest their bulbs and tubers for consumption. *Brodiaea coronaria* serves as a good indicator for other Indian potato species, as it tracks soil moisture. Indian potatoes grow in prairies and meadows in a variety of settings. Historically, species of Indian potato grew thick as grass in certain valleys in California. Karuk and other Native Californians know proper harvesting techniques that further proliferate these species by promoting bulblet production. As with many prairie and meadow species, Indian potatoes have experienced declines as a result of land cover change, fire suppression, and a reduction in the ability of indigenous peoples to steward the landscape. Burn timing in regard to this species needs to be refined to account for harvest timing and invasive species.

Bumblebees (*Bombus* and other genera) are important within grassland habitats in Karuk Aboriginal Territory. While bees require grassland habitat which is fire dependent, the specific relationships between bees and fire is less well understood. Loss and fragmentation of grassland habitat, as well as grazing, reduce nesting and foraging habitat quality for bees This is a species for which more traditional knowledge and scientific attention will be beneficial in the changing climate.

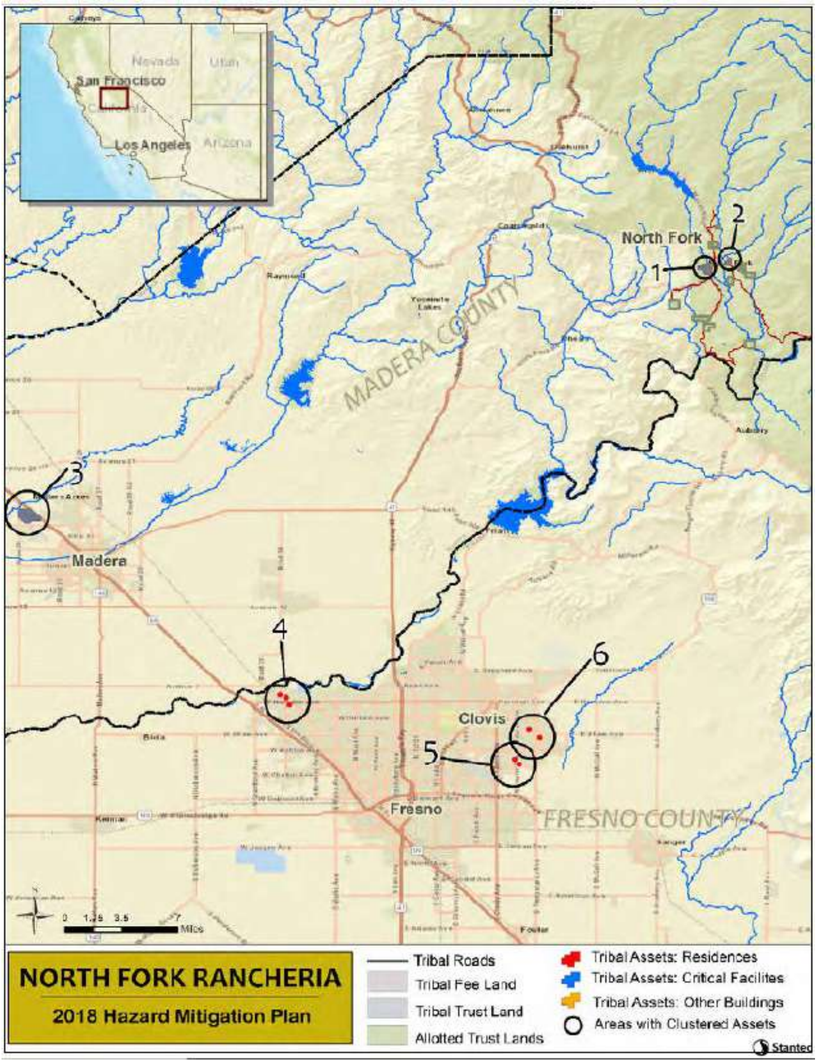
IMPACTS OF CLIMATE CHANGE ON THE NORTH FORK RANCHERIA OF MONO INDIANS OF CALIFORNIA

Elevated day and nighttime temperatures, drought, wildfire, and flooding due to increasingly variable precipitation patterns are threatening the physical, cultural, and spiritual health of the Tribe, its habitats and ecosystems, and its built environment.

Background

The North Fork Rancheria of Mono Indians of California (NFR) is a federally recognized Tribe currently located in Madera County, California. The North Fork Rancheria lies in the foothills of the Sierra Nevada Mountains, along the Sierra Vista National Scenic Byway. The Rancheria lies less than 40 miles from Fresno, California. The Western Mono have resided in the San Joaquin Valley for thousands of years (NFRMIC, 2018). However, after non-native encroachment of historical lands, the Tribe's ancestors concentrated around the town of North Fork, from which the Tribe's name was derived (Tatum, 2006). Intermarriage with other local Tribes occurred and sharing of the land and its resources was important for all the Tribes. Western Mono language is part of the Uto-Aztecan language family and is most similar to the Paiute-Shoshone languages.

Figure 1. Current North Fork Rancheria Lands and assets

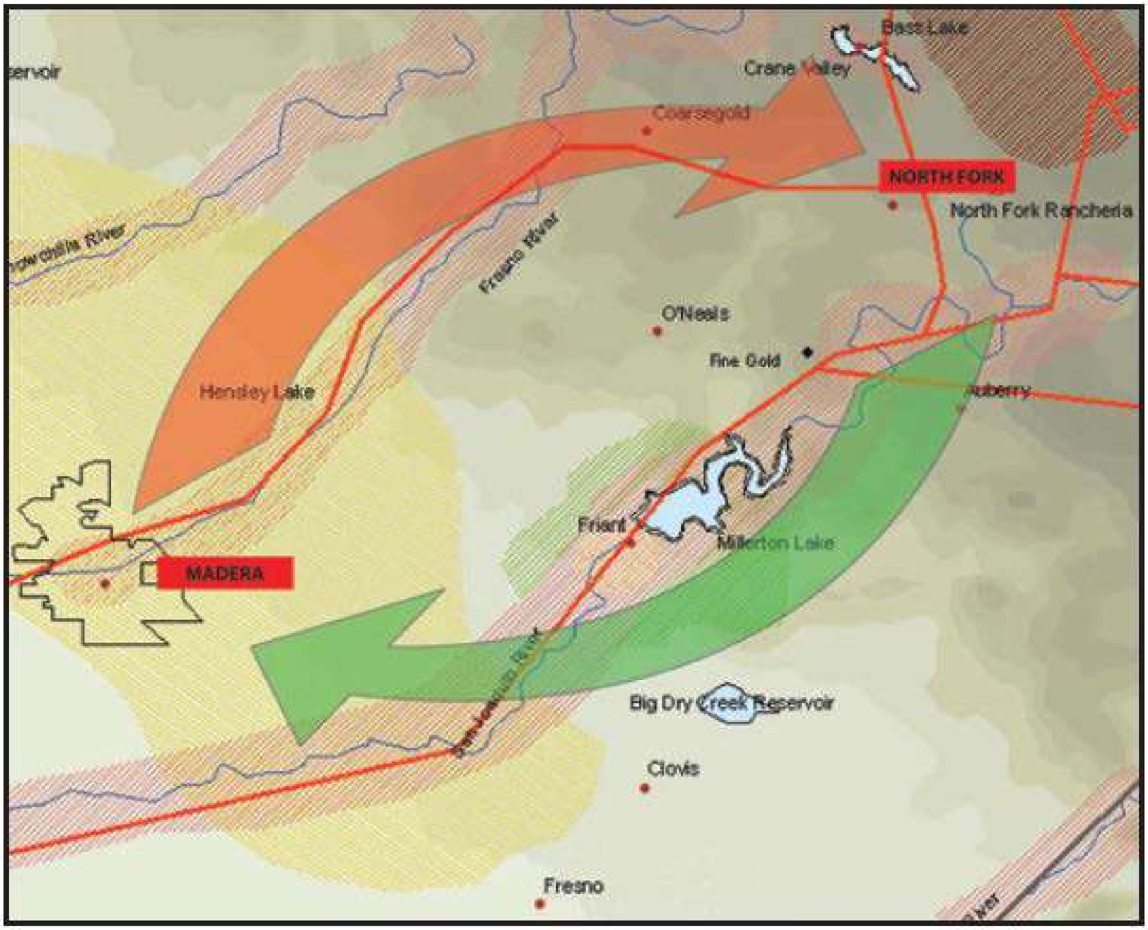


Source: NFRMIC. 2018

The Tribe has 2,310 citizens nationwide, with the majority residing in Fresno and Madera Counties, making them one of California's largest native Tribes (NFRMIC, 2018).

The first reservation lands were allotted in 1851 but failed treaty ratifications resulted in the closure of the reservation in 1860 (NFRMIC, 2006). Traditionally, the North Fork Mono travelled between the foothills of the Sierra Nevada and the San Joaquin Valley (Figure 2).

Figure 2. The North Fork Tribe migrated from the foothills down to the Valley for hunting and fishing and worked with other Tribes along the way.



Source: Tatum, 2006

The Tribe also traded throughout the Eastern side of the Sierras and have trail systems that go to Bishop, Yosemite, Mono Lake and through the Pacheco pass. Travel was vital for traditional hunting and gathering, ceremonies, and for trade with other Tribes creating a complex interdependent system of social, political, and economic ties between groups (NFRMIC, 2006). Historically, the weather in the foothills was more hospitable for permanent residence due to the severe heat, drought, and flooding in the Valley. In the Valley, the Mono hunted for large game like elk and antelope, fished for salmon, and gathered roots of the sedge plant found along the riverbanks on the Valley floor (Tatum, 2006). In contrast, in the foothills the Tribe had access to acorns from Black Oak trees, a staple for the North Fork Mono as their acorns made better flour than those from oak trees found closer to the Valley. Federal recognition as an Indian Tribe was restored in 1983 under a court-approved settlement, and the Tribe subsequently elected a governing body and adopted a Tribal Constitution in 1996. Today, tribal leadership consists of five elected members of the Tribe's citizenry who serve four-year terms elected on a two-year staggered basis. The 80-acre Rancheria is held in trust for descendants of one Mono family; therefore, the Tribe is considered 'landless' and has had to purchase land for its people.

Cultural and Spiritual Health

The wellness of the tribal people is tied to the lands from which the Tribe is from. The water, plants, soil, air, minerals, and other resources provide a connection to the landscape that is not easy to convey in written form. An example would be when a weaver gathers material for a baby basket, they must know where to go for materials, that material must grow in the right conditions, have plenty of water, and once cleaned and ready to use the weaver can be overcome with a feeling of reflection and relaxation as they weave the basket for a child.

Climate Change and Its Impacts

Unless otherwise stated, the *North Fork Rancheria Tribal Multi-Hazard Mitigation Plan* (NFRMIC, 2018) is the basis for the information below.

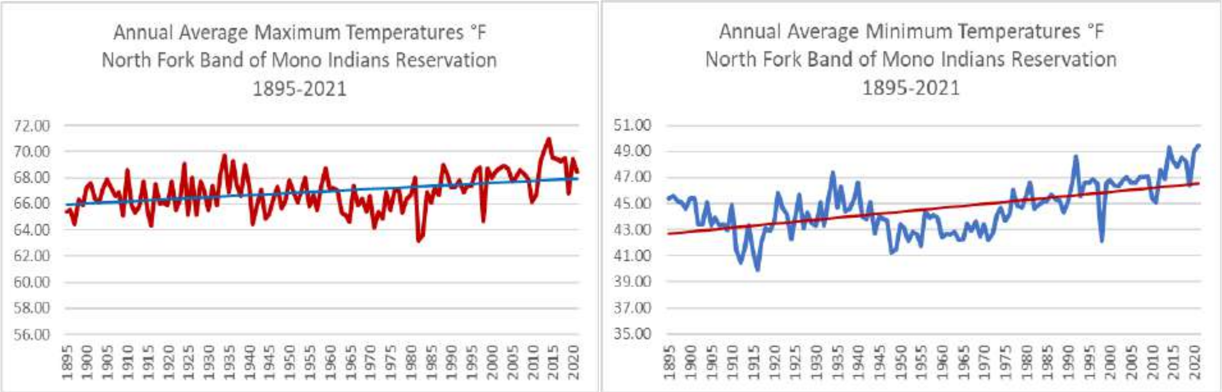
Elevated Temperatures

The North Fork have experienced warming temperatures across both the winter and summer months. In general, the area experiences both cold winters with temperatures below freezing as well as hot summers where temperatures exceed 100°F. However, accelerated warming over the last decade has contributed to warmer winters and hotter summers, which has impacted both the health of tribal citizens and the plant and animal resources on which they rely.

What does this indicator show?

At North Fork, both the nighttime temperatures and daytime temperatures have risen steadily since 1895. Looking first to daytime temperatures (Figure 3) we can see that temperatures have remained within 8°F but that the average temperature currently sits at around 68°F. However, in more recent years the temperature has varied more extremely with sharp increases and decreases from 1995 to 2021 (PRISM, 2022). Looking next to nighttime temperatures (Figure 4), we can see that temperatures cover a range of about 10°F, with temperatures remaining consistently above 45°F since 2001. Currently, the annual average minimum temperature is around 48°F. Overall, nighttime temperatures have increased at a much faster rate when compared to daytime temperatures over the last century, at 5°F compared to 2°F.

Figures 3 and 4. Annual Average Minimum and Maximum temperatures at North Fork Rancheria 1895-2020



Source: PRISM, 2022

Why is this indicator important?

Changing temperatures have cascading effects on other climatic variables, like precipitation, drought, and wildfires, further impacting the Tribe. Particularly important to the Tribe has been the decrease in acorn availability. The Tribe on the western side of the Sierra Mountains has depended heavily on acorn as a staple food for thousands of years. However, warming temperatures have decreased acorn availability especially during the drought between 2014 and 2016. During seasons when acorns are plentiful, the health of wildlife in the area benefits as well (McDonald, 2020).

As the climate has changed, the North Fork Rancheria has had to contend with a wide range of pests, disease, and non-native species (NFRMIC, 2018). Warming temperatures and extreme heat events contribute to drought stress on trees. The Tribe has observed instances of tree mortality over the last six to seven years, due to the combined effects of drought and bark beetles (McDonald, 2020). As water competition increases, trees become weakened, thus contributing to susceptibility to bark beetles (Preisler *et al*., 2017). The Tribe is concerned that Sudden Oak Death will become a problem in the area as the climate continues to change.

Warmer temperatures also negatively impact the health of Tribal Citizens. Ground ozone needs heat and sunlight to form, so hot temperatures have worsened air quality by exacerbating ground ozone levels. Data from CalEnviroScreen, California’s Environmental Justice Screening Tool, shows that ozone levels in North Fork are ranked in the 67th percentile compared to other areas across the state, meaning that North Fork has higher ozone levels than most of the communities in California (OEHHA, 2021). Vulnerable populations, especially children, the elderly, and the disabled are at the greatest risk of exposure to extreme heat. Those without air conditioning may be at higher risk (NFRMIC, 2018)

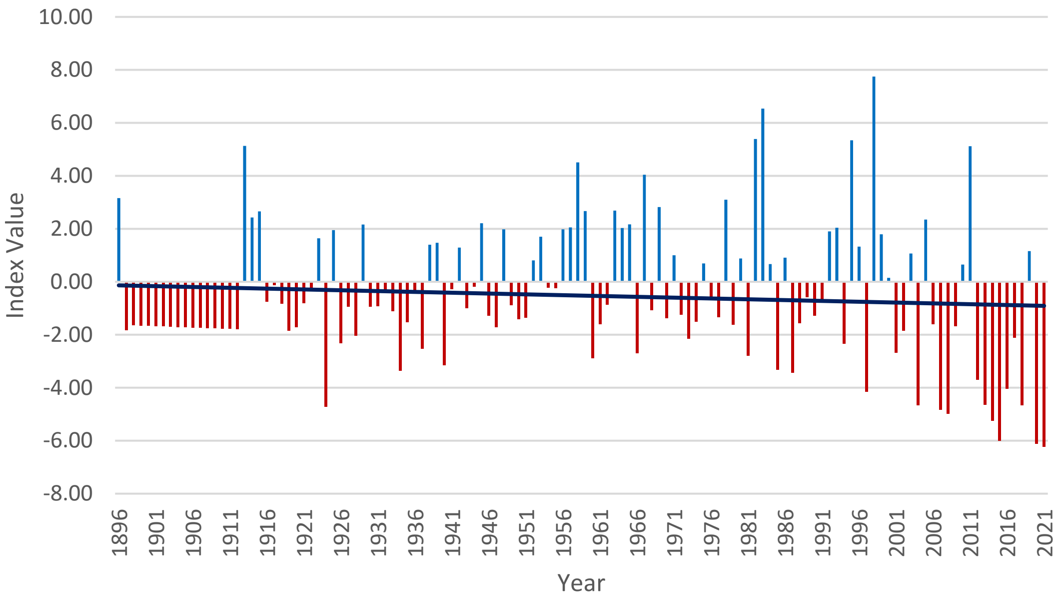
Drought

North Fork experiences clear wet and dry seasons, with the dry season lasting from mid-spring to late fall. Historically, the North Fork people have experienced multiple instances of the destructive effects of drought including failed crops and changes to land-use patterns. Local hazard identification efforts have determined that drought conditions are to be expected across 10 to 50 percent of the North Fork area, with critical severity in terms of property damage, facility shut down, and injuries expected in the next year-ten years (Madera County, 2016).

What does this indicator show?

Using the Palmer Drought Severity Index (PDSI), a value of 0 indicates normal conditions while negative numbers represent drought conditions and positive numbers correspond to wet spells. Looking specifically the North Fork Rancheria, PDSI values show that the Tribe has experienced many instances of extreme drought since 2000 (Figure 5). Over those 21 years, there were nine years of extreme drought (PDSI values below -4) and three years of moderate to severe drought (values between -2 and -3). While the Tribe did experience moderate drought in the 100 years prior, those droughts were milder. The Tribe is seeing a trend of increasingly severe droughts.

Figure 5. Palmer Drought Severity Index (PDSI) for the North Fork Rancheria, 1896-2021



Source: Abatzoglou *et al.*, 2022

Why is this indicator important?

The increase in frequency and severity of drought conditions for the North Fork have important implications for surrounding wildlife and traditional cultural practices. Drought has reduced the availability of materials needed for basket-making, disrupting cultural traditions, and impacting the ability to pass on practices to younger generations (BPT, 2020; McDonald, 2020).

Drought conditions in the area have had significant impacts on tree mortality in the Sierra National Forest, causing large-scale die offs that are fueling other effects such as disease, pests, and wildfire events (Madera County, 2016). As mentioned in the *Elevated Temperatures* section, drought conditions and resulting water competition have made trees susceptible to bark beetle populations, contributing to the mortality observed. Fallen trees in the area have reduced the availability of mushrooms, an important food resource to the Tribe, which grow when forest soil is exposed to air. Along with a reduction in mushroom availability, tribal members also note that access to prime resource areas has been impacted by the abundance of fallen trees, which are blocking paths and access routes (McDonald, 2020).

Drought also impacts other native plants such as the sourberry, used both medicinally and for basketry, which require an ecosystem that is disappearing. Manzanita and Black Oak acorns, other species heavily utilized by Tribal Citizens, have also been negatively impacted by drought. Lack of water reduces the availability of berries and dries out the branches of plants, making them difficult to use for basketry. This can trigger negatively re-enforcing feedback loops where surrounding plants and animals relying on threatened species are unable to survive themselves. Deer herds in the area have been in decline for decades due to forest conditions and forest health. Deer are indicators of forest health; resources that the Tribe uses are also utilized by the deer. Dry conditions additionally facilitate the occurrence of wildfire events further impacting the health of populations and lands.

