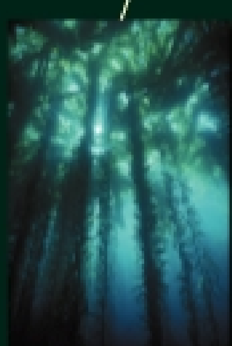
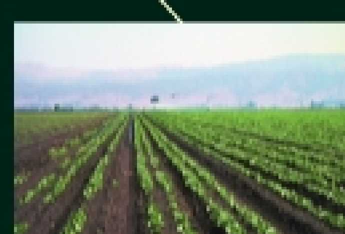
Confronting Climate Change in California

Ecological Impacts on the Golden State





A REPORT OF

The Union of Concerned Scientists

AND

The Ecological Society of America

Confronting Climate Change in California

Ecological Impacts on the Golden State

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Executive Summary

Over the past century, human activities have dramatically altered the natural landscape of California. Our historical legacy includes severe shrinkage and isolation of natural habitats, altered flows in streams and rivers, extensive introductions of non-native plants and animals, and pollution of the air, land, and water. As we enter the 21st century, a powerful new agent—global climate change—will increasingly interact with the human pressures that continue to stress California's ecosystems. In the future, direct impacts generated by the state's rapidly growing human population will be intensified by the impacts of climate change. *Confronting Climate Change in California* provides the California public and policy makers with insights drawn from the best available science—insights that may help us safeguard both our ecological heritage and our economic future. This summary highlights key findings.

What is the likely climate future for California?

It is highly probable that California winters will become warmer and wetter during the next century. Summers will also become warmer, but the temperature increase will not be as great as the winter increase. Most of California's precipitation falls in winter, and in the future more of it is likely to fall as rain, less as snow, a change that is likely to lead to increased winter runoff and decreased summer stream flow. The consequences for spring and summer soil moisture are difficult to predict, but the state's summers are likely to remain hot and dry, and perhaps become even hotter and drier. Such a consequence, combined with decreased summer stream flow, would exacerbate demands for water in the state.

El Niños, with their dramatic effects on California's weather and economy, may increase in intensity and/or frequency as the climate changes. Sea level is expected to rise by 8 to 12 inches, which is two to three times the increase experienced at San Francisco over the past 150 years. The impact of a rise in sea level on coastal wetlands, housing, and agriculture, as well as on roads, levees, and other public works, will be amplified by any increases in the frequency and/or intensity of major storms.

What might these changes mean for California ecosystems?

California's natural ecosystems—communities of plants and animals interacting in a physical environment—span 10 different biological categories, ranging from the cool, wet redwood forests of the North Coast to the hot, dry Mojave and Colorado deserts of the southeast. Many of these natural ecosystems—as well agricultural ones—are highly sensitive to the availability of water. Thus changes in the timing or amount of precipitation over the next century are likely to have a greater impact than changes in temperature. For example,

- Decreased summer stream flows would intensify competing demands for water to meet the needs of agriculture, industry, and urban areas, and to sustain the health of California's aquatic and streamside ecosystems.
- Intensified competition for an already oversubscribed water supply could lower the profitability of water-intensive crops, including alfalfa, cotton, and grapes.
- Reduced summer runoff of fresh water would increase summer salinity in San Francisco Bay, leading to changes in water circulation and quality and complex changes in the food web, including impacts on fish and invertebrates that use the bay as a nursery ground.
- Increases in the amount of winter rains could intensify flooding and landslide hazards.

The highly diverse California landscape includes ecosystem types ranging from desert to temperate rainforest, from largely pristine to intensively managed, and stretching from coastline to mountain ridges. Climate change will inevitably shift the suitable range for each type of ecosystem, as well as the mix of plants and animals and the vital flows of energy and nutrients that occur within them. Some of these changes are already occurring, providing a first glimpse of the kinds of processes and problems that are likely to intensify as climate change continues. For example,

- One species of butterfly, Edith's Checkerspot, is shifting from the southern to the northern limits of its range and from low-elevation to high-elevation sites, a likely consequence of rising temperatures.
- Warming of the California Current in recent decades has been linked to population declines of zooplankton and seabirds known as sooty shearwaters. On the rocky shores of Monterey Bay, southern animal species have increased in the warmer waters while native northern species have declined.
- In kelp forests off the Southern California coast, the proportion of northern, cold-water fish species —e.g., greenspotted rockfish—has dropped by half since the 1970s, and the proportion of southern warm-water fish species—e.g. Garibaldi—has increased nearly 50%.

Other shifts are likely in the future:

- Expanding grasslands will likely encroach on the foothill shrublands of the coastal ranges and the Sierra Nevada.
- At higher elevations, shrubs could proliferate at the expense of forests, and, where the peaks are high enough, forests could expand into the areas now occupied by tundra. In many cases, however, plant and animal species will not be able to shift northward or upslope because the potential habitat has been claimed by development, captured by non-native species, or contains unsuitable soils or other physical limitations.
- In California's agricultural ecosystems, important perennial crops such as fruit, nuts, and grapes will be most vulnerable, because it can take years for farmers to bring more suitable tree and vine cultivars into production to adapt to shifting conditions.

Many California ecosystems are effectively isolated, either as islands surrounded by human development or as remnant ecosystems hemmed in by contrasting soils, geographical features such as mountains, invading non-native species, or other factors. Isolation increases the vulnerability of these communities in the face of even modest climate changes, because it limits the ability of species to persist in place or to migrate in response to shifting conditions. Some of these isolated or "museum" ecosystems are likely to become more biologically impoverished and eventually to disappear if we fail to recognize that persistence in the short term is no guarantee of long-term success. For example,

- Individual redwoods may survive for centuries, even millennia—long past the point where climate changes make growth of new seedlings impossible. The same longevity of individuals that can mask the slow degradation of these landmark California forests can also provide time for restoration efforts.
- Isolated patches of unique grassland, marsh, and aquatic habitats—such as the Serpentine outcrops of Northern California and vernal pools in the Central Valley, which often harbor rare or spectacular species—are so poorly connected with other patches that migrations required by climate change may be difficult or impossible without human intervention.

A large proportion of the effects of climate change on California ecosystems will be indirect; climate change may alter the frequency and/or intensity of extreme weather events such as severe storms, winds, droughts, and frosts in still-uncertain ways. Similarly, the frequency and/or magnitude of some ecologically important processes such as wildfires, flooding, and disease and pest outbreaks is likely to alter as climate changes occur. Altogether, these difficult-to-predict phenomena, driven by shifts in climate patterns, may be more important for the future of California ecosystems than changes in average temperature and precipitation. For example,

- Any increase in Santa Ana wind conditions, combined with warmer, drier summers, could escalate economic and environmental loss to wildfires in California.
- An increase in the number or intensity of now-infrequent thunderstorms, which form over land and pick up more acids and other pollutants than Pacific frontal storms, may mean more acid rain and increased murkiness (from nutrient enrichment) for Sierra lakes.
- Pests such as pine bark beetles could become more prominent or more destructive if shifts in climate stress trees.
- El Niño warming may encourage toxic algal blooms in bays and estuaries and depress ocean productivity offshore.
- On shore, heavier and/or more frequent El Niño rains could increase the frequency of the rodent population booms that precede hantavirus outbreaks.

Although many California ecosystems are adapted for quick recovery from extreme events, increases in the frequency of such events could push some systems beyond their potential to recover. For example,

- Unlike redwood forests, coastal marine communities such as kelp forests can be destroyed in only a few seasons by disturbances such as severe El Niños. Yet they can also recover much more rapidly than terrestrial forests.
- Chaparral and closed-cone pine forests are adapted to fire and regenerate rapidly from fires that recur at certain intervals; however, fires in these habitats are a major threat to human property and lives in California.

How can Californians address the challenges of a shifting climate?

The impacts of climate change on California can best be appreciated in the context of the state's burgeoning population and how its residents currently use their natural resources. With a population exceeding 30 million, the state's landscape has been considerably transformed—from urban sprawl to intensive agriculture. Overall, the impacts of climate change on California ecosystems will exacerbate the consequences of these intensive human land-use practices and the pressures of a growing population. Fortunately, there are many actions the California public and policymakers can take *now* to safeguard and restore vulnerable ecosystems.

The steps that will provide the greatest protection for California's ecosystems from avoidable damage during climate change will also yield positive benefits for public safety, recreation, agriculture, fisheries, and our unique natural heritage—even without significant changes to the climate. One key step involves limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides. Another prudent step is designing nature reserves on land and in coastal waters that will provide California's unique plant and animal communities with room to adapt to the changing conditions created by a shifting climate.

Although Californians cannot act alone to stabilize the state's climate, they have the opportunity to make a large contribution to worldwide efforts to minimize the pace and intensity of greenhouse warming. For one thing, since Californians are substantial contributors of global greenhouse gases—emitting, for example, over 400 million tons of CO_2 a year—their individual actions as consumers and producers can be globally important. Another opportunity arises from California's stature as a bellwether for new attitudes and innovative practices, including many that help reduce emissions of greenhouse gases.

Today's Californians can continue to be models for the nation and the world by encouraging and embracing the development of novel energy, transportation, and land-use solutions to the problem of global climate change. Taking the lead in effective action to slow climate change and protect California's natural and human resources can help secure our economic and ecological future for many generations.

CHAPTER

One

California's Future Climate

Regional climate studies indicate that California is likely to see average annual temperatures rise by 3–4° Fahrenheit in the next century, with winters 5–6° F warmer and summers 1–2° F warmer. Winter precipitation will increase, particularly in the mountains, and more will fall as rain than snow. Summer stream flow and soil moisture required for plant growth are likely to decrease. Statewide averages and generalizations cannot tell the whole story, for impacts of climate change are likely to vary greatly from one place to another. Finally, El Niño conditions may occur more frequently in the future, bringing more extreme weather events.

Temperature

The most likely world climate future, based on current understanding, is a globally averaged warming of about 4° F (2° Celsius) by 2100. [See *The International Consensus on Climate Change*, page 12.] The Intergovernmental Panel on Climate Change (IPCC), a group of more than 500 scientists who reviewed the scientific literature on climate variability and change, concluded in 1995 that warming by 2100 will range between 2° and 6° F (1° and 3.5° C).[1] Actual changes could be larger or smaller, because major uncertainties remain in our understanding of climate, as well as in projections of fossil fuel use and other human activities that release climate-warming greenhouse gases such as carbon dioxide into the atmosphere. Yet inaction based on the long odds that climate change may turn out to be insignificant would be imprudent at best.

Translating global averages into specific regional climate projections also involves uncertainties. Most of the information on future climate change is generated by computer models called General Circulation Models (GCMs) that simulate movements and energy transfers in the atmosphere and ocean. Global GCMs tend to focus on the big picture but blur the details. For instance, global GCMs subdivide the earth's surface into a grid of sections several hundred miles on a side and assume that conditions within each section are uniform. This limits the models' ability to decipher local climates, especially where there are important local influences from coasts, mountain ranges, large lakes, or other major landscape features. Recently, however, scientists have made substantial progress in bringing models to a finer scale of resolution.[2]

In general, moderate-resolution global GCMs predict levels of climate change over western North

The International Consensus on Climate Change

The past century has seen an apparent four-fold increase in the rate at which the earth is warming. Measurements of historic global temperatures based on ice cores, bore holes, tree rings, and other sources indicate that the global surface air temperature increased approximately 0.9° F in the 400 years from 1500 to 1900. The air temperature increased a further 0.9° F from 1900 to the present. If we assume that the temperature has been rising at a steady pace, the rate of warming appears to have increased from 0.2° F per century before 1900 to 0.9° F per century since 1900.