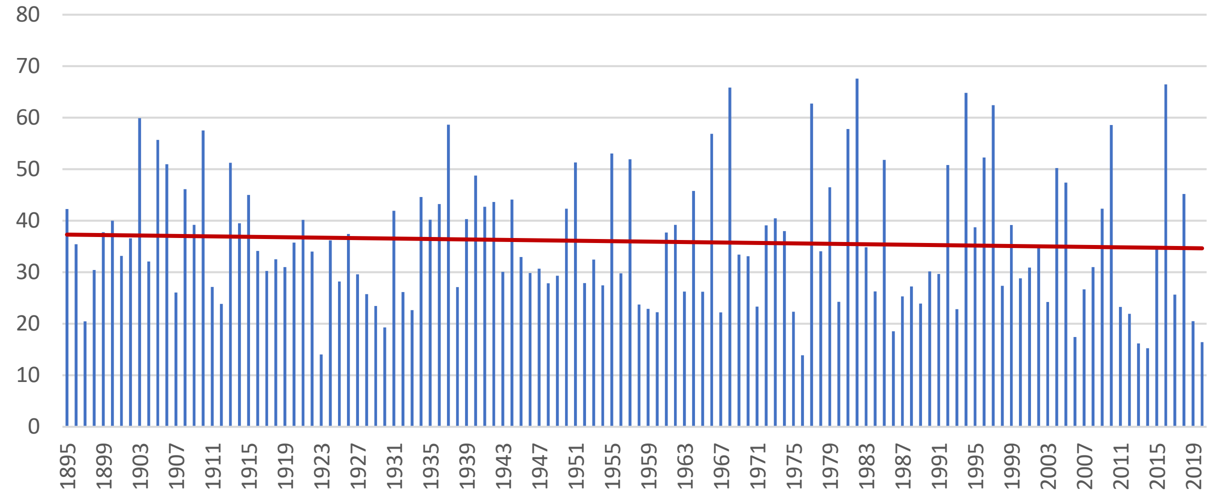
Precipitation

In addition to changing temperatures and instances of drought, the North Fork Rancheria has also experienced changes in precipitation patterns. Extreme precipitation events are expected to continue to impact the Tribe and the ensuing flooding can result in damages to property, roadways, and plant and animal species.

What does this indicator show?

Precipitation in North Fork has become more variable over time (Figure 6). Since 2010, the Tribe has seen large-scale differences from year to year, differences which are expected to continue as the climate continues to warm overall. Additionally, not specifically highlighted in annual rainfall summaries are instances of intense rainfall, which can lead to flooding, as well as periods of prolonged dryness (i.e., drought).

Figure 6 Annual precipitation by water year, North Fork Band of Mono Indians Reservation, 1895-2021



Source: PRISM, 2022

Why is this indicator important?

Changing precipitation patterns have the potential to significantly increase flooding at North Fork. Further, warming temperatures lead to precipitation falling as rain rather than snow, which in turn impacts the volume and timing of snowmelt in the Sierra Nevada mountains, and the sudden onset of early springtime warm temperatures and subsequent snowmelt have the potential to increase flooding (NFRMIC, 2018). Past flooding events have led to mandatory evacuations and have closed roadways – impacting the health and safety of tribal members.

Decreases in precipitation have contributed to lower-than-normal creek flows (BPT, 2020). Tribal members are dependent on water systems, and a reduction in creek flows has limited tribal access to additional clean water. According to CalEnviroScreen, North Fork is ranked in the 97th percentile compared to other areas across the state for drinking water contamination (OEHHA, 2021). This means only 3 percent of communities in the state evaluated by CalEnviroScreen have worse drinking water contamination issues. Aquatic ecosystems have also been affected by changes in precipitation patterns. Reduced creek flows have triggered large scale fish die-offs. This is concerning not only for the health of the aquatic ecosystem, but also for the diet of tribal populations. Central California roach, hardhead, Sacramento pikeminnow, Sacramento hitch, Sacramento perch, and Sacramento tule perch are all culturally important species to the North Fork Mono and the Tribe has seen reductions in numbers due to the diminished quality of aquatic ecosystems (SWRCB, 2014).

Flooding has impacted the gathering of materials for the Tribe. Basketry material such as sedge can be inaccessible during periods of high water and can also be impacted by large flood events, as increased flows can dislodge the root systems. The roots of the sedge are used for the basket material. Sedge is typically found in sandy areas, which tend to be prone to wash out in high flows.

Wildfire

Wildfires are expected to increase in frequency and severity as the climate warms. Across the entire state, fire season has started earlier in the year and has expanded across more areas. For the Tribe, more frequent and intense fires have enormous consequences on both physical and cultural health and well-being.

What does this indicator show?

Wildfires have had a significant impact of the North Fork Rancheria. Of the five largest fires (in terms of area), three have occurred in the last 20 years (Figure 7, Table 1). These fires, along with many smaller fires, have burned significant portions of North Fork lands and lands surrounding the Rancheria.

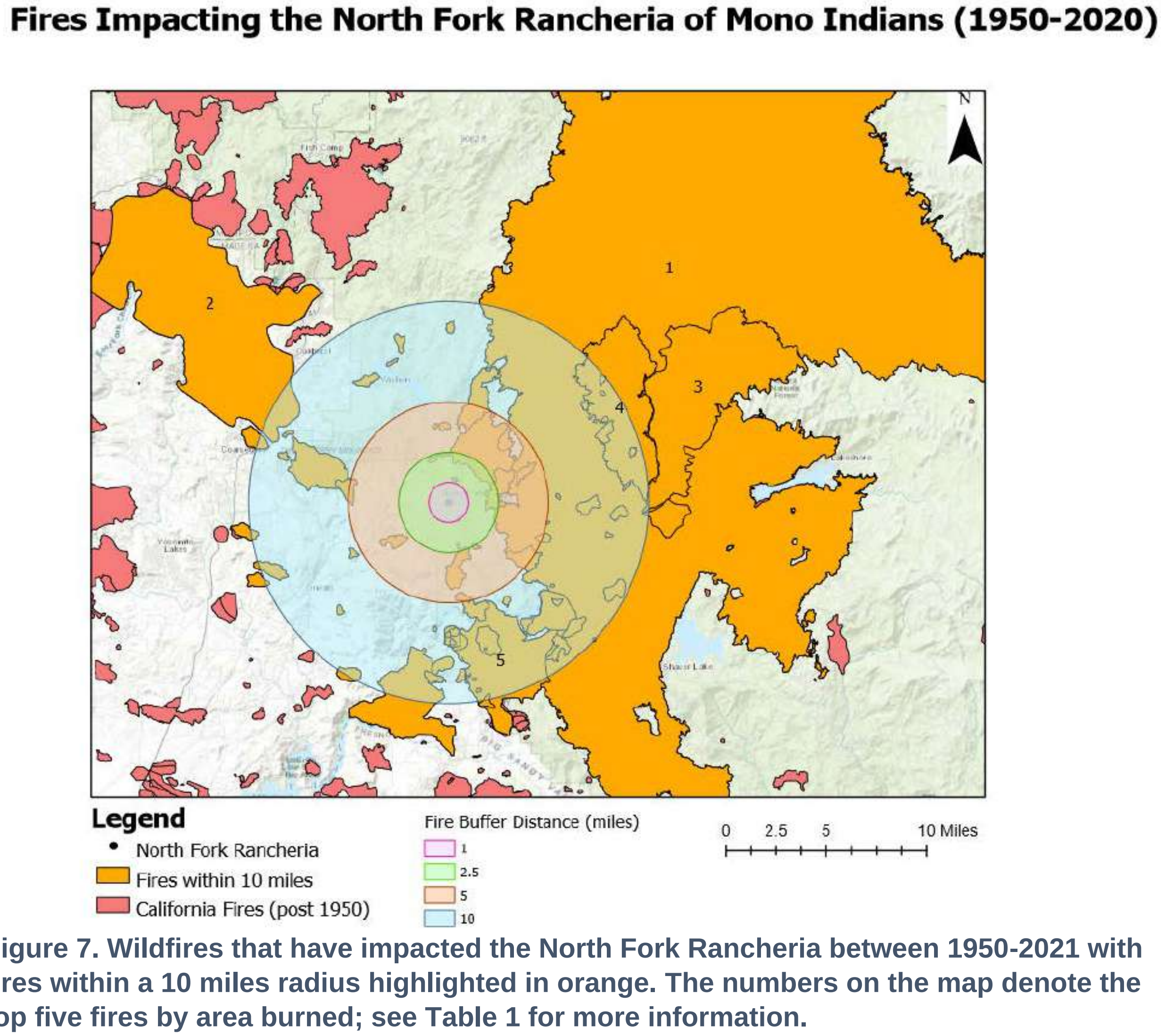


Figure 7. Wildfires that have impacted the North Fork Rancheria between 1950-2021 with fires within a 10 miles radius highlighted in orange. The numbers on the map denote the top five fires by area burned; see Table 1 for more information.

Source: CAL FIRE, 2021a

Table 1. Top 20 fires impacting the North Fork Rancheria of Mono Indians between 1961 and 2021, with the top 5 largest fires highlighted in blue.

RANK	YEAR	FIRE NAME	AREA (ACRES)
1	2020	CREEK	379,882
2	1961	HARLOW	43,331
3	2013	ASPEN	22,938
4	2014	FRENCH	13,832
5	1989	POWDERHOUSE	11,800
6	1982	TEMPERANCE FLAT	7,802
7	2015	WILLOW	5,701
8	2001	NORTH FORK	4,131
9	1968	THORNBERRY #2	3,131
10	1992	ITALIAN	2,157
11	1987	CHAWANAKEE	1,487
12	2017	MISSION	988
13	2015	CORRINE	922
14	1973	HORSESHOE	835
15	1985	MAMMOTH	764
16	1995	POWERHOUSE #2/#3	624
17	1970	LONG RIDGE	598
18	1961	MCALISTER FIRE	590
19	2005	QUARTZ	547
20	2003	NORTHFORK	472

Source: CAL FIRE, 2021b

In 2020 the Creek Fire – ranked the fifth largest wildfire in the state (CAL FIRE 2021a) -- devastated North Fork aboriginal territory. Of concern is the repeated burning of certain areas, as seen with the Creek Fire in 2020, the Aspen Fire in 2013 and French Fire in

2014 (Fires #1, #3 and #4 in Figure 7, Table 1). While it is uncommon for previously burned areas to re-burn, climatic changes are altering fire patterns that could influence the length of time between re-burns (Buma *et al.*, 2020). In total, there have been 73 fires within 10 miles of the North Fork Rancheria between 1950 and 2021. The loss of resources is severe, and it will take generations for the oak, pine, fir, and cedar to regrow.

Why is this indicator important?

Surrounding wildfires have contributed to both poor air and water quality in the North Fork Rancheria. Air pollution from wildfire smoke can lead to negative health outcomes like asthma, cardiovascular disease, and premature mortality. Soil erosion and sediment runoff from areas that have lost vegetation due to fires can degrade local surface water quality. This deposition of sediment, along with soot, can impact aquatic life in local waterways (BPT, 2020). Culturally important sites like the Mono Hot Springs have also been impacted. The alkaline runoff from wildfire soot increases the pH of water and the smoke from the wildfires lowers the temperatures (De Graff et al., 2018). On the North Fork Rancheria, fires have the potential to impact anywhere from 50-100 percent of the Tribe. Wildfires are likely to cause severe property damages, facility shutdowns, and injuries and illness (Madera County, 2016). Heavy rain, especially on wildfire-scarred land where the ground is unstable due to vegetation loss, can catalyze landslide events and severely threaten the health and safety of the surrounding community (NFRMIC, 2018).

The combined effects of multiple environmental stressors have been shown to directly impact wildfire events. Warming temperatures and drought conditions have exacerbated potential for wildfire (CAL FIRE, 2017). Drought and decreased snowpack have weakened trees, making them susceptible to disease and pest infestations; tree mortality in the Sierra National Forest has increased fuel loads, and thus the risk of wildfires (Madera County, 2016).

Another important consequence of increased frequency and intensity of fires across the state is the reduction in the number of days the Tribe can conduct cultural burning and fire ceremonies (BPT, 2020). For the North Fork Mono, regular burning encourages new growth of many species such as deer grass, sourberry and chapparal which are materials needed for basket-weaving. Since these plants are adapted to fire, after burning, the root stock remains intact and can resprout after spring rains. Due to long periods or dryness without regular prescribed burning, forests have become overgrown, causing conditions that could give rise to more extreme and dangerous fires. Additionally, vegetation management by Pacific Gas and Electric to remove brush and protect power lines has resulted in a loss of resources for the Tribe.

Summary

Warming temperatures, drought, wildfires, increasingly variable rainfall – and ensuing floods and erosion – have impacted the people of the North Fork Band of Mono Indians and their environment. In addition to exposures to temperatures much warmer than they are acclimated to, these changes have altered and disrupted the ecosystems within and around North Fork, impacting many species of cultural importance to the Tribe. The community is actively working to understand, adapt to, and mitigate the effects of climate change. With the Tribe's goal of being consistent, transparent, and honorable, the North Fork Band of Mono Indians continue to manage and protect their lands and limit the impact of climate change on the North Fork Tribe's right to hunt, fish, gather, and continue their cultural practices –activities that are integral to their cultural and psychosocial health, well-being, and livelihood.

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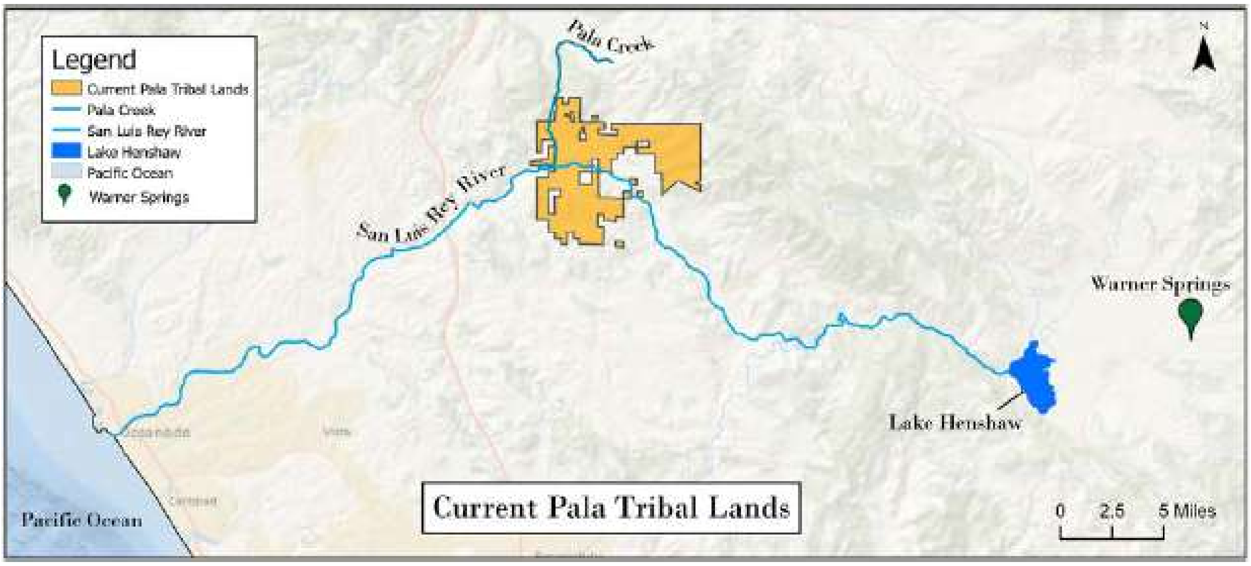
IMPACTS OF CLIMATE CHANGE ON THE PALA BAND OF MISSION INDIANS

Rising temperatures, drought, wildfires, and flooding are threatening the physical, cultural, and spiritual health of the Tribe, its habitats and ecosystems, and its built environment

Background

The Pala Band of Mission Indians is a federally acknowledged Native American Indian Tribe that has a current enrollment of approximately 983 tribal members. The Pala Band has jurisdiction over the Pala Indian Reservation that was established in 1875. The Pala Indian Reservation is located on approximately 13,000 acres in northern San Diego County, roughly 30 miles east of the Pacific Ocean (see Figure 1). The Pala Reservation sits next to the Palomar Mountain range that runs along 5,000 square miles of California desert. Adjacent to the reservation is the Cleveland National Forest to the north and east, and private agricultural lands to the south and west.

Figure 1. Map of Pala Lands



Source: Pala Environmental Department

The reservation lies within an alluvial valley surrounded by steep granite mountains and is divided into two areas by the San Luis Rey River; these are referred to as the north side and the south side. The north side contains most of the homes and development; however, there are also approximately 100 homes and structures south of the river. Elevations range from approximately 340 feet above mean sea level (MSL) at the valley floor to approximately 1,250 feet above MSL in the northern and southern mountainous areas, with most residential, agricultural, and industrial activities occurring in the lower elevations of the reservation. Approximately 88 percent of the land is currently undeveloped. Land uses include agricultural, mining, pastureland, commercial businesses including gaming, and residential uses.

The South Coast of California where Pala is located is home to one of the world's biodiversity hotspots. Rapid development occurring in the areas surrounding the reservation has increased the burden on natural resources and degraded ecosystems and habitats.

Prior to the construction of the Lake Henshaw Reservoir and Dam in 1923, Pala had access to the San Luis Rey River's perennial water supply. A complex history of water diversion by new settlers and legal battles ultimately led to a Congressional settlement that was signed into law. This law quantified the Tribe's prior and paramount water rights and provided for the construction of water projects to facilitate the exercise of Pala's rights. The source of the reservation's domestic water supply, which is drawn from wells scattered throughout the reservation, is the aquifer and underground stream of the Pala Groundwater Basin. The Basin lies directly underneath the San Luis Rey River and the Pala village area. It is replenished by rain events and surface water flows from local creeks and rivers (Pala, 2017).

The people of the Pala Band of Mission Indians have lived from time immemorial in this part of Southern California. Pala's tribal members have a rich and diverse tribal history with members that come from both Cupeño and Luiseño ancestry. They have endured and adapted to many significant impacts on their lands and community which have disrupted culture and traditions, political and social systems, and ecological environments for over hundreds of years beginning with the arrival of Spanish missionaries in 1769 (OPR, 2018). In 1903 the Cupeño Indians were forcibly removed from Warner Springs, shown on the map in Figure 1 (40 miles east) to Pala, joining with the Luiseño Indians already living there, ultimately combining to make the Pala Band. Ongoing development impacts the Pala community's ability to maintain traditional subsistence practices. The Pala people, however, continue to thrive, buoyed by their strong community and culture connectedness, co-existence with nature, and spiritual connections.