This apparent factor-of-four increase in the rate of warming may be caused partly by natural climate variability. However, the concentration of atmospheric carbon dioxide has increased in proportion with this temperature increase. Carbon dioxide and other greenhouse gases increase heating at the earth's surface by trapping solar energy within the atmosphere. Human activities such as burning of fossil fuels and timber cutting are considered responsible for much of the increase in greenhouse gases.

The average surface air temperature worldwide is about 59° F and has increased by about 0.5° to 1° F since 1900. Approximately 0.4° to 0.5° F of that increase has occurred since 1960. There are many uncertainties regarding these rates of change and related impacts. The following summary is based on the 1995 report of the International Panel on Climate Change (IPCC),[1] a 500-plus group of scientists that provides carefully reviewed studies on climate variability and climate change. These findings are now accepted by most climate scientists as well as policy makers throughout the world.

The 1995 IPCC report indicated heat-trapping greenhouse gas concentrations have increased since pre-industrial times and have resulted in climatic effects that extend beyond a heating of the surface air temperature. These effects include changes in the distribution of rainfall and the frequency of extreme weather events. Because warmer air can hold more moisture, a warmer lower atmosphere implies that more moisture will be retained and carried in the air instead of precipitating out. Thus, regions that previously received large amounts of precipitation may receive little, and formerly drier regions may receive large amounts. Also, observations from 1970 to 1995 show an increase in the frequency of extreme weather events. Spring snow cover has decreased by 10% in the Northern Hemisphere; sea ice extent is decreasing; sea level is rising; and mountain glaciers are retreating. 1994–1998 have been among the warmest since 1860. Additionally, nighttime temperatures have increased at a greater rate than daytime temperature, resulting in a narrowing of the daily temperature range. Regionally, the greatest warming has occurred over mid-latitude continents in the winter and spring. Warm El Niño events have been more frequent and persistent since 1990, a pattern considered unusual compared with the previous 120 years of sea surface measurements.

The continuing increase in human emissions of greenhouse gases into the atmosphere suggests that the warming trend will likely continue. Computer models estimate an increase in the average global surface temperature ranging from 2° F to 6° F by 2100.

America, including California, that fall in the middle of the IPCC projections. Under one IPCC climate change scenario that uses the middle of the range of greenhouse gas emissions (scenario IS92a), for example, annual mean warming in the western United States reaches about 4° F (2° C) by 2030–2050.[3] This corresponds to a winter warming of about 5° F (3° C) and a summer warming of about 2° F (1° C). [See *Current California Climate*, below.]

Current California Climate

California is a region of vast climatic diversity, with extremes of precipitation and temperature. Average rainfall at Brawley in the Mojave desert is about 2 inches per year; in the state's northwest corner, it exceeds 80 inches. Extreme temperatures range from 104° F or above in the southeast deserts to –40° F or colder at the highest elevations of the Sierra Nevada.

California's climate is controlled by broad interactions among the oceans, landforms, and atmosphere. Overall, California's climate shares many features with the climates of the southwest corners of the other major land masses—Europe, Africa, South America, and Australia. All are regions of Mediterranean-type climate, which is characterized by cool, wet winters and hot, dry summers. California receives 80% of its annual precipitation in winter.

In the summer, California's climate is dominated by the Pacific high, a zone of high pressure caused by the descent of dry air lofted high in the atmosphere by intense convection in the northern tropics. The Pacific high pushes the storm track to the north and creates hot, dry summers over most of the state. In the winter, the zone of tropical convection shifts to the southern tropics, and the zone of downwelling dry air and high pressure shifts to the south as well. This southward retreat of the Pacific high allows a parallel shift of the storm track, which opens Northern California to a series of storms arising from low-pressure cells generated over the Aleutian Islands. Usually, the Pacific high offers some protection to Southern California throughout the year, and precipitation totals there are typically lower than along the North coast by a factor of 10.[114] In any given winter, precipitation is very sensitive to the strength and position of the Pacific high.

The climate of coastal California is strongly influenced by the proximity of the Pacific Ocean. Cold, upwelling waters near the coast cool the air masses passing over them, providing a coastal "air conditioner," especially during hot periods when rising inland air masses pull ocean air onshore. This cooled air is usually fog laden, especially in Central and Northern California, where the coastal waters are cold enough to push the air temperature below the dew point. The interaction of topography and coastal fog creates habitats with spectacular local climate contrasts, because low hills can often halt and collect the surface flow carrying the fog.

California's topography is another major controller of climate. The coastal mountains and the much higher Sierra Nevada cool the eastward- and southward-moving storms, creating wet western slopes and substantial rain shadows to the east. The coastal ranges are generally too low for profound climate differences between their tops and bottoms, but the Sierras are high enough to create sharp contrasts between the hot desert of Death Valley and alpine tundra on the flanks of peaks that rise higher than 13,000 feet.

Most of the state's ecosystems experience some summer drought. Runoff is also highly seasonal, and the flow of many streams and rivers varies tremendously through the year, with many carrying water for only a few weeks or months. In the larger rivers, flow is now almost exclusively under human control. California has more than 1,200 reservoirs, which regulate most of the state's rivers.

Year-to-year variation in climate is important in almost all parts of California. In the past few decades, major droughts and floods, frosts, and hot spells have caused billions of dollars in damages. These weather extremes have also laid the groundwork for follow-on disasters, ranging from devastating fires to biological invasions.