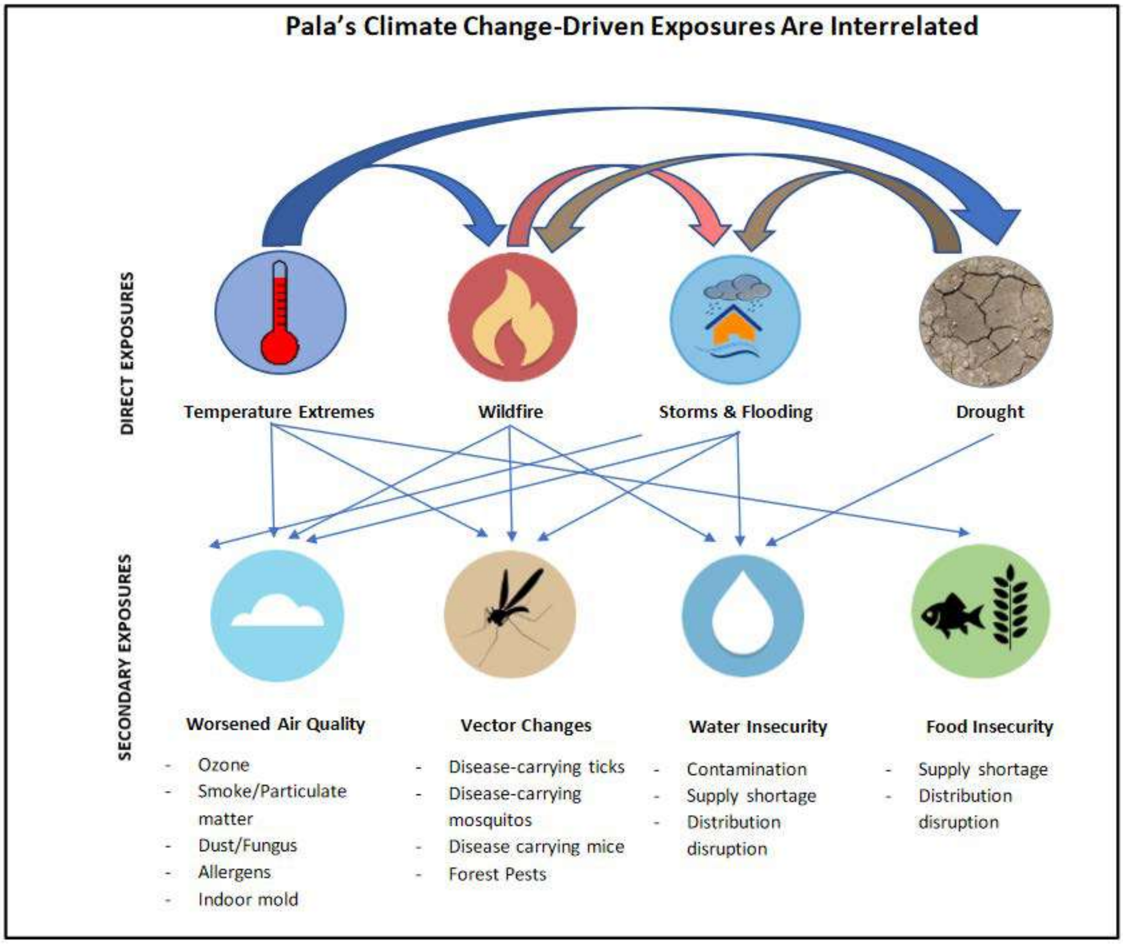
Climate change and the Pala Tribe

Pala's climate has been characterized by moist, mild winters and dry, warm summers, also known as "Mediterranean summers". Temperatures in the Pala Valley are historically relatively moderate, ranging from an average of 60 degrees Fahrenheit during the winter months to an average of 80 degrees Fahrenheit during the summer. Annual precipitation within the Pala Valley averages about 10 to 12 inches a year, and between 25 to 45 inches in the Palomar Mountains, 12 miles east of Pala. Roughly 75 percent of the annual precipitation falls within the basin between December and March (Pala, 2016).

The climate change impacts the Tribe has seen threaten a variety of Pala's community assets and values, ranging from water resources to human health and tribal sovereignty

(Pala, 2019). Pala conducted a vulnerability assessment, based on Tribal science, knowledge and observations shared by Pala's residents, which matches the more recent scientific evidence and literature. This 2019 Vulnerability assessment is the basis for much of this report. Pala's location in the southwest region of the United States, within the inland valley and mountainous areas of San Diego County, makes it susceptible to a variety of interrelated climatic exposures as well as secondary exposures. These secondary exposures (e.g., worsened air quality, water insecurity, etc.) occur as a result of direct exposures. The exposures that present the most significant and interrelated risks for Pala are shown in Figure 2 (Pala, 2019).

Figure 2. Interrelated Climate Change Exposures



Source: Pala Environmental Department

There are characteristics of the area and of the Tribe that make Pala either more vulnerable to possible impacts of climate change, or more capable of adapting to these impacts. For example, Pala has buildings considered at high risk from flood and critical facilities in a high-risk wildfire area (Pala, 2016). In addition, only 53 percent of residents have air conditioning in their homes to buffer them from heat impacts. However, Pala also has more tree canopy cover, lower percentages of impervious surfaces, and a lower urban heat island index than most census tracts in California, (Public Health Alliance of Southern California, 2018) which may help buffer residents from expected impacts of extreme heat. Having overcome ecological and human changes on their lands for thousands of years, the people of Pala have also demonstrated exceptional strength, resourcefulness, and resilience, in the face of continued and increasing climate change impacts.

> *"The summers are extremely hot, which is a concern for our elders, even our natural flowers are blooming late in the year. We need change!"*
> *~Pala Tribal Member Survey Respondent*

Cultural and Spiritual Health

At Pala, the people, the culture, and the environment are connected. Thus, it is impossible to tease out climate change impacts that affect cultural and spiritual health from those that do not. For example, the plants and animals that are being impacted by climate change are often used in traditional practices and ceremonies. When medicinal plants are impacted by climate change, the Tribe's traditional healing practices are affected. The absence of culturally important foods, such as acorns, limits their use in celebrations.

Habitable climate is critical to protecting tribal sovereignty, culture, and community cohesion for the people of Pala. Extreme heat days can threaten cultural expressions and traditional ways of life at Pala, including disruptions to culturally and/or spiritually important activities such as traditional gatherings, annual ceremonies, traditional food foraging, performances by traditional bird singers, and basket weaving. As temperatures continue to rise, residents may opt out of these traditions, modify how they are conducted, or relocate their household out of the area; this affects community cohesion and cultural identity and sovereignty (Pala, 2019).

Increased temperatures also result in a variety of ecosystem disruptions. For Pala, that can mean declines or disappearance of culturally important plants and animals. At Pala, survey respondents were concerned about culturally important plants including those required for baskets, ceremonial structures, or foods, such as rushes (*Juncus)*, sourberry (*Rhus trilobata)*, acorns, sage (*Artemisia californica*), willow, and tobacco. Community members report that culturally important plants like basket rush (*Juncus textilis*) and ferns have also become harder to find (Pala, 2018).

Declining trees and plants impact resources that support the Tribe's cultural traditions. The coast live oak (*Quercus agrifolia*) was known as wi'awlet to the Cupeño people. For many Tribes, oak trees were a key source of nutrition (acorn mush or wi'wish) and are a symbol of life, growth, and the cycle of the seasons.

As climate change puts Pala at increased risk, impacts to the psychosocial health of the community are inevitable. Psychosocial health refers to the mental, social, spiritual, and emotional health of a community. While Pala has been committed to addressing these impacts, the stress on the community from heat, drought, severe weather, loss of species and cultural sites, and wildfires cannot be ignored.

Elevated Temperatures

Temperatures have been increasing at Pala. Elevated temperatures affect human health, mental health, cultural and spiritual health, and socio-economic health, as well as the plants and animals that are part of Pala. Elders, children, outdoor workers, and those with existing medical conditions are particularly susceptible to these impacts (Pala, 2019).

<u>What does this indicator show?</u>

At Pala, both the nighttime temperatures (Tmin) and daytime temperatures (Tmax) are rising, with the nighttime temperatures rising more quickly. As shown in Figure 3, before 1950 the annual average minimum temperature varied between 44.7 degrees Fahrenheit (°F) and 51.3°F and the average maximum annual temperatures varied between 74.5°F -and 78.6°F. Since 1950 the annual average minimum temperature has been between 47.7°F and 54.4°F and the annual average maximum temperature has ranged from 74.3°F -79.2°F (PRISM, 2022).

Figure 3. Annual average temperatures at Pala

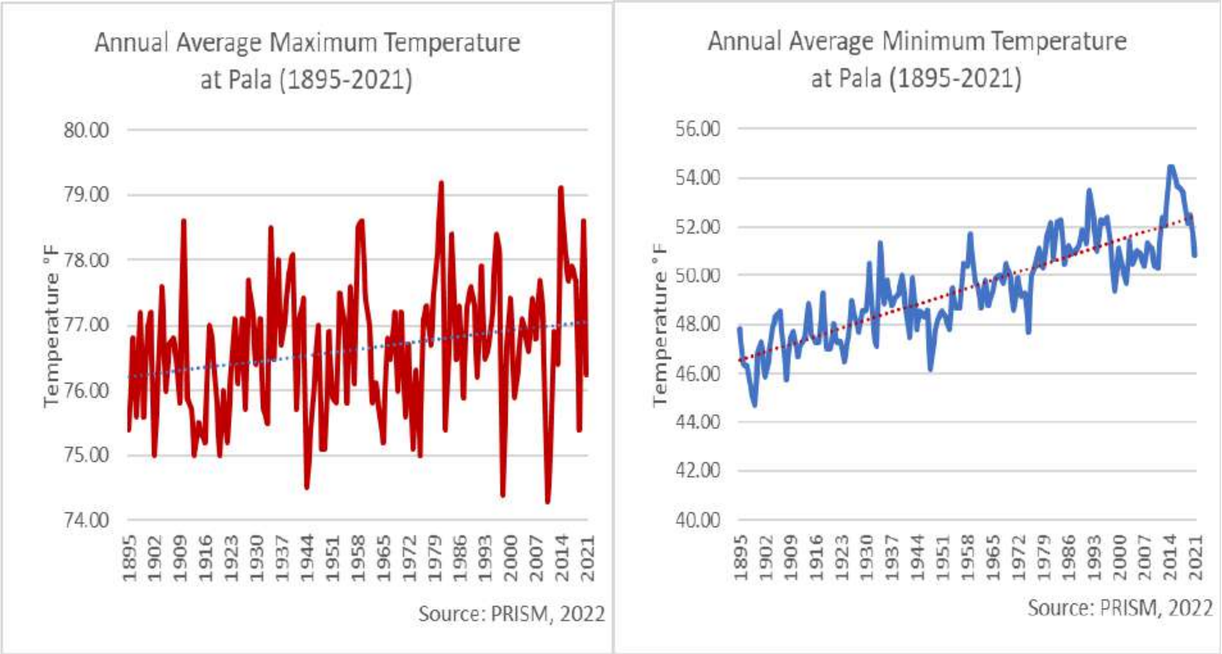


Table 1. Change in Day and Nighttime Average Annual Temperatures Over Time at Pala

Time Period	30-year Annual Average Minimum Temperature (Tmin)	30-year Annual Average Maximum Temperature (Tmax)
1895-1924	47.17°F	76.19
1925-1954	48.59°F	76.60
1955-1984	50.05	76.76
1985-2014	51.31	76.83
2015-2019*	52.95	77.38
*7 years		

Source: PRISM, 2022

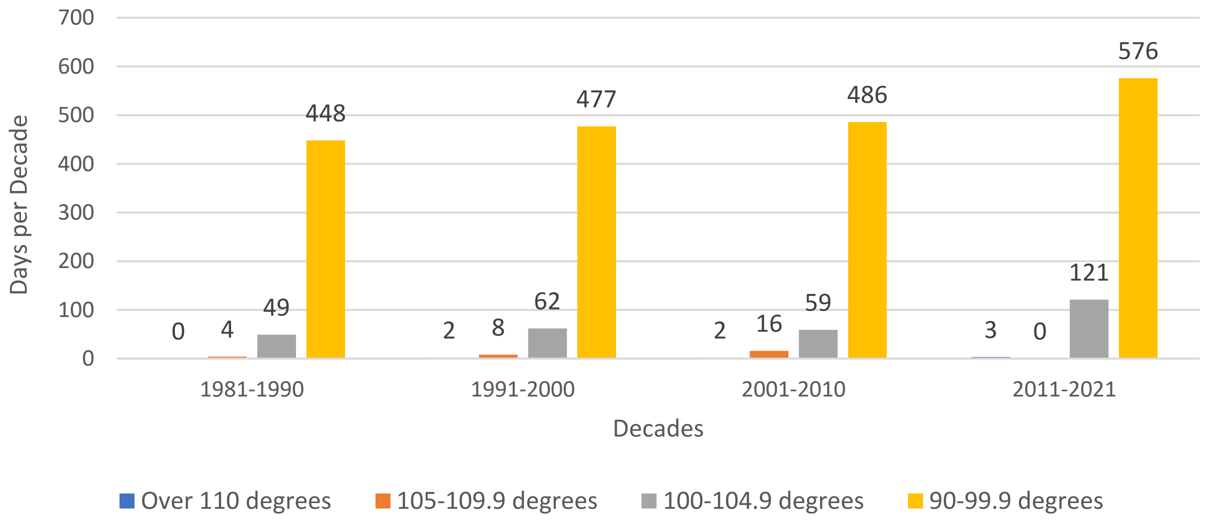
Table 1 shows the averages of the annual minimum (nighttime) temperatures (Tmin) and the annual maximum (daytime) temperatures (Tmax) during 30-year periods from 1895-2021. The Tmin has risen 5.8°F and the Tmax 1.2°F over the last 125 years.

Why is this indicator important?

Warming temperatures are considered a high-risk exposure for the Pala Tribe. Heat waves consisting of multiple consecutive days of triple-digit heat have increased and are expected to become more common. As is evident from the increasing minimum temperatures, the cooling nights that Pala is accustomed to are warming over time. The combination of warmer daytime and nighttime temperatures are impacting both the human and the plant communities (Pala, 2016).

As shown in Figure 4, in the 30 years from 1981 – 2010 there were an average of 67.3 days per decade with temperatures over 100 degrees. The 11 years after that (2011-2021) had 124 days with temperatures over 100 degrees.

Figure 4. Extreme Heat at Pala



Source: PRISM, 2022

As temperatures have increased, Pala's Environmental Department staff have observed declining areas of important habitats including chaparral, native grasslands, wetlands, riparian, and upland habitats and increasing areas of non-native grasslands. Pala has observed impacts to production of some crops cultivated on the Reservation, including avocado and citrus fruit. These trees need a certain number of chilling hours in the winter when temperatures are between 32 and 50°F; as temperatures increase and chilling hours are reduced, crop yield decreases (Pala, 2019).

> *"The summers are extremely hot, which is a concern for our elders, even our natural flowers are blooming late in the year. We need change!"*
> *~Pala Tribal Member Survey Respondent*

Climate changes are also causing certain native animal populations to decline in Pala's region. Temperature increases are altering habitat suitability for endemic species like the federally endangered Quino checkerspot butterfly and California gnatcatcher, for which range shifts have been observed (Parmesan, 2015).

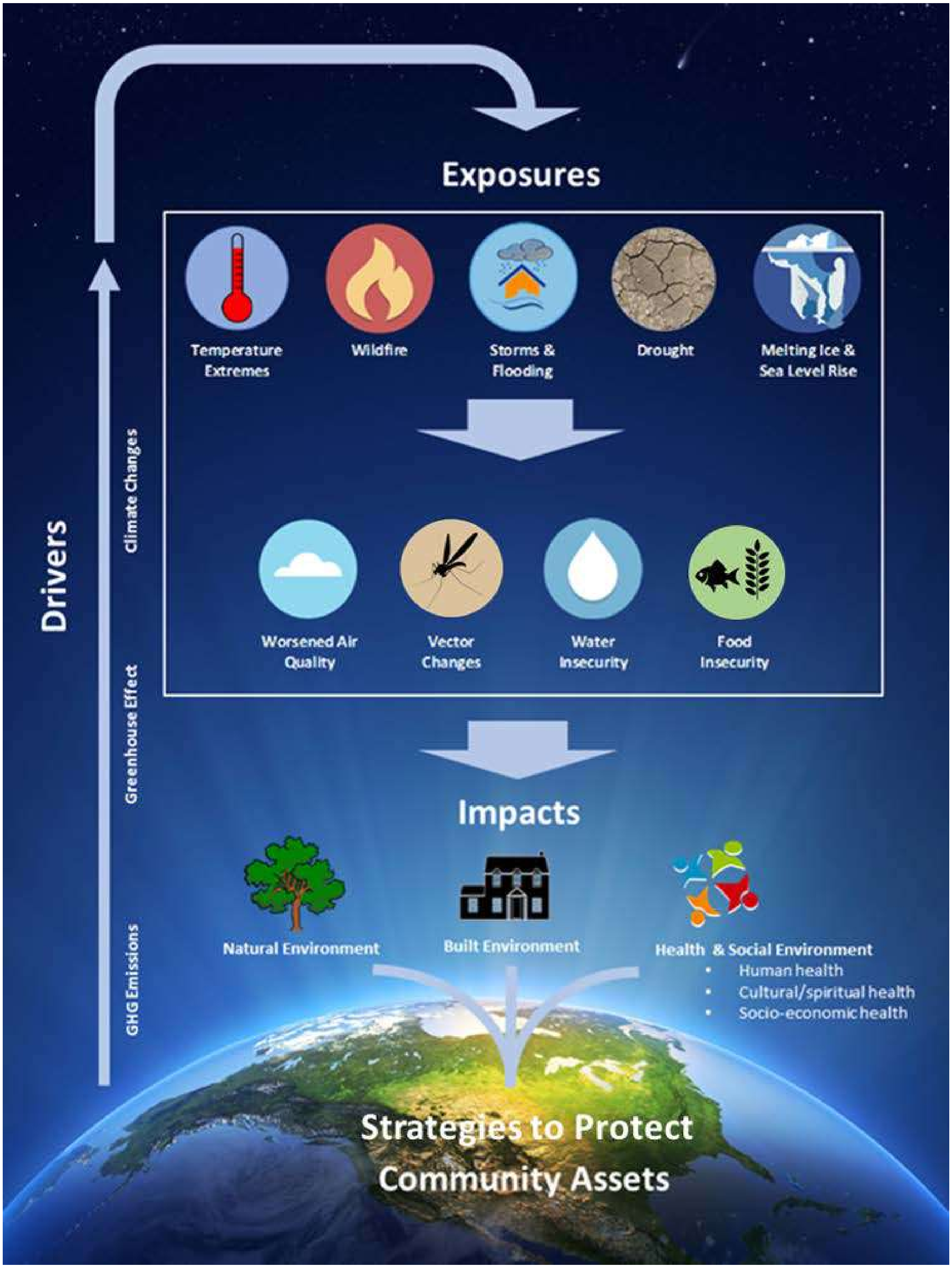
Increasing temperatures and earlier spring warming can also trigger extensive and prolonged algal blooms. These temperature shifts can also impact the breeding cycles of aquatic species that are triggered by warming temperatures, like the federally endangered arroyo toad (*Anaxyrus californicus*). Algal blooms can also negatively impact overall productivity of instream communities (CEC, 2018).

A Tribe's social and economic institutions are an important factor in its overall community health. Extreme heat and its effects on human health can result in a variety of negative socio-economic impacts. Health impacts and power disruptions triggered by extreme heat can result in lost work days and revenues for tribal businesses. For Pala, critical economic drivers include gaming, entertainment, hospitality, and other business ventures. Health impacts and power outages can also result in lost school days and closures of school and afterschool activities that impact Pala's youth.

Figure 5 shows how changing exposures impact health, social, natural, and built environments (Pala, 2019).

Elevated temperatures at Pala increase water evaporation and lower water levels in rivers, streams, and aquifers. This presents a challenging scenario as Pala already relies on groundwater for domestic water and irrigation. Increased water demand from development in the region, coupled with declining water supply from the California snowpack and the Colorado River, will place additional burdens on local water resources.

Figure 5. Interaction of Climate Change Impacts



Source: Pala Environmental Department

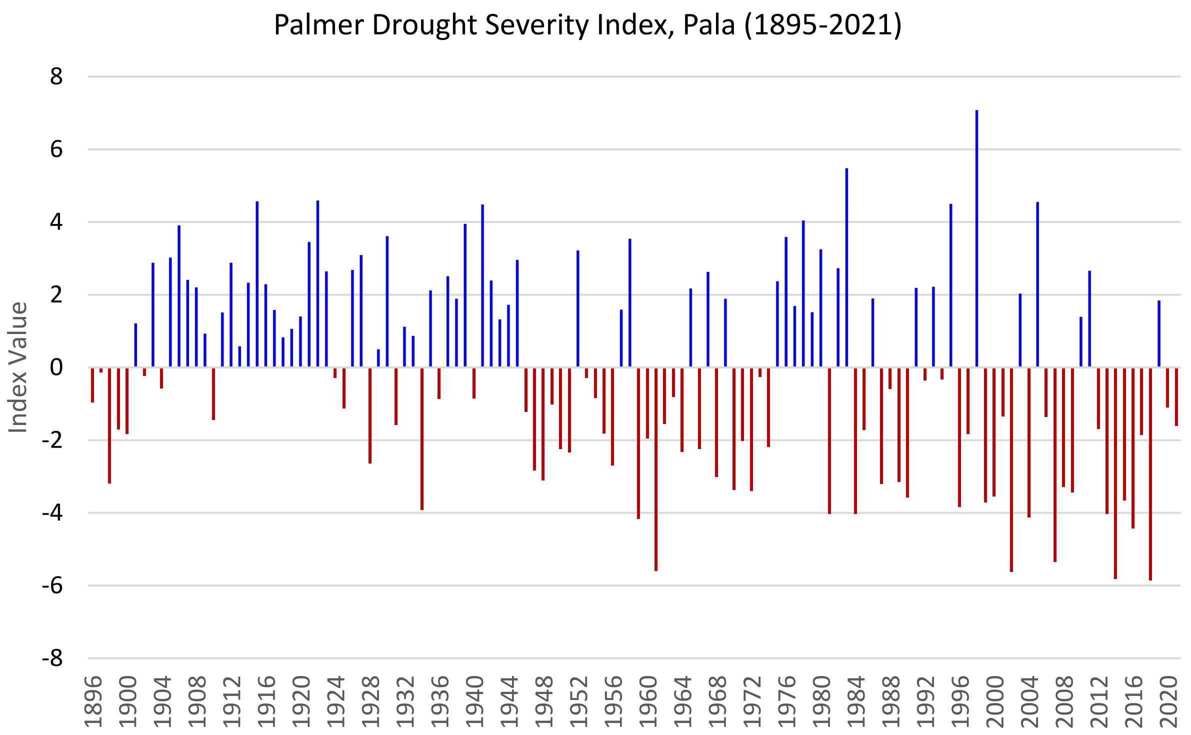
Increased heat intensifies photochemical reactions that produce ground level ozone, a key component of smog associated with motor vehicles, wildfires, and power generation. Levels of ozone at Pala are higher than in 71 percent of the census tracts in California (OEHHA, 2021).

Ozone and smog irritate the human respiratory system and can contribute to and exacerbate respiratory diseases. As a result, Pala residents may experience more cases of decreased lung function, respiratory symptoms, hospitalizations for cardiopulmonary causes, emergency room visits for asthma, and premature death. Anecdotal reports by Pala tribal members indicate an increase in the severity and frequency of asthma symptoms in recent years (Pala, 2019).

Drought

The Palmer Drought Severity Index (PDSI) combines both temperature and precipitation data to provide data on relative dryness (drought) on a scale from +10 (wet) to -10 (dry). The lower the number the drier the conditions. As is shown below in Figure 6, Pala is having more frequent, and more intense, dry years. Prior to 1950, dry years (with PDSI values below zero) occurred 20 times, none of which were classified as extreme drought (PDSI at or below -4). From 1951 to 2021 Pala experienced 48 dry years, including 11 years of extreme drought (Abatzoglou et al., 2022).

Figure 6. Drought at Pala



Source: Abatzoglou et al., 2022

What does this indicator show?

Drought, combined with climate change driven extreme heat, season shifts, and insect and pest outbreaks can weaken plants, trees, and forests or shift growth patterns. There is ample evidence of such drought impacts in Southern California. Some vegetation types in Southern California (e.g., chaparral and coastal sage scrub) have experienced declines in vegetation greenness over the last 17 years (Pala, 2019).

Why is this indicator important?

Pala Environmental Department staff note that manzanita and other upland plants are moving into the riverbed as riparian vegetation and wetlands dry up. Reduced riparian vegetation lowers the area's natural capacity to absorb storm water, which exacerbates flooding threats on the Reservation. Gold spotted oak borer beetle is a concern for the oak groves on the reservation, particularly in light of the increased drought, which has taken a toll on native oak species. Pala Environmental Department staff note declining numbers of Englemann (*Quercus engelmanni*) and coast live oak (*Quercus agrifolia*) trees, which are considered culturally important (Pala, 2019).

Pala Creek used to flow for many days after a substantial precipitation event, but that is no longer the case since repeated droughts have reduced the groundwater basin. Pala staff report that the San Luis Rey River and Pala Creek no longer have regular flow.

Because water levels have been so low in the river and streams, Pala Environmental Department notes that aquatic species such as the arroyo toad and anadromous fish such as Steelhead and Pacific Lamprey are no longer present in significant numbers.

According to Pala Environmental Department's Wildlife Biologist, Pala's reservation is home to endangered or threatened plant species including Parry's tetracoccus (*Tetracoccus dioicus*) and Rainbow manzanita (*Arctostaphylos rainbowensis*). Drought, along with increased temperature, stresses these plants and creates conditions for certain non-native, invasive species to thrive. Examples of invasive species present on the Pala Reservation are eucalyptus, A*rundo*, and tamarisk. These species can degrade habitat quality for native wildlife and contribute to increased wildfire frequencies.

Figure 7. Southwestern willow flycatcher

Source: USFWS

The loss of habitat combined with drought is assumed to be the cause of the disappearance of the southwestern willow flycatcher (*Empidonax trailii extimus*).

Southwestern willow flycatchers live in moist microclimatic and vegetative conditions and breed only in dense riparian vegetation near surface water or saturated soil. Southwestern willow flycatchers have not been seen at Pala since 2013 and are assumed to be extirpated (Pala, 2019).

Drought and changes in precipitation contribute to species migration and range shifts. Native bird species at Pala are dependent on native vegetation for habitat, which has declined during severe drought (Assoc FWS, 2012). At Pala, tree and habitat losses have affected several bird species. In addition to the southwestern willow flycatcher, Pala biologists have also observed a reduction of acorn woodpeckers (*Melanerpes formicivorus*), a species tied to oak trees.

Storms and Flooding

As precipitation becomes less predictable and more intense, flooding is a high concern for Pala and has impacted the Tribe (Prosper Sustainably, 2018). Drought conditions and lower soil moisture lead to flash floods in inland areas, as well as mudslides and landslides, especially in areas recently affected by wildfire.

What does this Indicator show?

Since 1895 Pala has received less annual rainfall over time. When the rains come, these rain events are becoming more intense, causing flooding that rises and falls quickly. (Prosper Sustainably, 2018) The Pala Environmental Department tracks rainfall, water flows, stream levels, storm damage, and flooding at multiple locations on the Reservation. Flooding has become a regular occurrence at Pala. Between 1917 and 1997 there were two major flood events. Since 1997 there have been 22 major floods impacting which flooded roads, damaged property, and trapped residents (Pala ED, 2019).

Figure 8. Flooding across Lilac Extension Road at Pala, February 2019

Source: Pala Environmental Department

Why is this indicator important?

Flooding can weaken and remove vegetation and soil leading to downed trees, erosion, and mudslides. Pala staff have observed that floods have shifted riparian habitats. For example, shifting river sediments and braided water flows during heavy storms have created new San Luis Rey River channels in some areas, while silting and blocking previous flow channels. This leads to a shifting riparian regime that can change between major flood events.

Loss of riparian vegetation reduces the ability of the floodplain to naturally absorb and manage high levels of stormwater. Certain invasive species on Pala lands, such as *Arundo donax* and tamarisk easily spread in flood conditions.

Animals that depend on the riparian habitat and may be temporarily or permanently displaced by storms and flooding including endangered species at Pala such as the southwestern willow flycatcher, yellow-billed cuckoo, coastal California gnatcatcher, and the arroyo toad. The yellow-billed cuckoos (*Coccyzus americanus*) historically nested on or near the San Luis Rey River (USFWS, 2019). According to a recent study (HT Harvey and Associates, 2015)., habitat at Bubble Up Creek and Pala Creek (south of the San Luis Rey River), was of poor quality and unsuitable for breeding, due in part to the minimal width of the riparian habitat.

Figure 9. Flooding at a Pala home, February 2019

Source: Pala Environmental Department

Severe storms, flooding, and runoff can contaminate water supplies with bacteria, viruses, and other pathogens and toxins, limiting the availability of safe drinking water. For example, the 2017 flood event at Pala exposed drinking water pipelines and caused a substantial rise in influent into the wastewater treatment plant (Pala, 2017).

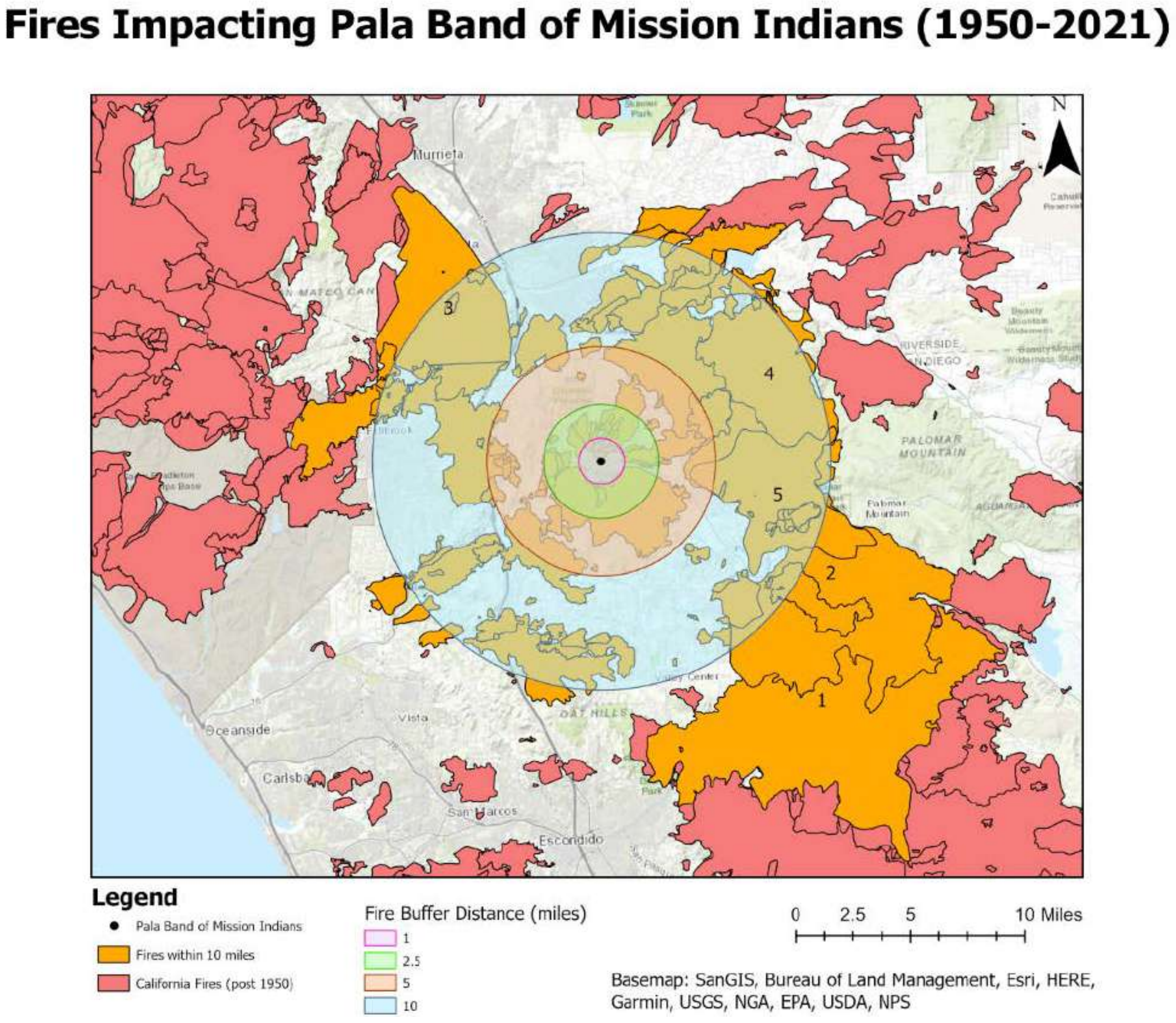
The changing and intensifying storm and flooding patterns Pala has seen have harmful effects on the natural environment. The effects of changing precipitation over time and the difficulty in predicting future rainfall are compounded by uncertainty in how much the inherent resiliency of plants and animals adapted for dry, variable climates can accommodate changing conditions (CEC, 2018).

Wildfire

<u>What does this Indicator show?</u>

The incidence of large forest fires in the western United States has increased since the early 1980s (Wehner et al., 2018). Fire season in California is starting earlier and ending later each year (CAL FIRE, 2020a). There were 40 fires from 1920 to 2021 that affected Pala directly. Recent fires have burned significant portions of Pala's lands (Gaughen, 2020). Three of California's largest wildfires, occurred in San Diego County (CAL FIRE, 2021): The Cedar Fire in 2003, the Poomcha Complex/Witch Fire in 2007 and the Laguna Fire in 2007. These fires burned 273,246 acres, 240,207 acres, and 175,425 acres respectively (CAL FIRE, 2020b). Figure 10 shows fires in the area of the Pala lands that occurred between 1950 and 2021 (CAL FIRE, 2021). In 2021 two fires directly impacted the Pala Reservation.

Figure 10.



Fires Impacting Pala Band of Mission Indians (1950-2021)

Basemap: SanGIS, Bureau of Land Management, Esri, HERE, Garmin, USGS, NGA, EPA, USDA, NPS

Source CAL FIRE, 2021

Why is this indicator important?

Wildfire is considered a high-risk exposure for the Pala Tribe. Nearly a third of Pala's population lives in a high-risk wildfire area. Historically, large, high intensity fires occurred regularly but infrequently in the region. Climate factors including Southern

California's uniquely intense Santa Ana winds, increasing temperatures, and severe drought conditions are increasing the wildfire risk at Pala (OPR, 2018).

Burned areas that then experience heavy rain will be subject to flooding, landslides and rockfalls. Large rain events after wildfires have caused extensive flooding and mudslides at Pala.

Exposure to smoke-related air pollutants, including particulate matter (PM) from wildfires has been associated with a wide range of human health effects, including cardiovascular consequences, early deaths and low infant birth weight, and acute respiratory illness (CARB, 2019).

At Pala, water security, compounded by drought, is an ongoing concern. Wildfire can further stress water supplies if watersheds or water treatment infrastructure are damaged during a wildfire, or when domestic water supplies are used to combat the fire.

Figure 11. Retardant drop on fire near Pala

Source: Pala Environmental Department

Wildfire can destroy culturally important ecosystems, sacred sites, and points of access to culturally important places to Pala. Numerous cultural sites, functions or traditions are in danger of wildfire encroachment and damage. This can threaten Pala's traditional practices, sovereignty, and community cohesion, which are considered highly important community assets (Prosper Sustainably, 2018).

Wildfires have caused evacuations and disruptions at Pala. The Poomacha Fire in 2007 resulted in evacuation of 400 tribal members and closure of the Pala Casino, causing temporary but significant impacts to educational and economic opportunities. Fires at Pala have also disrupted telecommunication lines, hampering the Tribe's ability to do business (Pala, 2016).

Wildfire can initially increase the abundance of ticks and increase the risk of Lyme disease (MacDonald, et al. 2018). There have been cases of Lyme disease in the Pala region in recent years.

Wildfire risk can also increase due to pest infestations and disease vectors affecting forest health (e.g., bark beetles, fungus, shothole borer). Invasive forest pests and tree diseases increase wildfire risk by stressing and killing trees, which increases the mass of dead and dying vegetation that can fuel wildfire outbreaks. Pala environmental staff have observed an increase in diseased trees and an overall decline in oak trees as a result of invasive forest pests.

Pala's wildlife depends on healthy, large, and connected habitats to roam, breed, and hunt. Impacts of wildfire include habitat loss, degradation, and fragmentation that result in genetic isolation. Burned areas are subject to increased erosion resulting in the siltation of creeks, streams, and rivers. This can result in channel aggradation (wider, slower channels) and steep slopes destabilized due to the lack of vegetation (Pala, 2019).

Repeated wildfires at intervals too short to allow recovery of natural vegetation facilitate the conversion of natural woody shrublands (e.g., coastal sage scrub) to weedy, flammable annual grasses. For example, the large fire events of 2007 in San Diego resulted in nearly 74,000 acres of overlap with the four-year-old recovering vegetation that burned in the 2003 Cedar Fire. At Pala, the Poomacha fire burned most of the vegetation in the eastern mountainous region, and the area is now dominated by scrub and non-native grasses (Pala, 2016). The US Forest Service documented that shrublands have converted to non-native annual grasslands on a widespread scale across the Cleveland National Forest, which borders the Pala Reservation (OPR, 2018).

Wildfire and its impact on vegetation conversion, habitat connectivity, food, and freshwater supplies can force animal species to migrate from the area. In San Diego County, repeated fires reduce habitat for shrubland threatened species like the California gnatcatcher (CEC, 2018).

Summary

The people of the Pala Band of Mission Indians continue to work to protect and enhance the natural resources and habitat of their lands. Climate change continues to deeply affect the environment and alter and disrupt the ecosystems within and around Pala. The Pala community is actively working to understand, adapt to, and mitigate the effects of climate change. Their goal is to continue to manage and protect their lands and limit the impact climate change is having on Pala's right to hunt, fish, gather, and continue their cultural practices; activities that are integral to their cultural and psychosocial health, well-being, and livelihood.

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IMPACTS OF CLIMATE CHANGE ON THE SANTA YNEZ BAND OF CHUMASH INDIANS

Sea level rise, flooding, erosion, drought, air quality and changes in flora and fauna are threatening the physical, cultural, and spiritual health of the Tribe, its habitats and ecosystems, and its built environment.