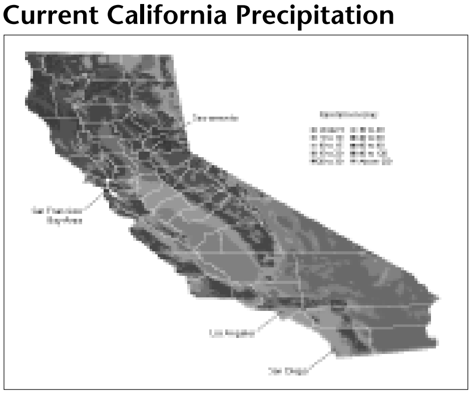
Much of the year-to-year variation in California's climate is connected to the El Niño Southern Oscillation, or ENSO. During the ENSO warm phase (El Niño), the tropical westerlies lose strength, and the warm waters of the western tropical Pacific spread far to the east, bringing much warmer than usual surface waters to the west coasts of North and South America. El Niño effects on California vary across the state but typically include above-normal winter rains and storminess.

Over the past century, California has experienced a 2° F warming. Annual precipitation has decreased over much of the state, with decreases of 10% to 25% in many regions.[148] Decreased annual precipitation during the period from 1900 to 1995 was characteristic of all five of the world's Mediterranean climate regions. This contrasts with increased precipitation over much of the United States and Canada, where the largest increases were at the highest latitudes.

Precipitation

A warmer global climate will increase evaporation from the oceans, increase moisture in the atmosphere (because warmer air can hold more water), and increase worldwide precipitation. These changes in the global water cycle are likely to bring more rain to the western edges of the continents in major frontal storms and to increase the number and/or intensity of convective storms (i.e., thunderstorms) generated by rising warm air masses over land that bring brief bursts of heavy rainfall.

FIGURE 1
Current California Precipitation



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To get meaningful projections of future rain and snow patterns across California's highly varied landscape, scientists must work at finer scales of resolution than global GCMs provide. Moderate-resolution GCMs, for instance, project average statewide precipitation changes in California of less than 0.02 inches (0.5 mm) a day, year round.[4] Yet studies using models or statistical techniques to achieve higher spatial resolution yield quite a different picture of winter precipitation in a warmer climate. One model reveals a large increase in precipitation over California, but with strong "rain shadows" (dry areas) to the east of the Cascades and the Sierra mountain ranges that are largely invisible to the global models. This regional model projects that winter precipitation over the coast and Sierra will rise by 25% or more.[5] Another high-resolution calculation indicates a similar pattern of striking variations in rainfall across the state.[6] These simulations pinpoint the strongest warming in the Northern Sierra and Central Valley, with drying in the southeastern corner of the state. Such results confirm that climate change is likely to be highly variable across California, and that local impacts may be much greater than statewide averages would indicate.

The combination of increased winter precipitation and warmer winter temperatures will mean that more of the precipitation falls as rain and less falls as snow. As a consequence, less water will be stored in the snow pack and more will move as winter runoff.[7] The impacts of this change for flooding and peak stream flows are difficult to predict. When snowmelt occurs along with major rainstorms, peak runoff may increase. But peak runoff can also decrease when rains fall before the snow pack accumulates or after it melts. Because California soils are often saturated in the winter, they cannot soak up more water to mete out slowly to streams. Instead, increased winter precipitation in regions without snow probably will end up largely as runoff, creating the possibility of increased flooding and erosion.

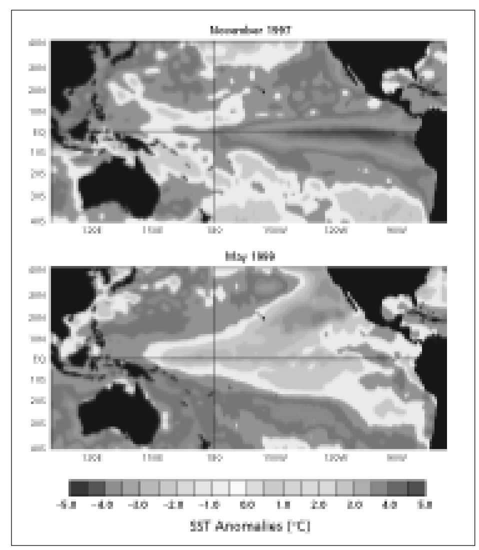
In the future, increased winter precipitation could delay the seasonal onset of dry soils that characterize summers in California. But if the increased winter rain leads to increased winter runoff, California's lengthy summer drought could be just as dry as, and even warmer than, at present.

Storminess

Changes in the frequency of storms are very difficult to predict with confidence at regional scales. The general locations of the storm tracks are unlikely to change significantly,[3] although some models suggest modest northward shifts in the storm tracks, and one suggests an eastward shift in the storm track in the North Pacific.[8] Counteracting forces in a warming atmosphere, however, make it uncertain whether overall storminess will increase or decrease.

Thunderstorms that bring brief bursts of heavy rainfall, especially to the southern deserts and the Sierra Nevada in summer, are minor players in California's climate today, yet there are indications that such convective storms may increase in number and/or intensity in a warmer climate[9]. A few extra storms could be significant. The extra moisture could bring a major change in water balance to the deserts. An increase in lightning provides more opportunities for igniting wildfires. Further, thunderstorms that arise over land generate dirtier, more acidic precipitation than the Pacific frontal storms that now supply most of California's rain, increasing the likelihood of murkier Sierra lakes due to nutrient-laden runoff.

FIGURE 2
Sea Surface Temperatures—El Niño and La Niña



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El Niño

Much of the year-to-year variation in California's current climate is tied to the El Niño Southern Oscillation (ENSO), a natural phenomenon that recurs approximately every two to seven years. It starts with a warming of the surface waters in the tropical Pacific and causes weather anomalies worldwide.[10,11] ENSO effects on California vary across the state. In the south, the warm (El Niño) phase typically brings above-normal winter rains and storminess. The cold (La Niña) phase brings cool temperatures and below-normal precipitation. Toward the northern end of the state, this pattern weakens or reverses. A strong El Niño, such as occurred in 1982-83 or 1997-98, has a major impact on California's economy, causing landslides, floods, power outages, extreme tides, and dramatic changes in ocean fisheries. El Niños, especially strong El Niños, have been unusually common in recent years.[12]

The possibility of a connection between global warming and El Niño frequency has been difficult to investigate using global GCMs, because the origin of the ENSO event appears to involve changes in winds and ocean circulation in areas of the Pacific too small to be accurately resolved with any but the most recent climate models.[13] New models that couple the dynamics of the ocean and atmosphere are beginning to produce ENSO-like phenomena, however,[14] and provide increasing evidence that El Niños may become more frequent and produce stronger cold phases.[15] If global warming does enhance ENSO, California climate over the next several decades may look like an amplified version of that over the past several decades. That forecast would mean large and important year-to-year variations, with shifts in the mean climate being driven largely by changes in the frequency and intensity of warm and cold phases.

Predicting Impacts on California Ecosystems

Human pressures are now impinging on California's natural and managed (ie., agriculture and forestry) ecosystems—communities of plants and animals interacting in a physical environment. *Confronting Climate Change in California* examines the implications of climate change for these ecosystems. In some cases, this report explores ecosystem responses to very specific scenarios that are generated by particular climate models. In most cases, however, the report takes a broader approach, looking at the likely range of ecosystem responses to the most probable trends in future climate. With this approach, a broad range of ecological information can be included, while topics that are just beginning to be accounted for in the formal models can also be considered—topics such as disease patterns, changes in the rate of invasions by non-native plants and animals, and wildfire frequency in response to climate change. The report emphasizes the most likely responses to climate change, but a few impacts that may have a low probability but profoundly important consequences if they did occur are also examined (see *Confidence Levels*, page 51).

Unfortunately, looking at general trends rather than specific scenarios provides little insight into two key questions: at what level of warming do ecosystems begin to respond? and at what level would they begin to fail catastrophically? The ability to predict such specific quantitative impacts is limited by the evolving scientific understanding at all scales—from physical processes such as changes in runoff and soil moisture to ecological processes such as changes in plant growth and shifts in the distribution of various types of communities across the landscape. Of course, predictions will evolve as scientific understanding increases.[16] In general, this report focuses on the next 50–100 years—a reasonable time frame within which to make assumptions about the future of climate as well as about human population growth, land-use patterns, and economic aspirations.

A likely climate change scenario: more rain and less snow, resulting in greater winter runoff and less flow in summer streams. Increasing evidence suggests more frequent and possibly more intense El Niños as the climate changes.

One final consideration is that the earth's ecosystems are never static, even in the absence of human influences. They are dynamic, shifting, and reorganizing on a variety of time scales in response to diverse external and internal forces: seasonal changes in plant or animal populations, the recolonization of an area scorched by fire or a kelp forest devastated by storms, the emergence of new species through evolution, or the reassembly of a living community on land buried for millennia under glacial ice. Future climate change will almost certainly lead to alterations in the earth's ecosystems, but those will be superimposed onto a complex tapestry of ongoing changes.

CHAPTER
Two

California's Unique Ecosystems

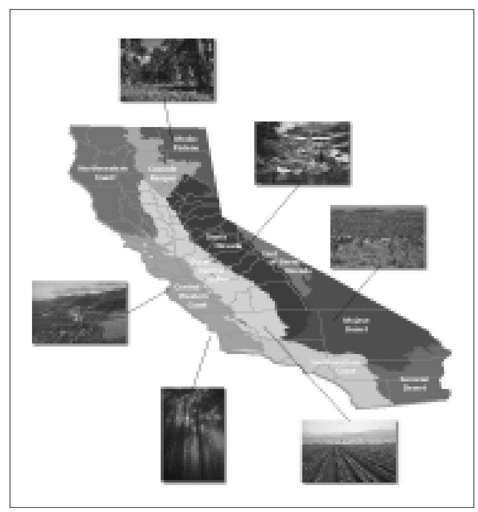
Californians enjoy an unusually diverse, spectacular, and productive natural heritage. As dramatic as the landscape are the natural processes such as fire and summer drought that have shaped the character of its ecological communities.

California boasts a varied and dramatic landscape stretching from offshore kelp forests and coastal marshes to temperate rainforests, Sierra peaks, and deserts. The state's unique ecosystems also teem with an unusually rich diversity of plants and animals. The ecological goods and services supplied by this bountiful natural heritage, from productive fisheries and fertile croplands to pure water and year-round recreational opportunities [see *Ecosystem Services*, next page], have helped California to develop the world's seventh largest economy.

Agricultural fields, orchards, and vineyards cover 11% of California's landscape and produce nearly twice the farm income of any other state. The dramatic natural landscape itself provides the setting for California's unique lifestyle and lures tourists from around the world. California's state and national parks are key elements in its tourism business, a sector that employs 673,000 people and generates more than $60 billion in annual revenues.[17]

On the land, California's natural ecosystems—communities of plants and animals interacting in a physical environment—span 10 different biological categories, ranging from the cool, wet redwood forests of the North Coast to the hot, dry Mojave and Colorado deserts of the southeast. In general, each of these types of biological communities occupies a distinct and consistent climate zone.[18] The plant life of California is particularly diverse, including some 5,057 native species and nearly 1,000 introduced species.[19]

FIGURE 3
California's Distinctive Ecosystems



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Historically, climate and fire have played powerful roles in shaping the structure and functioning of California ecosystems. For plants, a key feature of California's climate is the strong seasonality of precipitation, with wet winters and dry summers. In general, moisture is available when the plants do not need it, and it is scarce when the demand is greatest.[20] Plants have evolved a number of mechanisms to deal with this fact. A large fraction of the flora, for instance, is composed of annual plants, which escape the summer drought by flowering and setting seeds in the spring. Of the perennials, some cease physiological activity

Ecosystem Services

Californians derive many benefits from the state's natural ecosystems. These include the production of a diversity of ecosystem goods, or extractive benefits, such as seafood, forage, timber, and raw materials for industrial and pharmaceutical products. The harvest and trade of these goods represent an important and familiar part of the economy. Ecosystems also provide us with services—non-extractive benefits—including fundamental life-support processes such as water purification, pollination of crops and wild plants, renewal of soil fertility, and climate regulation. These services are essential not only to the state's agriculture and forestry sectors but also much more broadly to tourism, recreation, human health, and quality of life. Ecosystems also perform important life-fulfilling functions, including providing Californians and visitors with unparalleled aesthetic experiences as well as cultural, intellectual, and spiritual benefits.