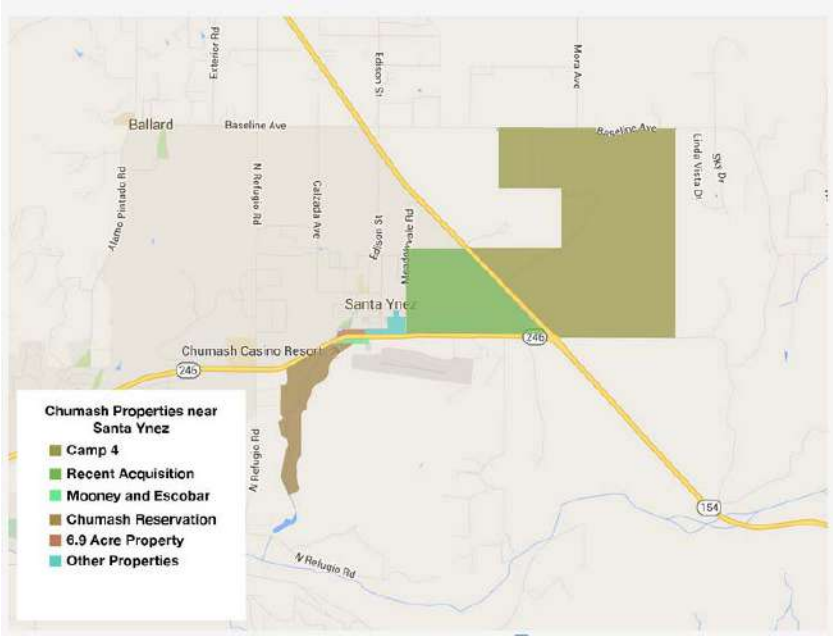
Background

The Santa Ynez Band of Chumash Indians is a sovereign nation located in Santa Barbara County. They are currently the only federally recognized band of Chumash Indians. Santa Ynez is leading a coordinated effort of 11 of the 14 (SYBCI, 2020b) bands of Chumash Indians to document the impacts of climate change on the traditional Chumash territory (SYBCI, 2020a).

> *The culture of the Santa Ynez Band of Chumash Indians is deep within the souls of every tribal member and rests within our hearts. Throughout time, and in spite of challenges, the Tribe has maintained a connection to its ancestors and to a core identity of being Chumash. The Chumash have survived because of their strength as a Tribe and their spiritual connection to Chumash heritage and lands"*
>
> *~Nakia Zavalla, Santa Ynez Chumash Cultural Director*

For over 15,000 years the Chumash lived in a territory that encompassed approximately 7,000 square miles and ranged from the Channel Islands and Malibu to Paso Robles, then inland to the western edge of the San Joaquin Valley (Thornton, 2000). The Chumash population of approximately 25,000 people was decimated by disease and genocide, first by the Spanish starting in 1769, then by the

Figure 1. Chumash properties near Santa Ynez



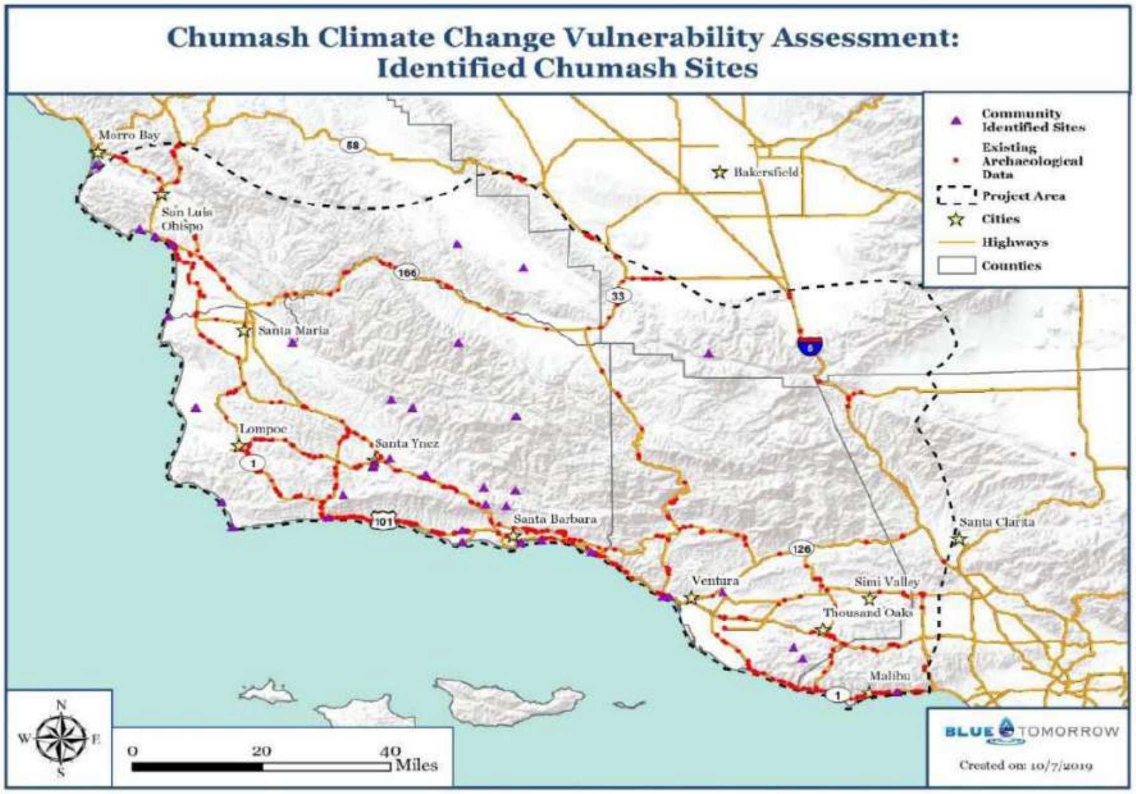
Source: County of Santa Barbara, 2021

Mission system and immigrant Americans colonizing the West (McWilliams, 1983). Today there are approximately 3,000 Chumash.

The Santa Ynez area is primarily rural, with vegetable and flower fields, cattle and horse ranches, vineyards, and wineries. As shown in Figure 1, access to the Santa Ynez reservation is via State Route 246, which connects on the west to Highway 101 and on the east to Highway 154. A creek bed separates the reservation into the Upper Reservation (west) and Lower Reservation (east). The original reservation covered 99 acres. In 2010, the tribe purchased 1,427 acres of land known as the Camp 4 property. The Camp 4 addition brought the size of the reservation to 1,526 acres (SYBCI, 2019). This addition also improved the overall lands of the Santa Ynez Chumash as the original reservation was intentionally placed along a floodplain (McCormick, 1996).

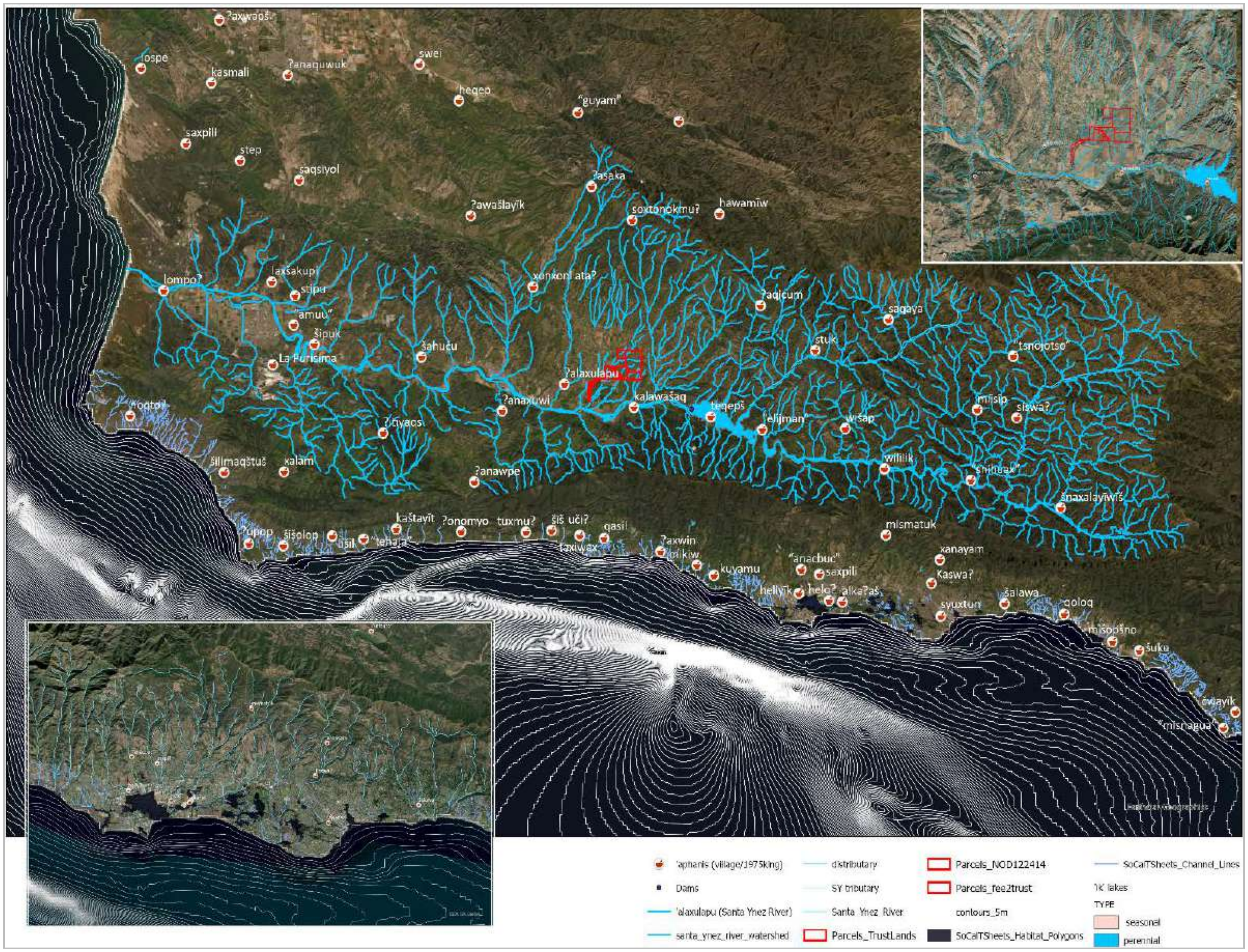
In assessing the impacts of climate change, the Chumash considered the approximate range of traditional Chumash tribal lands as those lands still hold important Chumash cultural sites (see map, Figure 2). Non-federally recognized Chumash bands and sacred and important Chumash cultural sites are located throughout this area (SYBCI, 2020a).

Figure 2. Chumash area considered in assessing the Tribe's vulnerability to climate change ("Project Area," dotted line), and sites of cultural significance to the Tribe



Source: SYBCI, 2020a

Figure 3. Watershed areas and creeks listed in Samala



Source: SYCEO, 2021a

Samala is the primary language traditionally spoken by the Santa Ynez Chumash people. Recent years have seen a renaissance of Chumash pride and identity, including efforts to continue to teach Samala and other Chumash languages (SYBCI, 2020a). For example, the watershed map in Figure 3 identifies creeks using their Samala names within the Chumash tribal area.

Climate change and the Santa Ynez Tribe

According to the Santa Ynez Chumash Environmental Office (SYCEO) Tribal Hazard Mitigation Plan, by 2100 the average temperatures are predicted to rise by over 7 degrees Fahrenheit (˚F), resulting in over six times as many extreme heat days. Average precipitation, currently about 16 inches per year (SB County, 2021), will increase by approximately 4 inches and hectares burned in wildfire will increase by over 20%.

Increasing temperatures, changing precipitation patterns, sea-level rise, wildfires, drought, and debris flows can all cause impacts to the Chumash by disturbing plants and animals, potentially leading to their local extinction. These disturbances in turn may impact traditional hunting and gathering practices, the timing of spiritual practices, and the loss of local food sources, traditional medicinal plants, and traditional materials used for jewelry, sculptures, ceremonial pieces, basketry, nets, and lodgings (SYBCI, 2020a).

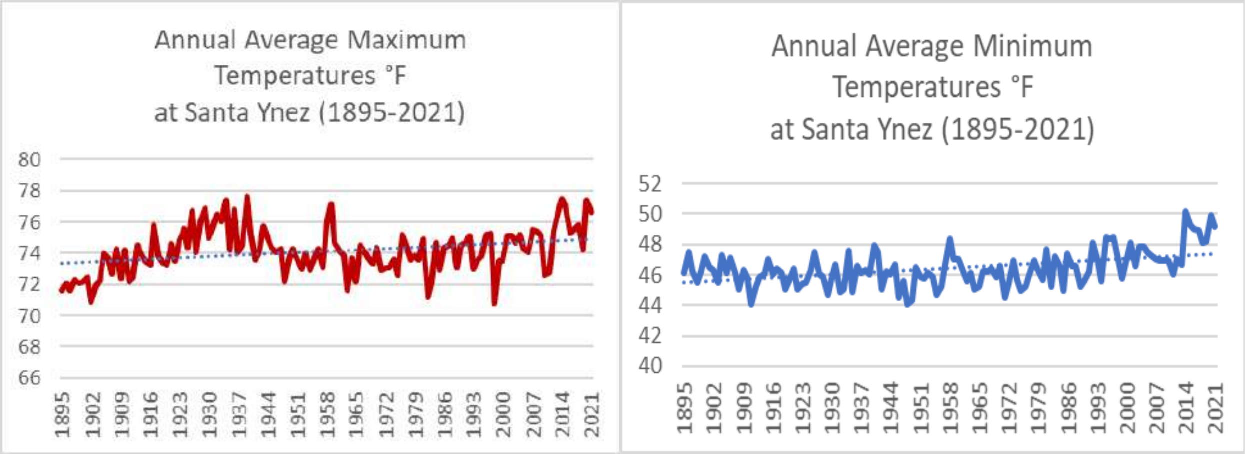
In a survey conducted by the SYCEO as part of a Climate Change Vulnerability Assessment, 90% of respondents stated that climate change and the resulting sea level rise, flooding, erosion, wildfires, reduction and extirpation of plants and animals, has already had an effect on access to cultural sites (Figure 2) and resources, including the availability of plant and animal resources (SYBCI, 2020a).

Elevated Temperatures

What does this Indicator show?

At Santa Ynez, both the nighttime temperatures and daytime temperatures are rising, with the nighttime temperatures rising more quickly. As shown in Figure 4, before 1950 the annual average minimum temperature varied between 41.5°F and 46.1°F and the annual average maximum temperature varied between 72.5°F and 77.5°F. Since 1950 the annual average minimum temperature has been between 42.2°F and 48.5°F and the annual average maximum temperatures has ranged from 71.6°F to 77.6°F (PRISM, 2022).

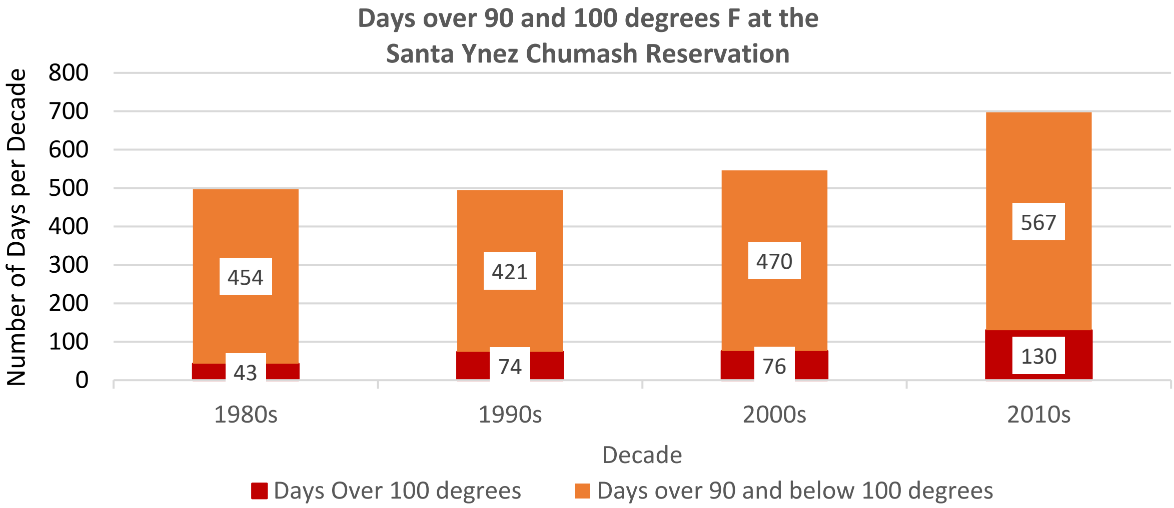
Figure 4. Annual average temperatures at Santa Ynez 1895-2021



Source: PRISM 2022

The number of extreme heat days has increased as well. As shown in Figure 5 the number of days with temperatures over 100°F has more than tripled since the 1980s (PRISM, 2022). In 2020 and 2021 the Tribe experienced 111 days over 90°F and 17 days with temperatures over 100°F.

Figure 5.



Source: PRISM, 2022

<u>Why is this indicator important?</u>

Elevated temperatures affect human health, mental health, cultural and spiritual health, and socio-economic health, as well as the plants and animals that are part of the Santa Ynez Chumash environment. Elders, children, outdoor workers, and those with existing medical conditions are particularly susceptible to these impacts.

With the increasing nighttime temperatures, people do not have the chance to cool down. In addition, in traditionally temperate areas such as Santa Ynez, people are not physiologically acclimated to higher temperatures. The Tribe currently does not have enough cooling centers to help members in need during times of extreme heat.

Many indigenous cultural practices rely on natural or seasonal cycles associated with changes in weather patterns, plants, and animals. Increased temperatures, extreme heat, and heat waves affect the traditional timing of Chumash cultural practices due to climate's effect on the landscape. Warmer temperatures and changes to precipitation patterns may cause plants to fail to grow in one area and be able to grow in another. Some species may be able to expand their range, while others may experience a decrease in range. The Tribe has already seen traditional plants migrating to different areas and the off-season blooming and fruiting of many species (SYBCI, 2020a).

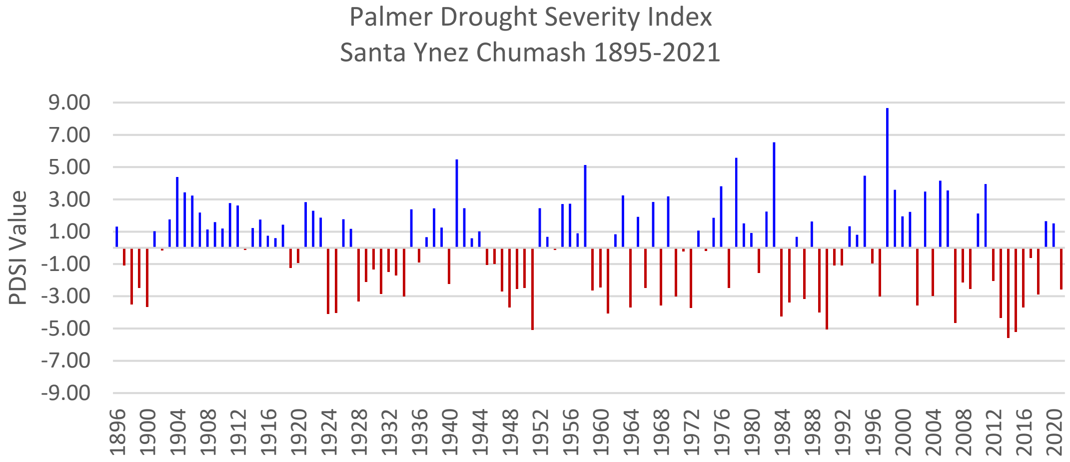
Drought

What does this indicator show?

Because of its geography, Santa Barbara County does not always experience drought at the same time as the rest of California. The county has been free of drought at times of state-declared drought emergencies, but also has experienced drought when there is no state-declared drought. For example, after the state lifted its declaration for the drought of 2014 – 2017, Santa Barbara County's local drought declaration remained in place. As a result, examining impacts at a local level reveals a more accurate picture of drought impacts (SYBCI, 2020a).