Ecosystem services are generated by a complex of natural cycles, ranging from the fleeting life cycles of tiny bacteria that help fertilize the soil to the long-term and planet-wide cycles of elements, such as carbon. All of the cycles are ancient, the product of billions of years of evolution, and have existed in forms very similar to those seen today for at least hundreds of millions of years. They are absolutely pervasive and yet largely unnoticed by most people as they go about their daily lives. Nonetheless, the ecosystem services these cycles create are essential to human existence and operate on such a grand scale, and in such intricate and little-explored ways, that most could not be replaced by technology. Escalating impacts of human activities on natural ecosystems imperil the delivery of these services.

Globally, ecosystem services may be worth many trillions of dollars annually. Yet because most of the benefits are not traded in economic markets, they carry no price tags that could alert society to changes in their supply or to deterioration of underlying ecological systems and cycles that generate them. There is a critical need for identification and monitoring of ecosystem services both locally and globally, and for the incorporation of their value into decision-making processes.

Californians are already confronted with trade-offs in the allocation of resources such as land and water to competing uses and users. In the future, these trade-offs will become increasingly vexing and difficult to resolve, from both ethical and practical perspectives. They involve our most important ideals, such as ensuring a prosperous future for our children, as well as our oldest tensions, such as balancing the competing interests of individuals and of society. Only by recognizing and fairly valuing the many subsidies and services our society receives from healthy ecosystems will we be able to make wise decisions about resource allocations for the future.

and go into dormancy during the summer drought. Others have evolved deep roots that can provide year-round access to soil moisture.[21] The most water-demanding species, however, are restricted to permanently wet sites such as stream banks, wetlands, and foggy coastal areas.

Wildfires are a fundamental regenerative force, vital for the long-term health of many classically "Californian" ecosystems. Chaparral shrub communities and closed-cone pine forests both evolved in the presence of fire and have developed adaptations that allow them either to survive fires and resprout from the ashes or to reestablish from seed after a fire. Chaparral communities, for instance, harbor species of annual plants whose seeds germinate after a fire[22] and grow actively for only a year or two until they are shaded out by recovering shrubs. The seeds of these annuals then persist in the soil until the next fire. In many of California's forests, fire was historically common in the understory, where it consumed litter and controlled the hazard of giant, catastrophic fires. Even in moist coastal redwood forests, fires burned on average every six to eight years over the last 270 years.[23] Because of human developments in these fire-prone settings, wildfire has also become a destructive force in California. Since 1923, the 20 largest fires in California have destroyed more than 8,000 structures and taken 42 lives.[24]

The character of California's aquatic ecosystems has been shaped by geography and climate. Moisture-laden weather fronts sweeping inland from the Pacific Ocean drop most of their snow and rain on the western slopes of the coastal ranges and the Sierra Nevada, creating freshwater lakes such as Clear Lake. In the rain shadows on the eastern slopes, saline waters such as Mono Lake and dry basins such as Death Valley can be found.[7] Numerous streams and medium-sized rivers and small, high-elevation lakes occur in California. The Sierra Nevada, for instance, hosts more than 2,000 lakes. Natural and artificial wetlands are scattered throughout the state, including vernal pools, waterfowl reserves, streamside corridors, perennial springs, alkali flats, and coastal estuaries.

Offshore, giant kelp forests are central to the ecology of California's coastal waters. These kelp forests are among the most productive and diverse communities in the world, comparable to tropical rainforests on land.[25]

CHAPTER
Three

Human Influences on California Ecosystems

California has the nation's largest population, and human impacts on the landscape are ubiquitous. Even lands not bulldozed, plowed, or drained for human uses have been changed in character by non-native species, fire suppression, and other human activities. California has more threatened and endangered plants than any other state. In fact, Southern California alone has one of the largest concentrations of endangered species in the United States, and more generally, rare and endangered species are native to many of the most populous areas of the state. Continued population growth ensures that conflicts over land and water use will persist, and a changing climate will intensify these problems.

California's ecosystems are rich providers, supporting the country's largest agricultural economy, a substantial timber industry, and a wealth of recreational opportunities. This natural wealth is one reason that California is the country's most populous state. With a total human population exceeding 30 million, California has an average population density nearly three times the U.S. average. Because of this, human impacts on California are pervasive. Much of the state's forest has been logged and most of its rivers are dammed. Since 1850, California has lost 80% of its coastal wetlands, 96% of its interior wetlands, and 99% of its valley grassland.[26] Increasingly, human influences extend into ecosystems not subject to intensive management. Most of California's remaining grasslands are dominated by grasses introduced from other continents,[19] and fire suppression has altered the character of California's forests and shrublands.[27]

Biological invasions are a major feature of California's ecosystems. Invaders are plants, animals, or microbes introduced from other regions or continents, either deliberately or accidentally, which spread out of control and cause ecological or economic harm. Two thirds of California's current crop losses are caused by introduced weeds, and a new agricultural pest is introduced into California every 60 days, on average.[28] In natural areas, invaders may threaten native species by competing with them for resources, preying on them, hybridizing with them, or even changing the character of the environment.