The Palmer Drought Severity Index (PDSI) combines both temperature and precipitation data to provide data on relative dryness (drought) on a scale from +10 (wet) to -10 (dry). The lower the number the drier the conditions. As is shown below in Figure 6, the Santa Ynez Chumash Tribe is having more, and more intense, dry years. Prior to 1950, dry years (with PDSI values below zero) occurred 26 times, three of which were classified as extreme drought (PDSI at or below -4). From 1951 to 2021 Santa Ynez experienced 35 dry years, including 7 years of extreme drought.

Figure 6. Drought at Santa Ynez



Source: Abatzoglou et al., 2022

Why is this indicator important?

The Tribe has observed that ground water levels on the Santa Ynez reservation have dropped during drought, and that plants are migrating to higher elevations or are not propagating due to a combination of drought and extreme heat.

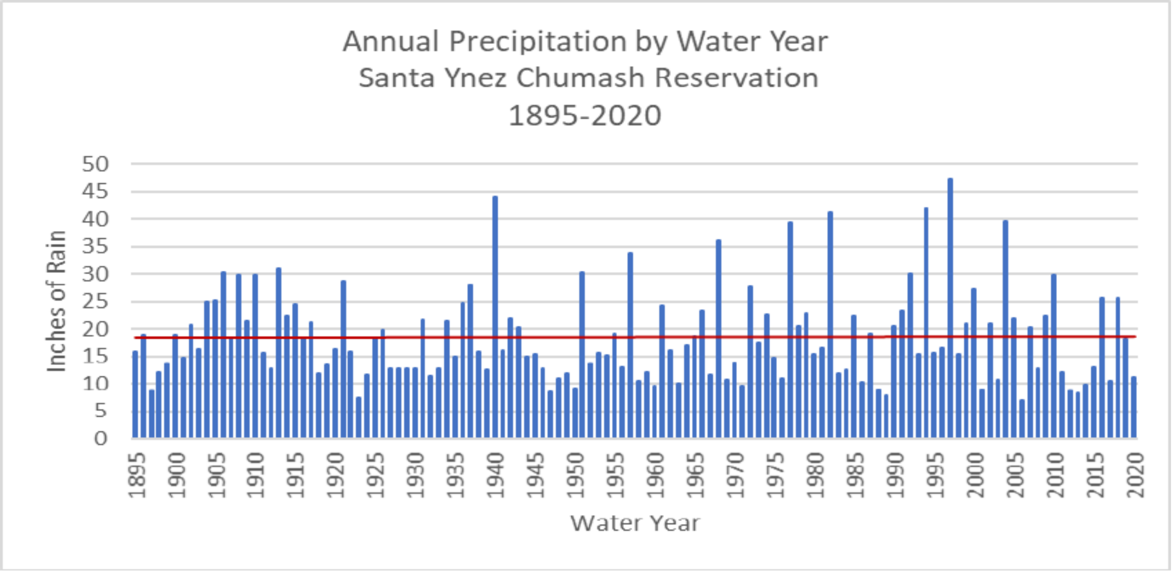
During interviews with the Chumash community, 74 plant species were identified that have traditionally been or currently are gathered. Approximately 76% of respondents (22 individuals) said that they have noticed changes in the availability of plant and animal resources in recent years, with 20 respondents experiencing a decrease in availability. For those respondents who experienced a decrease in plant and animal resource availability, the commonly reported reasons for the decline included: loss of access, overharvest, drought, lack of instream water availability, and development (SYBCI, 2020c).

Precipitation and Flooding

What does this indicator show?

As shown in Figure 7, while the total amount of rain over time has remained steady, the fluctuation in wet and dry years has grown greater over time. Looking at water years, which start in October and run through September the following year, between 1895 and 1958 the Santa Ynez Chumash experienced one year with rainfall over 35 inches. From 1959 to 2020 the Santa Ynez Chumash experienced six years with rainfall of over 35 inches per year. This high intensity rain is matched with high runoff and the Chumash have seen that groundwater is not being recharged as a result (PBMI and SYBCI, 2021).

Figure 7. Annual Precipitation at the Santa Ynez Chumash reservation

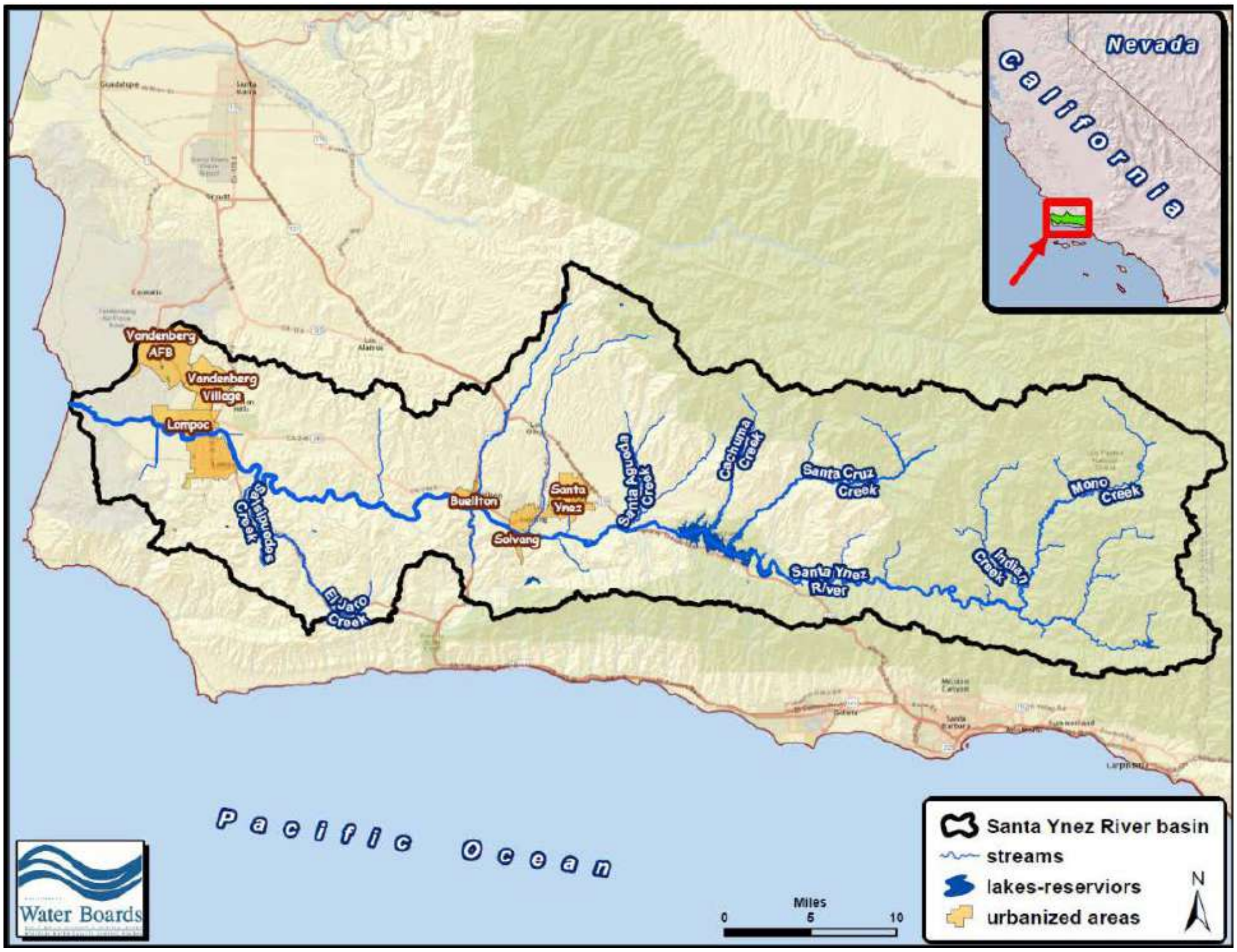


Source: PRISM 2022

Why is this indicator important?

The Santa Ynez Reservation lies within the Santa Ynez River Watershed (See Figure 8, Watershed subbasins). The Santa Ynez River borders the southerly edge of the Santa Ynez Valley, along the northern slopes of the Santa Ynez Mountains. One of the largest rivers on the Central Coast of California, the Santa Ynez River is 92 miles long, flowing east to west across the valley, through Solvang, Buellton, and Lompoc. The watershed encompasses 897 square miles. It drains from the Santa Ynez River's headwaters in the Santa Ynez Mountains west through the Santa Ynez Valley before emptying directly into the Pacific Ocean north of Surf Beach. Elevations range from 4 feet at the head of the estuary to 6,820 feet in the Santa Ynez Mountain headwaters.

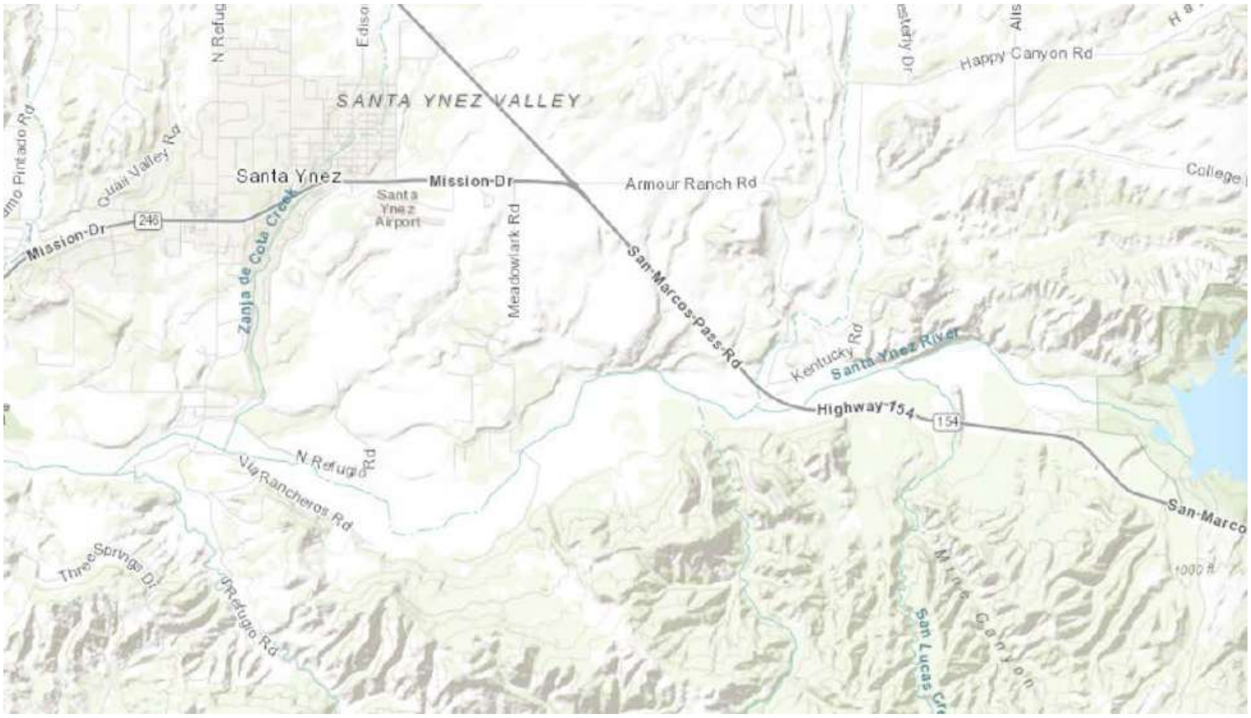
Figure 8. Santa Ynez River watershed subbasins



Source: Waterboards, 2016

The USGS designates the Santa Ynez River as a fourth-order river (medium sized) with 2,077 miles of total tributary stream length: 1,663 intermittent miles, 350 perennial miles, and 63 miles of man-made channels. Drainages exiting the hills and draining to the Santa Ynez River cross the valley northeast to southwest. The most significant surface water for the Santa Ynez Tribe is the Zanja de Cota Creek (see Figure 9) which bisects the original Santa Ynez Chumash reservation lands.

Figure 9. Zanja de Cota Creek



Source: USGS, 2021

With increasingly variable precipitation, extreme rainfall events are projected to pose a risk of flooding. (Coastal Resilience, 2020). Santa Barbara County experienced 14 significant floods between 1862 and the 1998. Eight of these floods were declared state and federal disasters. The Santa Ynez Reservation has seen major flooding along Zanja de Cota Creek and the Santa Ynez River. In recent years, major flooding along the creek occurred in 1980, 1995 and 1997.

The 2019 Santa Ynez Band of Chumash Multi-Hazard Mitigation Plan (SYBCI, 2019) provides an account of flooding on the reservation along Zanja de Cota Creek and the Santa Ynez River. As is summarized below in the first 130 years of modern flood records the Santa Ynez Chumash endured four major floods; in the last 30 years the Santa Ynez Chumash have experienced five major floods.

Summary of major flood events

- 1862—Great Flood
- 1907—Flood flows on the Santa Ynez River engulfed the entire Lompoc Valley
- 1969—California declared Santa Barbara County a disaster area on January 25; major flooding along the Zanja de Cota; Santa Ynez River experienced the highest flows in almost 3,000 years; 16 inches of rain fell at Juncal Dam (Goleta)

in a 24-hour period; in the Upper Santa Ynez watershed, the flood was equivalent to a 100-year storm

- 1980—Major flooding along the Zanja de Cota; mudslides in some areas
- 1992–1993—Santa Ynez Valley received approximately 180 percent of normal rainfall
- 1995—Major flooding along the Zanja de Cota; part of widespread flooding throughout the County
- 1997–1998—Flooding along the Zanja de Cota; several record-breaking rainfalls with 50-year storm event intensities in February 1998
- 2011 (March) Santa Ynez River flooding
- 2018 Montecito debris flow. This debris flow impacted local Chumash cultural resources and caused damage to the reservation.

Sea level rise

What does this Indicator show?

The Nation Oceanic and Atmospheric Administration (NOAA) reports that the mean sea level in Santa Barbara County has increased an average of 1.08 millimeter per year between 1973 and 2020 (NOAA, 2021).

Why is this indicator important?

Sea level rise and the resulting erosion are already impacting important Chumash cultural sites along the coast (PBMI and SYBMI, 2021). Like many cultures, the Santa Ynez Chumash youth are taught by parents or elders in the group. As sea levels rise, sites previously used for gathering are no longer accessible. In addition, the Tribe has seen damage to cultural sites due to erosion along the coast. Without access to these traditional sites, knowledge can be disrupted, and the weight of that loss is felt by generations of tribal members (PBMI and SYBMI, 2021).

Olivella shells (Figure 10), are gathered by the Tribe for use in shell money, jewelry, and regalia, are becoming more scarce and traditional areas for gathering are often no longer accessible (PBMI and SYBMI, 2021).

While sea water intrusion is not expected to impact the Santa Ynez reservation directly, its impact on other aquifers will likely increase dependency on the other groundwater basins between the Santa Ynez Mountains and the Pacific Ocean (Coastal Resilience, 2020).

Figure 10. Olivella shells carved by the Chumash

Source: Science News, 2021

Impacts on Plants and Animals

What does this indicator show?

The Santa Ynez Chumash have already seen a reduction or extirpation of species such as steelhead, red-legged frogs, kelp, sea grass and Olivella. Both Chia Sage (*Salvia columbariae*) and Chuchupate (*Ligusticum porter*) are no longer found in the area and grow only at higher elevations where temperatures are cooler, and more water is available.

Plant communities and animal habitats are anticipated to be further affected by changes to primary (temperature, precipitation, sea-level rise) and secondary (drought, wildfire, flooding, flooding, cliff erosion, debris flows, and wildfire) climate change impacts (SYBCI, 2020a).

Why is this indicator important?

The Chumash have always harvested from both the land and the sea. Changes in ocean temperature and ocean acidification have impacted species important to the tribe (PBMI and SYBMI, 2021). In 2013 sea stars, the main predator of purple urchin, were decimated by the sea star wasting disease virus; while the causes of the incident have not been established, it is hypothesized that elevated ocean water temperatures may have been an exacerbating factor (Miner et al., 2018). With sea stars gone, the urchin population grew unchecked.

2014 brought a marine heat wave, which was followed in 2015 by an El Niño causing the ocean waters to warm further. These warm waters contained fewer nutrients than the normally cold coastal California waters, which caused kelp to grow more slowly. Urchin and abalone both mainly eat kelp. The explosion in the urchin population and the reduction in kelp due to warming waters impacted two species important to the Chumash: kelp and abalone (UCD, 2021).

Many species which are important to the Santa Ynez Chumash are currently threatened by climate change such as: Belding’s Savannah Sparrow, tidewater goby, steelhead, snowy plover, willow flycatcher, white-tailed kite, monarch butterfly, Coastal Range newt, Western Pond Turtle, and brown pelican. Waqaqˀ (red-legged frogs, Figure 11), in particular, used to thrive on the reservation, are no longer present.

Figure 11. Waqaq' (California red-legged frog)

Source: Los Padres Forest Watch

The Zanja de Cota Creek that flows through the reservation used to be the site of steelhead fishing derbies (Figure 12). Due to the drop in water in the creeks, and an increase in pesticide runoff, there are no steelhead remaining in the creeks.

Figure 12. Historic photo - steelhead caught along Zanja de Cota Creek (1912)

Source: Lompoc Historic Society

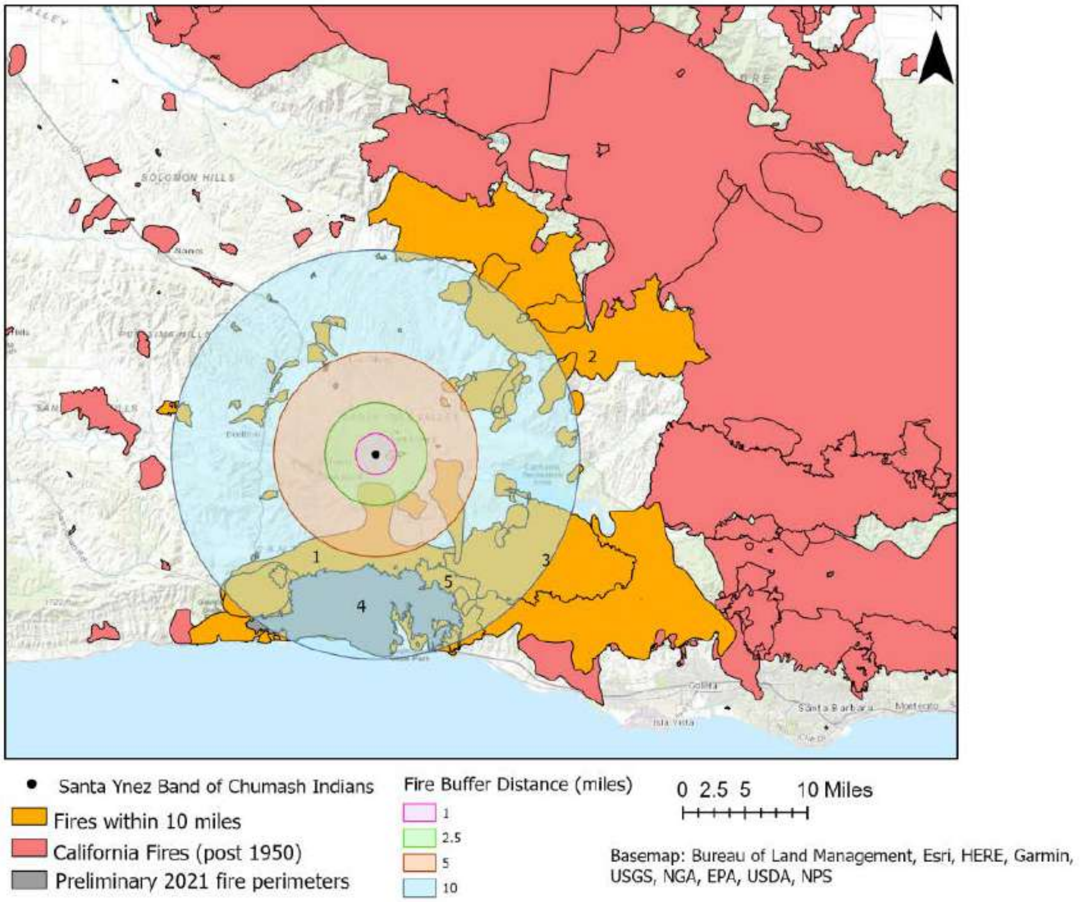
Wildfire

What does the indicator show?