The first European organisms probably arrived with Junipero Serra, who founded the first permanent European settlement in California in 1769. Annual grasses from southern Europe and the Near

East quickly became established. By 1860, California already had 134 species of naturalized non-native plants.[19] Species such as wild oats (*Avena*), brome (*Bromus*), and rye grass (*Lolium*) that have a relatively high tolerance to heavy grazing soon replaced the native perennial grasses as dominant plants in California grasslands. Even when livestock is removed, the invaders persist, yielding to the native perennials only slowly, if at all. After the arrival of the grasses, California experienced many additional plant introductions, including weeds, woody perennials, garden ornamentals such as Pampas grass that escaped into the wild, and even trees. Some introduced species are innocuous or even useful, but others are devastating. Yellow starthistle, for example, now infests 22 million acres of grasslands and woodlands, often completely eliminating palatable forage for cattle.[28] At present, the California flora contains nearly 1,000 non-native species, about 20% of the total.[29] Not coincidentally, California's flora also includes the largest number of threatened and endangered native species of any state.[30]

Invaders are not limited to plants. The state's lakes, rivers, and streams are often dominated by introduced fish.[31] Indeed, 37% of the fish species in the state are introduced. About 8% of the mammal species and 2% of the birds are also introduced.[31]

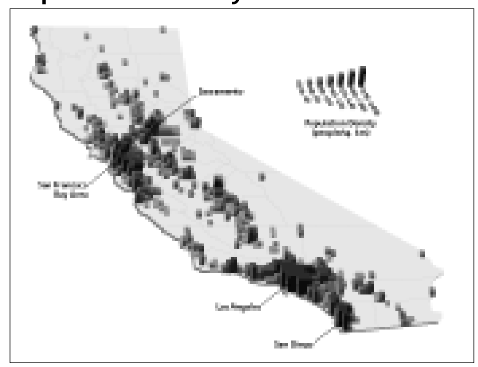
Bays and estuaries have been invaded more recently. San Francisco Bay has at least 234 established exotic species, which now constitute the majority of the organisms that live in the bottom sediments, fouling communities that cling to ship hulls and piling, brackish-water zooplankton, and freshwater fish.[32] Approximately half of these invaders have arrived since 1961, which represents an arrival rate of approximately one new species every 14 weeks. Factors such as extensive ship traffic and commerce, a bay that was initially limited in biological diversity, and extensive disturbance have combined to make San Francisco Bay perhaps the most invaded aquatic ecosystem in the world.[32]

The greatest concentrations of endangered species in the United States occur in four regions: Hawaii, the southeastern coastal states, southern Appalachia, and Southern California.[30] California has a total of 359 federally listed species, including federally protected endangered and threatened species, proposed endangered, proposed threatened, and Category 1 candidate species (those that await only administrative processes to become protected species).[33] This group includes mammals, birds, fish, plants, insects, reptiles, amphibians, shrimp, and snails.

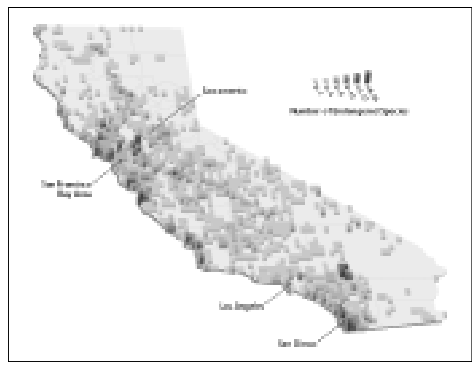
Human influences on aquatic habitats are considerable in the more populated southern and central portion of California but are less noticeable in much of the northern portion of the state and at high elevations. As noted, most of California's wetlands have been greatly diminished in area and are thus highly sensitive to climatic and human-induced changes in water supply. Approximately 60% of the Sacramento-San Joaquin Delta water is diverted for human use, and 95% of salmon and steelhead trout habitat for spawning in the Central Valley has been lost.[34] Lakes and streams in the Sierra Nevada are generally very clean. None are currently acidified as a result of wind-borne deposits of pollutants[35] although they remain vulnerable to increased inputs of nutrients, such as those found in fertilizers or sewage, or other pollutants. In addition, widespread introductions of several exotic species of trout have altered their biota significantly.

FIGURE 4

Population Density



Endangered Species



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Coastal regions of Southern California have experienced major losses of freshwater organisms because of fragmentation of freshwater habitats by dams and diversions, widespread pollution, and introduction of exotic species. Most of the freshwater fish native to Southern California are extinct, rare, or endangered. Aquatic reptile and amphibian populations also have been reduced or extirpated by destruction of habitat.

Runoff from the mountains supplies most of the freshwater used by the cities of San Francisco and

Los Angeles and the rich agricultural lands of the Central Valley. California has more than 1,200 reservoirs with a total storage capacity of about 42 million acre-feet. A network of storage reservoirs and irrigation channels disperses water into regions with naturally low rainfall and high evaporation. As urban demands have increased, agricultural uses have declined in the past two decades. Further, court-ordered environmental flows (water left in streams to support aquatic life) have increased and compete with agricultural and urban uses. Currently, every major water supply source in California is at its limit of sustainability, and options for increasing water imports are severely limited. Clearly, any further reductions or redistributions of water supply in California caused by climate change are a serious concern for both natural ecosystems and human endeavors.

> As more and more people draw on limited water resources, any climate changes that lead to increased drought will pose serious problems.

In spite of these human influences, many California ecosystems remain rich and often spectacularly beautiful. Safeguarding the state's natural treasures in the face of continuing human pressures is a major challenge for the future, especially given the uncertainties of a changing climate.

The California Department of Finance predicts continued population growth, with the state reaching about 58 million, or nearly twice the 1990 population, by 2040.[36] Independent of changes in climate, this growing population will place huge demands on the state's remaining natural ecosystems, and any attempt to understand ecosystem responses to climate change must factor in this complex human context. This is a challenging task, however, in part because there are few historical parallels for guidance and also because it is difficult to anticipate future cultural, political, and economic trends. Nonetheless, this report generally assumes that California's human population will continue to increase at the rates and with the spatial patterns presented by the California Department of Finance, and that economic development will continue, with agriculture and forestry remaining important, though increasingly minor, components of the state's financial base.