The incidence of large forest fires in the western United States has increased since the early 1980s (Wehner et al., 2018). Fire season in California is starting earlier and ending later each year (CAL FIRE, 2020). A study of microscopic charcoal from the Santa Barbara Channel indicates that over the past 560 years large wildfires (greater than 500 acres) occurred in the Santa Barbara County area an average of every 20 to 30 years (Mensing et al., 1999). Prior to the 1950s, the greater Santa Barbara area averaged one large fire per decade; however, the number of large fires within and adjacent to the County has increased substantially. There were 93 large fires within Santa Barbara County between 1955 and 2021 that burned over 1,475,042 acres. This equates to 1.4 significant fires every year (SB Fire Safe Council, 2021, CAL FIRE 2021). Figure 13 shows the fires that came from within one to ten miles of the Santa Ynez Chumash reservation between 1950 and 2021.

Figure 13.

Fires Impacting the Santa Ynez Band of Chumash Indians (1950-2021)



Source: CAL FIRE, 2021. Map generated using fire perimeter data from CAL FIRE

<u>Why is this indicator important?</u>

Wildfire is considered a high-risk exposure for the Santa Ynez Chumash tribe. Climate factors including Santa Barbara's Sundowner winds (Ryan et al., 1992), increasing temperatures, and severe drought conditions are increasing the wildfire risk at Santa Ynez.

Firefighting equipment can expose and destroy cultural sites. Burned areas that are then subjected to heavy rain will be subject to flooding, landslides and rockfalls. Cleanup of burned areas can expose cultural artifacts and destroy sites important to the Tribe. SYCEO has begun studying impacts in burn scar areas, including loss of trees and species that are returning to these areas. Some burn scar areas are not supporting the growth and reproduction of tree seedlings, likely due to warmer temperatures or insufficient moisture related to climate change, in addition to the wildfires.

Poor air quality, caused by wildfire smoke, is of great concern on the reservation; when wildfire smoke is present outdoor activities cannot occur, ceremonies and gathering activities are cancelled. Smoke more heavily impacts Tribal members who have asthma, or other respiratory related health issues such as chronic obstructive pulmonary disease (COPD).

Summary

Warming temperatures, drought, increasingly variable rainfall – and ensuing floods – erosion resulting from sea level rise, and wildfires have impacted the people of the Santa Ynez Band of Chumash Indians and their environment. In addition to exposures to temperatures much warmer than they are acclimated to, these changes have altered and disrupted the ecosystems within and around Santa Ynez, impacting many species of cultural importance to the Tribe, and interfering with their ability to carry out traditional practices. The community is actively working to understand, adapt to, and mitigate the effects of climate change. Their goal is to continue to manage and protect their lands and limit the impact of climate change on the Santa Ynez Chumash Tribe's right to hunt, fish, gather, and continue their cultural practices –activities that are integral to their cultural and psychosocial health, well-being, and livelihood.

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Emerging climate change issues

Scientists are reporting changes in California’s environment that are plausibly — but not yet established to be — influenced by climate change. The link to climate change is supported by scientifically defensible hypotheses, models, and/or limited data. However, deciphering the influence of climate among other factors presents a challenge. Factors such as land use and environmental pollution, as well as the inherent variability of the climate system, make it difficult to attribute some of these changes and impacts to climate change. Environmental changes and trends for which the influence of climate change remains uncertain are discussed in this section as ***emerging issues***. Additional data or further analyses are needed to determine the extent by which climate change plays a role.

Changes in Climate

Central Valley Fog

Fog, which is a cloud (stratus or stratocumulus) at or near the ground or ocean surface, consists of droplets 100 times smaller than raindrops that stay suspended in air, sometimes coalescing into drizzle or collecting on surfaces to form “fog drip” (AMS, 2022). Valley fog promotes colder temperatures during the winter, a critical factor for achieving a period of dormancy (“winter chill”) in agricultural regions such as the Central Valley. Both anecdotal evidence and field measurements indicate that California’s Central Valley winters are less foggy than they were several decades ago. In one study, scientists collected data from satellite imagery and weather stations to analyze weather conditions and occurrences, spatial extent and long-term trends in “tule fog” — a thick winter ground fog that blankets the valley (Baldocchi and Waller, 2014). The researchers paired satellite records from the National Aeronautics and Space Administration and the National Oceanic and Atmospheric Administration with data from a network of valley weather stations and counted the number of days each year when fog occurred during the winter from 1981-2014. Over the 33-year timespan, the number of winter fog events decreased 46 percent, on average, with much year-to-year variability. The optimal meteorology for Central Valley fog formation occurs during winters with periodic storms followed by periods of high pressure across California. This allows ample humidity from evaporating soil moisture to condense and form fog during the cold, clear nights (Baldocchi and Waller, 2014).

Rising temperatures in densely populated areas (the “urban heat island effect”) have been associated with a decline in the number of days and spatial extent of valley fog (Klemm and Neng-Huei, 2016). Increasing temperatures make it more difficult for atmospheric water vapor to condense and less likely for fog to form. Further, higher temperatures can evaporate fog that forms (hence, fog evaporates in the morning when the sun rises). In addition to air temperature, drought years tend to be associated with lower numbers of fog days because there is not enough evaporating soil moisture to form fog (Baldocchi and Waller, 2014).

Other studies report that the observed reduction in fog in the Central Valley and in other areas worldwide correlates more with a decline in air pollution (Gray et al., 2019; Gray et al., 2016; Klemm and Neng-Huei, 2016). Airborne particles, including dust and other air pollutants, serve as nuclei for water vapor to condense around. One study concluded that climate variables (in particular, the difference between ambient temperatures and dew point) strongly influenced the short-term, year-to-year variability in fog frequency; however, changes in air pollution are driving long-term temporal and spatial trends in Central Valley fog (Gray et al., 2019). This study found that from 1930 to 1970, valley fog significantly increased due to high levels of nitrogen oxide emissions attributed to a surge in use of motor vehicles. The downward trend in fog frequency since 1980 is consistent with the trend of decreasing air pollution due to statewide vehicular emissions regulations over the past decades. While decreasing air pollution appears to be a major factor in the decline of fog formation, scientists recognize that rising temperatures also play a role and will likely have a significant impact as temperatures continue to rise in the future. The concurrent roles of changes in air pollution (including agricultural burning) and climate on changing fog trends in the Central Valley remain an area of ongoing research.

Coastal Fog

Coastal marine fog is an important climatological feature of California (USGS, 2022). It is formed by complex interactions involving ocean evaporation, aerosols, atmospheric pressure, vertical air layering, onshore-offshore temperature gradients, and coastal mountain topography. In hilly terrain along the California coast, the low cloud layer touches the ground at higher elevations. Coastal fog is a result of a delicate balance between moist marine air cooled by the ocean and an upper layer of drier, warmer air capping the fog layer, forming an inversion. As it moves from the ocean into coastal California, marine fog provides moisture to the arid and semi-arid coast, especially in the warm summer months.

Globally, observations of fog from ships since 1800 are available, as well as observations from airports since 1950, and from satellites since 1980. Each of these vantage points gives a different perspective on long-term trends. Off the California coast, ship-based observations show an increasing trend in summertime marine fog (that is, fog over the ocean) since 1950 (Dorman, 2017). Over land, a study found a 33 percent reduction in summertime coastal fog frequencies along California’s coastal redwood region from 1951 to 2008 (Johnstone and Dawson, 2010). Reductions in summertime coastal fog due to shifts in coupled ocean-atmospheric processes have also been observed globally, including Hokkaido, Japan (Sugimoto et al., 2013); the Kiril Islands, Russia (Zhang et al., 2015); and in Europe (Egli et al., 2017).

Coastal fog formation is driven by many climate processes and physical influences (Clemesha et al., 2017; Koračin et al., 2014). High pressure zones over the Pacific, which help to produce inversions, can change position leading to changes in fog frequency. Strong coastal winds can increase colder ocean water upwelling, leading to a thicker fog layer (Dorman, 2017). Turbulence between layers of moist air and dry air can carry moisture out of the fog layer as it mixes into the drier air layer above it, dissipating the fog. In addition, highly localized offshore and onshore movements of fog are affected by complex topographical features such as mountains and other geological barriers (Torregrosa et al., 2016; Wang and Ullrich, 2017).

Warming temperatures can have a strong influence on some of the processes affecting fog formation. Periodic increases of coastal fog have been associated with the warm phase of the Pacific Decadal Oscillation, an ocean temperature index (Witiw and LaDochy, 2015). Changes in global air patterns can also cause strong changes in fog at the local level. For example, the resilient atmospheric ridge that parked warm dry air over California in August 2017 shut down the usual pattern of onshore coastal fog advection into coastal ecosystems (see also September 2010 event, Kaplan et al., 2017). How these climate processes work together under the influence of changing climate conditions is not well understood.

In addition to large-scale climate forces, fog formation is influenced by local conditions. Studies of coastal fog in Southern California report reductions in fog near densely populated urban areas (LaDochy and Witiw, 2012; Williams et al., 2015). Urban surfaces warm during the day, causing warmer nighttime air temperatures that prevent fog droplets from forming. Declining atmospheric particulate levels are also associated with reductions in coastal fog in Southern California.

Fog plays a vital role in coastal ecosystems. Species restricted to the coastal zone such as coastal redwood trees can get up to a third of their water from fog (Burgess and Dawson, 2004). Plants in fog-filled forests can take in water through their leaves, supplying lifesaving “fog drip” to salmon and trout in low flow coastal streams that would otherwise dry out during the late summer dry season (Dawson, 1998; Sawaske and Freyberg, 2015). Shade from summertime fog and low clouds cool coastal systems, reducing the rate of plant evapotranspiration and plant uptake of subsurface water reserves, leaving more water in the system (Chung et al., 2017). Summertime fog and low clouds carried by winds move deep into California’s northwestern oriented valleys that are some of the states’ most productive agricultural regions, including the Salinas Valley and the wine grape growing regions of Sonoma and Napa counties (Torregrosa et al., 2016). Crop irrigation demand has been shown to decrease during fog events (Baguskasa, 2018).

The disappearance of fog in late summer can exacerbate the climatic water deficit for entire watersheds, leading to fire-ready tinder conditions. In urban areas, the disappearance of summertime fog leads to warmer summertime temperatures that result in greater electrical demand for cooling. Coastal fog and cloud cover can also play a role in a watershed's capacity to provide cool water to streams that serve as habitat for Coho salmon and other salmonids (Torregrosa, et al., 2020). The importance of fog to California's water and energy balance and to human and ecosystem wellbeing is receiving increased attention and study (Burns, 2017; McLaughlin et al., 2017; Torregrosa et al., 2014). Research on climate change impacts on fog formation will help to improve forecasts of future trends and understanding of coastal fog impacts on California. Researchers are even exploring the use of geoengineering to increase marine clouds to cool the planet (Ahlm et al., 2017).

Lightning

Lightning is a transient, high-current electric discharge in the atmosphere. Air movements and collisions between particles of liquid water, ice crystals and hail in clouds cause these particles to become charged. Air acts as an insulator between the positive and negative charges in the cloud and between the cloud and the ground. When the opposite charges build up above a certain threshold, the insulating capacity of air breaks down, resulting in a rapid discharge of electricity known as lightning. The flash of lightning temporarily equalizes the charged regions in the atmosphere until the opposite charges build up again (NSSL, 2018, Schumann and Huntrieser, 2007).

Source: NASA

A number of studies have shown that lightning activity is sensitive to surface air temperature changes (Price, 2013). An analysis of observational data for the contiguous United States found precipitation and convective available potential energy (CAPE), a measure of atmospheric instability, to be highly correlated with lightning frequency (Romps et al., 2014). Using climate models that predict an increase in CAPE and variable changes in precipitation over the 21st century, the researchers estimated an increase in annual mean lightning strike frequency of 12 percent per degree Celsius (^{o}C) increase in global average temperature (an increase of about 50 percent over this century, based on a projected 3.6^{o}C increase in temperature). However, other studies that account for the effect of warming temperatures on the formation of ice particles in clouds projected decreases in lightning activity globally (Finney, et al., 2018; Jacobson and Street, 2009). Aerosols from industrial processes and transportation services may also impact lightning; during the COVID-19 lockdown period, lightning strikes decreased drastically in Europe and

Oceania compared to the previous year due to reduced human activity and significant reduction in particulate matter and aerosol concentrations (Yusfiandika, et al., 2021).

A review of studies on the effect of climate change on lightning found inconsistent projections, and concluded that the widely different results indicate a need to better understand the dynamics and life-cycle of thunderstorms in different geographical and seasonal settings (Yair, 2018; Holzworth et al., 2021). These conflicting findings suggest the need for further research, particularly in light of the role that lightning plays in initiating wildfires.

Lightning can amplify climate-related impacts by igniting wildfires and producing atmospheric greenhouse gases. Lightning-initiated wildfires have driven most of the recent increase in large wildfires in the forests of western United States, including California (NIFC, 2022; Li, et al., 2020). Lightning produces nitrogen oxides that lead to the production of tropospheric ozone, a potent greenhouse gas (Schumann and Huntrieser, 2007).

Vegetation and Wildlife

Cyanobacterial Harmful Algal Blooms (Freshwater)

Cyanobacterial harmful algal blooms (CyanoHABs) are colonies of plant-like bacteria that grow out of control and often produce toxins (cyanotoxins), threatening inland water ecosystems, public health, and economies. In California, CyanoHABs mainly occur in freshwater and low salinity waterbodies. Globally, they are expanding in occurrence, distribution, intensity, and toxicity due to a combination of climate change and anthropogenic eutrophication (the overabundance of nutrients in a waterbody due to the actions of people) (Ho et al. 2019; Paerl and Barnard, 2020; Taranu et al. 2015,). In California, CyanoHABs have been increasing over the past 40 years based on periodic and anecdotal data (SWRCB, 2021). Ongoing observational data between 2016 and 2020 also show that CyanoHABs are increasing spatially and temporally throughout the state, occurring in freshwater bodies from high elevation to the coast and sometimes lasting from 6 to 12 months. In 2020, California received 370 reports of CyanoHABs compared with 190 reports in 2018. Reporting is voluntary so this is likely an undercount of CyanoHABs for the state.

Climate change drivers of CyanoHABs include increasing water temperatures, changing precipitation rates, rising occurrences of extreme storm events, and increasing carbon dioxide levels (Paerl 2016; Paerl and Paul 2012; Paerl et al. 2018). Increasing temperatures cause CyanoHABs to grow faster, to appear in places that were previously unsuitable to them and to appear at new times of the year and for longer durations (Suikkanen et al., 2013). Increasing temperatures also result in water stratification, which provides an excellent setting for CyanoHABs. Increased precipitation significantly increases the transport of nutrients from land to surface waters, which promotes the growth and duration of CyanoHABs (Carey et al., 2012; IPCC, 2014b). In shallow waterbodies, increased precipitation can also elevate the flux of legacy nutrients stored in the sediment to the surface (Paerl and Barnard, 2020). Extreme storms can promote CyanoHABs through wind forcing and vertical mixing, which causes sediment resuspension and the release of legacy nutrients (Wells et al., 2015). Decreased levels of precipitation can slow the flow of rivers and streams, leading to hydrologically stagnant waters, which promote the occurrence of CyanoHABs (Paerl and Huisman, 2008). Another climate driver of CyanoHABs is the increasing levels of dissolved carbon dioxide in waterbodies. Elevated carbon dioxide levels can lead to increased growth rates of cyanobacteria, which will intensify CyanoHABs (Raven et al., 2020; Verspagen et al., 2014; Visser et al., 2016).

CyanoHABs are also associated with anthropogenic eutrophication, such as agricultural land use, animal wastes, sewage and industrial and household use of products containing phosphorus and nitrogen (Le Moal et al., 2019). Nutrients from these processes enter waterbodies through runoff, storm drains, wastewater, and other direct discharges. Excess nutrients lead to enhanced growth of cyanobacteria, phytoplankton, and aquatic vegetation. Anthropogenic eutrophication is increasing due to land use changes, urbanization, and industry. The influence of eutrophication on CyanoHABs is difficult to distinguish from that of climate change (Wells et al., 2020).

CyanoHABs in California significantly threaten aquatic ecosystems and species that interact with them. CyanoHAB-related fish and wildlife kills are reported every year in California (SWRCB, 2021). People and domestic animals are exposed to cyanotoxins through drinking water, fish or shellfish consumption, or water recreational activities. In California, the number of public health advisories at recreational waterbodies has doubled since 2016 (SWRCB, 2021). Every year the state receives reports of illnesses in people and death in domestic animals following exposures to cyanotoxins (SWRCB, 2021). Economic losses due to CyanoHABs in the United States are estimated to be four billion dollars annually from impacts on drinking water, recreation, tourism, and aquatic food production (Kudela et al., 2015).

Invasive Agricultural Pests

Current warming has already enabled many invasive species worldwide, including insects, to extend their distributions into new areas (IPCC, 2022). Generally, the establishment and spread of an introduced species will be most successful when it has characteristics favored by the changing climate, such as being drought tolerant. While climate change increases the likelihood of the establishment, growth, spread, and survival of invasive populations, human factors such as the movement of goods and people and habitat disturbance are overwhelmingly more important (IPCC, 2014).

Temperature is probably the single most important environmental factor influencing insect behavior, distribution, development, survival and reproduction (Das et al., 2011). Generally, increasing air temperature is beneficial to insect pests. For those insects that breed continuously, as long as upper critical limits are not exceeded, rising temperatures accelerate every stage of an insect’s life cycle. The reduced time between generations leads to larger insect populations. In addition, warming temperatures can cause host crops to ripen early and prompt an earlier invasion by insect pests; at the same time, warming also lengthens the growing season, providing more opportunities for insects to inflict more damage on crops. During the winter, warmer temperatures will reduce insect death, allowing greater numbers to survive and reproduce in subsequent growing seasons (USDA, 2013).

Credit: Scott Bauer, USDA

Adult female oriental fruit fly, *Bactrocera dorsalis*, laying eggs by inserting her ovipositor in a papaya.

In California, new insect species arrive frequently. Warmer temperatures can allow such species to thrive where they previously could not survive. Invasive species include insects destructive to a wide variety of crops grown in the state, such as the *Bactrocera dorsalis,* also known as the Oriental fruit fly (OFF). OFF is endemic to Southern Asia and established in the Hawaiian Islands. These flies were first found in California in 1960 and have been reintroduced every year since 1966 through the movement of infested goods into the state. Economic impacts from establishment of this fly include damaged fruit and adverse impacts on native plants, increased pesticide use statewide by commercial and residential growers and loss of revenue due to export restrictions on fruit. In 2015 the estimated value of crops affected by OFF was over $16.4 billion (CDFA, 2018). It has been estimated that the cost of not eradicating OFF in California would range from $44 to $176 million in crop losses, additional pesticide use, and quarantine requirements (CDFA, 2018).

Climate change may be influencing OFF populations in California. Records from the California Department of Food and Agriculture (CDFA) and County Agricultural Commissioners of over 63,000 detection traps statewide for exotic fruit flies (CDFA, 2022), show that historical trappings of OFF were reported primarily between the months of June through December. In the past decade, detections have continued into January and February (2011 and 2015), suggesting that winter temperatures may be becoming more favorable for the insects (CDFA, 2018). Furthermore, earlier detections in April and May have become a common occurrence. These changes may be due to the earlier importation of infested fruit into the state (as fruit ripen earlier at their location of origin with warming temperatures). Likewise, warmer temperatures in California are likely to cause earlier ripening of host fruits, increase fly populations, and reduce temperature-related mortality. Scientists caution that biological responses are complex and cannot be predicted by single variables (e.g., increase in temperature or rainfall) (CDFA, 2013). Attributing changes in invasive pest populations to climate change is difficult without accounting for dynamic interactions between multiple species and climate variables as well as human influences. It should be noted that there have been fewer detections of pests during the COVID-19 pandemic, likely due to reduced travel and trade.

Eradication actions undertaken by CDFA and the US Department of Agriculture over the years have prevented invasive pest introductions from becoming permanently established. CDFA has initiated efforts to evaluate pest and invasive species movement with climate change using internal pest detection databases. This information informs the development of predictive models that assist CDFA's invasive species programs to effectively control invasive species and mitigate food crop loss (California Natural Resources Agency, 2016).

Bluetongue in Livestock

A warming climate can impact livestock directly by causing heat stress and indirectly by affecting vector-borne disease occurrence (IPCC, 2022). Bluetongue (BT) is a vector-borne viral disease of sheep, goats and cattle transmitted by biting midges of the arthropod genus *Culicoides.* Bluetongue infections cause high morbidity and mortality primarily in sheep. Disease outbreaks can also influence international trade, movement of livestock, animal production and welfare, and can have major economic consequences; for example, in Ontario, Canada the detection of infected cattle in 2015 caused the immediate suspension of exports of live animals, semen, and embryos, valued at nearly 300 million Canadian dollars (Mann, 2015).

Bluetongue disease occurs globally and is common throughout California, primarily in the San Joaquin and Sacramento River valleys (Moeller, 2016). Although BT is endemic in the US, climate change may alter the transmission of this and other similar arthropod-borne viruses, and increase the threat to both domestic and wild ruminants.

As discussed above, insects are sensitive to changes in temperature, suggesting they are likely to respond to climate change. Warming temperatures can alter the distribution of vectors and accelerate disease transmission (see *Vector-borne diseases* indicator). BT incidents have expanded northward and persisted in Europe and Canada, and have extended farther south than the traditional range into Victoria, Australia; in the United States, eleven previously exotic serotypes of BT virus have been detected since 1999 (serotypes are groups within a single species of microorganisms, such as bacteria or viruses, which share distinctive surface structures) (Mellor et al., 2008, Jimenez-Clavero, 2012; Maclachlan et al., 2018). Some of these non-endemic serotypes are being detected farther away from the southeastern United States where they are usually confined, suggesting increase in distribution and potential for persistence (Schirtzinger et al., 2018). Researchers suggest the *Culicoides* vector is especially responsive to climate change (Purse et al., 2005, 2008). In general, warm temperatures enhance the recruitment, development, activity and survival rates of *Culicoides* vectors. Scientists expect increases in temperature (particularly at night-time and in winter) — as well as precipitation (particularly in dry areas) — to lead to an increased geographical and seasonal incidence of BT virus transmission. Investigators modeling the distribution of

Culicoides in North America using future climate scenarios predict expansion of the vector beyond the current northern limit and increased risk of Culicoides-borne disease over the next several decades, particularly at the US-Canada border (Zuliani et al., 2015). The northward expansion of BT outbreaks in Europe in recent decades has been examined with climate-driven models that show increasing temperatures may explain aspects of this expansion (Guis et al., 2012) and predict a trend of increasing risk globally using future climate scenarios (Samy and Peterson, 2016). However, BT incidence is influenced by many factors, including vector ecology and transmission cycles, water availability, land use, and agricultural management, which hampers the ability to link climate change with disease outcome.

Research has continued on the ecology of the vector, and what climatic, environmental, and anthropogenic factors may affect disease transmission in California and in North America (Mayo et al., 2016 and 2020). This information will help direct risk assessment and targeted surveillance for presence of the virus, as well as potential mitigation strategies. Bluetongue occurrence in livestock is currently reportable to and monitored by the California Department of Food and Agriculture's Animal Health Branch.

Bumble Bee Populations

Bumble bees (genus *Bombus*) are major pollinators worldwide. By transferring pollen from one plant to another, they assist in fertilization and the production of seeds. They significantly contribute to the global agricultural industry and are essential to the environment (Hatfield and Jepsen, 2021). California is home to more than half (27) of the approximately 50 bumble bee species in North America — more than any other state in the country. Two of California's species, Franklin's bumble bee (*B. franklini*) and Crotch's bumble bee (*B. crotchii*), are largely endemic (Hatfield and Jepsen, 2021).

Bumble bee populations are declining worldwide (Cameron and Sadd, 2020), including eight of California's bumble bee species (Hatfield and Jepsen, 2021). The specific causes of bumble bee declines are largely unknown, although shifts in temperature and rainfall associated with climate change may be pushing bumble bees to their ecological limits (Kerr et al., 2015; Soroye et al., 2020). Other key threats that have been identified include pathogen infection (Cameron et al., 2016), insecticides (Wood and Goulson 2017), and habitat loss (Williams and Osborne 2009). These factors likely interact, creating synergistic effects and accelerating declines (Cameron and Sadd, 2020). Climate change, for instance, can influence bee diseases, parasites, predators, and pesticide use (Vercelli et al., 2021).

Bumble bees are native to California and important pollinators for the environment as agricultural crops.

A study that mapped 66 bumble bee species across North American and European sites from 1900 to 2014 found that increased frequency and severity of hotter temperatures between 1900-1974 and 2000-2014 correlated with increased local extinction rates, reduced colonization (spread of species to new areas), and decreased species richness (the number of different bumble bee species present together in local regions) (Soroye et al., 2020). Effects were independent of land use and were greatest in warmer parts of the Northern Hemisphere. Bumble bees have both contracted their ranges in warmer regions and expanded into cooler regions, although the extent of range loss far exceeds their range expansion. Because this study's analysis documented average change over a large area with many species, specific conclusions cannot be drawn at the state level. Comprehensive monitoring efforts are needed to better understand California bumble bee diversity and abundance statewide and the influence of climate change (Fisher et al., 2022).

Human Health

Aeroallergens

The prevalence of hay fever and asthma, including forms of the diseases known to be triggered by aeroallergens, is on the rise worldwide (Schmidt, 2016). The risk of respiratory diseases associated with aeroallergens (as well as ozone) is projected to increase in the future (Pörtner et al., 2022). Aeroallergens are airborne substances such as pollen or spores from molds that trigger allergic reactions in sensitized individuals. Most aeroallergens come from trees, weeds, and grasses that rely on wind to distribute their pollen or spores.

A growing number of experimental and field studies provide compelling evidence that warming temperatures and changing patterns of precipitation, along with increasing carbon dioxide (CO_2) levels, increase plant growth and pollen production (including pollen yields, pollen season timing and length, allergen content of pollen grains) (Anderegg et al., 2021; Anenberg et al., 2017; Ray and Ming, 2020; USGCRP, 2018; Zhang and Steiner, 2022; Ziska et al., 2019). Elevated CO_2 concentrations have also been experimentally shown to amplify allergenic mold spore production from leaves of timothy grass, a common livestock feed (Wolf et al., 2010).

Heavy short-term rainfall significantly reduces atmospheric pollen concentrations by wet deposition while changes in long-term precipitation patterns enhance or inhibit plant growth and alter total pollen production (Zhang and Steiner, 2022). Thunderstorms, which have become more frequent with warming ocean temperatures, have also been linked to increases in aeroallergen levels. Thunderstorms during the pollen season have been reported to trigger severe asthmatic symptoms in people with underlying asthma, hay fever, and allergic rhinitis (D'Amato et al., 2020; Ray and Ming, 2020). Scientists have hypothesized that during rainy storms, pollen grains are broken up into smaller allergenic particles that can induce severe asthma. There is also evidence that thunderstorms increase atmospheric mold spore concentrations and contribute to asthma-related hospital emergency visits (D'Amato et al., 2020).

Pollen and allergy seasons, already increasing in length and intensity, are expected to increase further as the climate warms (Nolte et al., 2018). Over the last several decades, warmer temperatures have been driving earlier (3 to 22 days) pollen season start dates for spring-flowering plants (e.g., deciduous trees), while late-flowering plants (e.g., grasses) have delayed pollen season start dates by up to 27 days (Zhang and Steiner, 2022). Since 1995, the ragweed pollen season has lengthened by more than 20 days in some parts of the United States (Rudolph et al, 2018). Eleven locations in the Northern Hemisphere showed a significant increase in pollen season duration over a 20-year period, with an average of 0.9 additional days per year (Ziska et al., 2019). Pollen records from 1990-2018 at 60 stations across North America, including five California cities, show an approximately 20-day advance and 8-day lengthening of the pollen season (Anderegg et al., 2021). Climate model simulations suggest that human-caused climate change was the dominant driver of the most recent changes (2003-2018).

A study has linked exposure to extreme heat events between 1997 and 2013 with an increased prevalence of hay fever among US adults (Upperman et al., 2017). Climate change is also linked to increased concentrations of air pollutants such as ozone, nitric oxide, and other volatile organic chemicals which may also be partially responsible for the increase in allergic respiratory disease reported over the past several decades (Ray and Ming, 2020).

Foodborne and Waterborne Infectious Diseases

Climate change is expected to adversely impact both food- and water-borne diseases. Factors such as increased air and water temperature as well as fluctuations in relative humidity and precipitation patterns could extend the time period and expand the geographical range of climatic conditions favorable to the survival, proliferation, and transmission of food- and water-borne microbial pathogens. As climate and the environmental landscape changes, so too will the residential, occupational, and recreational patterns of California residents, potentially increasing their opportunity to intersect with pathogens that formerly enjoyed comparatively restricted distribution, thus amplifying risk of infection.

Vibrio bacteria

Vibrio species bacteria, which exist naturally in coastal waters and are associated with shellfish, increase in numbers as seawater temperature rises and salinity profiles change (e.g., due to sea level rise). Illness occurs among persons who eat raw shellfish such as oysters and persons with fresh skin wounds exposed to contaminated seawater or shellfish. Although uncommon, *Vibrio vulnificus* is a leading cause of death from seafood contamination in the US. And globally, toxigenic *Vibrio cholerae* remains the cause of cholera outbreaks and epidemics, often waterborne. Rapidly changing global oceanic conditions have pushed *Vibrio* geographical ranges farther north into historically colder regions (Vezzulli et al., 2016), with detection of Vibrio in areas where the bacteria were previously absent or rarely reported (Baker-Austin et al., 2010). The spread of Vibrio will increase the potential exposure of shellfish consumers and recreational ocean water users throughout the coastal regions of the US, including in California.

Legionnaires' disease (LD)

Legionnaires' disease (LD) is a severe form of pneumonia usually caused by inhalation of aerosolized water containing *Legionella* bacteria. *Legionella* are found naturally in freshwater sources and can grow and spread in artificial water systems such as cooling towers, hot water tanks, hot tubs, decorative fountains, and large buildings with complex water systems. People are exposed to the bacteria when devices aerosolize the contaminated water.

LD is more common during warm summer months, with increased rates of LD during periods of increased relative heat, humidity or greater rainfall (Fisman et al., 2005, Gleason et al., 2016; Hicks et al., 2007; Rickets et al., 2009; Simmering et al., 2017). This is likely due to both ecological and human factors. *Legionella* proliferate in warm, wet environments with temperatures between 77 and 113° F (CDC, 2020; Yu et al., 2019). Increased numbers of *Legionella* in the environment, including in water supplies (e.g., water reservoirs) could facilitate further downstream amplification within artificial water systems used by humans and subsequent exposure (Walker, 2018). In artificial water systems already contaminated with *Legionella*, these conditions encourage bacterial proliferation. Increased use of cooling devices such as cooling towers during warm weather increase the aerosolization of *Legionella*. Once aerosolized in water, warm and humid environments increase the distance that aerosolized water can travel as well as survival of *Legionella* within that water, increasing the potential infectious range.

Increased frequency and severity of extreme weather events and natural disasters may also lead to intrusion of contaminated water into artificial water systems (e.g., damaging water infrastructure, flooding events contaminating water supply; Brigmon et al., 2020; Walker 2018). Storm events may themselves enhance conditions for *Legionella* growth in water systems by favorably altering oxygen levels and biological and chemical makeup of the water supply (Brigmon et al., 2020). Droughts may cause further reliance on alternative water collection and storage methods (e.g., rainwater collection), which can increase the risk of *Legionella* growth due to favorable environmental conditions including contamination, stagnation and warm outdoor temperatures (Walker, 2018).

Zoönoses

"Zoönosis" is the classic term for an infectious disease that is shared between humans and animals. The roles that animals play in "sharing" zoönoses are varied. Animals can serve as the incubator from which bacteria or viruses emerge that can cause illness in humans. Measles, AIDS, and most recently COVID-19 are examples of diseases that originated in animals—cattle, non-human primates, and bats, respectively—but have evolved to be efficiently transmitted directly between humans (Düx et al., 2020; Furuse et al., 2010; Lytras et al., 2021; Sharp et al., 2011). Animals can also serve as a reservoir for microbial pathogens, maintaining infection but without suffering any ill-health themselves. *Borrelia burgdorferi*, the bacterial agent of Lyme disease, and Sin Nombre virus, the cause of hantavirus pulmonary syndrome (HPS), are both maintained in wild mice. Infected mice do not develop disease but can transmit the pathogens to humans indirectly (via ticks for Lyme disease) or directly (through aerosolized urine or feces for HPS). Finally, some zoönotic pathogens cause disease in both human and animal hosts; for example, the bacterial agents of anthrax and plague can cause severe and often fatal disease in wild animals, domestic animals, and humans.

Transmission of disease agents between humans and animals is in part dependent on their respective populations' distributions, densities, and proximity. For animals, these population dynamics are defined by the type of habitat—or habitats—in which the animal exists. Habitat—food, shelter, water—is largely determined by the prevailing climatic conditions. Significant changes to these conditions can alter the character of a geographic region to render it more or less conducive to the species' survival. Animals may adapt to changing environments through the random mechanism of natural selection. However, the dramatic environmental transformations wrought by anthropogenic climate change outpace the ability of most species to evolve. The only other responses available to most animal species are to reduce their population to a size that the altered habitat can continue to support, or to adjust their geographic range to areas that remain hospitable. For California, these climatologic changes will likely favor those species that can endure higher temperatures and more arid conditions, or can relocate to regions that remain relatively cooler and wetter. Both responses could change the frequency and intimacy with which some animals and humans interact, enhancing opportunities for zoonotic disease transmission (Heffernan, 2018; Hoberg and Brooks, 2015; Lorentzen et al., 2020; Morand and Walter, 2020).

Hotter, drier conditions can impact the size or density of zoönotic animal host and vector populations. Sustained elevated temperatures result in mosquitoes maturing more quickly and lead to larger populations (Mills et al., 2020). Protracted drought may reduce aquatic breeding habitat for some mosquito species, but can benefit others by transforming previously free-flowing rivers and creeks into stagnant pools (Bartlow et al., 2019). Changes to local conditions that favor some generalist species but reduce or eliminate species with unique habitual needs can reduce local biodiversity, potentially to the benefit of zoönotic disease reservoirs. For example, reduced diversity of bat species can facilitate perpetuation of rabies virus, leading to greater incidence among viable host species and increased risk of transmission to non-hosts such as humans (Patil et al., 2017).

Species that are unable to adapt to hotter or drier conditions may adjust their ranges toward higher elevations or polar latitudes. These movements could alternatively introduce zoönotic diseases into previously unaffected human populations, or dissociate disease agents from human contact. For example, the bacteria that cause plague (*Yersinia pestis*) and tick-borne relapsing fever (*Borrelia hermsii*) in California are maintained in wild rodents and transmitted via flea and tick bite, respectively; with incrementally hotter average temperatures, their current foci in mid- and upper-elevations of the Sierra Nevada may shift to higher and constricted elevations, possibly farther displaced from areas where humans reside or visit. Approximately half of the 28 species surveyed in Yosemite National Park—including squirrel (*Spermophilus* spp.) and chipmunk (*Tamias* sp.), reservoir species for Y. pestis—had upslope shifts of range limits compared with similar surveys conducted approximately 100 years earlier, when minimum temperatures were 3°C lower (Moritz et al., 2008). This shift from temperate to alpine regions parallels a similar shift of hosts and vectors of zoönoses previously concentrated in tropical and subtropical latitudes to temperate regions. In the last decade, vampire bats (*Desmodus rotundus*) and mosquitoes (*Aedes aegypti*, *Ae. albopictus*) have encroached northward from Latin America, threatening local transmission of rabies and arboviruses (e.g., Zika, Chikungunya, dengue), respectively, in North America (Hayes and Piaggio, 2018; Iwamura et al., 2020; Ryan et al., 2019).

Loss of natural food, water, or harborage may stimulate some animal species to seek these essentials from areas of human development and residence. Deforestation, including via climate-enhanced mega-wildfires, has been cited as possibly contributing to displacement of bats from natural roosting sites in favor of concentration around human habitations, leading to the emergence of bat-borne zoönotic viruses such as Nipah and Hendra (Halpin et al., 2000) and the SARS-type coronaviruses (Afelt et al, 2018). Water stored near human communities may attract wild mammals such as skunks, raccoons, and coyotes, increasing the peri-residential risk of zoönoses such as rabies and Toxocara and Baylisascaris larval migrans. Standing water in eaves, yards, and patios can provide habitat for mosquito breeding, increasing peri-residential risk of West Nile virus and other mosquito-borne arboviruses.

As hospitable habitat contracts, individual animals are drawn into more confined areas, resulting in more frequent competition and contact which enables transmission of zoönotic pathogens. In 2021, 29 cases of salmonellosis among human residents of eight states, including California, were traced to unusual concentrations of songbirds densely congregating at backyard feeders and bird baths (CDC, 2021), possibly as a result of reduced natural food and water sources. Avian influenza viruses have traditionally resided in and emerged from wild birds, particularly migratory waterfowl. As drought and development displace natural wetlands along avian flyways, this traditional breeding ground for avian influenza might diminish. If wild waterfowl seek alternative water and food resources near poultry operations, this proximity can enhance transmission of influenza viruses to domestic poultry and one step nearer to humans (Gilbert et al., 2008).

The impact of climate change on zoönotic disease epidemiology in California and the western U.S. has yet to be fully understood. Effective preparation will require an integrated collaboration of human health and animal health professionals and environmental scientists to identify and respond to climate-induced changes in zoönotic disease incidence and distribution in a timely, comprehensive, and effective manner.

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[*] Note: The findings and conclusions in this report are those of the author and do not necessarily represent the views or opinions of the California Department of Public Health or the California Health and Human Services Agency.

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