An increasing number of people moving into California's urban areas likely means an increasing demand for natural and managed ecosystems as sites for recreation and spiritual growth. Even with an increased emphasis on conservation, conflicts over land and water that pit the needs of urban development and agriculture against the need to maintain healthy natural ecosystems will probably intensify. Decisions about how to resolve these land-use and resource conflicts will be a major determinant of the future status of California ecosystems, regardless of climate change.

CHAPTER
Four

Ecological Consequences of a Changing Climate

Potential responses of California ecosystems to climate change fall generally into three categories. The responses may be geographic; the boundaries between ecosystem types will move and the character of landscapes will inevitably change along with shifts in climate. The responses may involve changes in the way ecological processes work and in the goods and services that ecosystems supply to human societies (such as purification of air and water, decomposition of wastes, maintenance of soil fertility, control of pests, pollination services, recreational opportunities, plant productivity, the health of fisheries). Finally, the responses may entail changes in the kinds of plants and animals that live in a community, and these necessarily lead to changes in how the ecosystem works.

All three types of responses are interrelated. For example, the introduction of Australian eucalyptus trees into California grasslands and shrublands has led to large increases in plant biomass (because trees produce a greater mass of living material than shrubs) and changes in the water and fire cycles (because the trees use more water and produce larger amounts of flammable bark and leaves).[37]

Freshwater Ecosystems

In a warmer climate, more of California's winter precipitation is likely to fall as rain rather than snow, a change that would lead to increased winter runoff and decreased summer stream flow. There is some evidence that climate warming over the past half-century may already be having this effect in the Sierra. Such changes in the amount or timing of freshwater runoff could alter physical and ecological conditions in coastal waters such as San Francisco Bay and the Santa Barbara Channel, in other California estuaries, and in inland saline lakes. Rain in the Sierra transports much higher concentrations of nutrients and pollutants than does snow. A shift to more rain is likely to increase deposition of contaminants into relatively pristine mountain lakes, reducing clarity and increasing the potential for acidification.

Stream flow in California comes from seasonal rainfall and snowmelt and is extensively modified by dams, reservoirs, and diversion channels. Flow in rivers is highly variable in time, both within and between years. For example, annual volumes of Sierra rivers can be 20 times greater in very wet years than in very dry years. Peak flows result from snowmelt, warm winter storms, and infrequent convective storms in summer and early autumn.

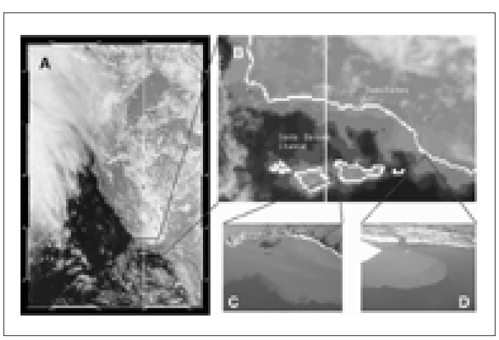
There is some evidence that climate warming is already causing changes in the timing of Sierra runoff. Since about 1950 in the Sierra Nevada, the proportion of total annual stream flow occurring during the autumn and winter has increased, whereas the portion during April through July has decreased.[38] This could be caused by a change in the timing of rainfall. During the same period, increases in autumn precipitation and decreases in precipitation in May through July have been recorded. But climatic warming also may be playing a role by decreasing the amount of precipitation that falls as snow, leaving less snow to melt and generate runoff in spring and summer. A study that examined 50 years of historical records for two streams in the northern Sierra Nevada reported increased winter and early spring runoff during the period 1965–1990 compared with 1939–1964 and attributed it to small increases in temperature that enhanced the rain-to-snow ratio.[39]

Climate changes could increase peak flows, leading to greater flooding, especially in winter.

Although the primary effect of a warmer climate on the water cycle in California would be a higher proportion of rain to snow, other consequences could include large increases in maximum flood height and the occurrence of many large floods in winter rather than spring.[40]

Changes in the amount or timing of freshwater runoff may alter physical and ecological conditions in California's coastal waters, estuaries, and inland saline lakes. More winter runoff may bring larger sediment flows into coastal waters, with adverse consequences for human health. Many of Santa Barbara's popular beaches were closed in 1998 because of high bacterial counts from the intense El Niño storm runoff.[41] A very different type of effect comes with springs that are warm, dry, or both—which tend to cause earlier snow-melt and reduced summer runoff. The result in San Francisco Bay, for example, is higher autumn salinity, because less fresh water flows in to dilute the salt water.[42] Diversions for irrigation, urban water supplies, and other human uses tend to further reduce spring inflows to San Francisco Bay, and these diversions are generally greater during drier periods.

FIGURE 5
Greater Health Risks from Storm Runoff



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Higher salinity in the bay can alter circulation within it and affect all levels of the food web, from phytoplankton (algae) to predators, including fish, in complex ways.[43] That is because much of the spatial distribution of organisms is determined by the salinity gradient across the estuary, and the amount and timing of freshwater input has a major influence on the salinity gradient. Variations in the extent and location of the salinity-based habitats within the bay have attained more importance because of declining populations of various zooplankton and of fishes of economic or recreational interest, such as chinook salmon or striped bass. Decreased river inflow caused by drought or increased water diversions for human uses have been implicated in declines of some species.

In saline lakes on the dry eastern side of the Sierra Nevada, variations in total runoff can lead to important changes in lake functioning. Diversions and droughts increase salinity and lower lake levels. As salt levels increase, aquatic organisms living in these waters must expend more of their metabolic energy to regulate the water balance in their tissues, leaving less energy for growth and reproduction. Thus, productivity in these lakes is expected to decline under more saline conditions.

Conversely, abrupt increases in freshwater inflow that dilute salinity may also create problems. Such sudden increases in lake level have been observed when El Niño storms lead to exceptionally high snow or rainfall and runoff. Although the increased inflow slightly dilutes the saline water, it can also cause persistent chemical stratification and prevent the mixing of surface and bottom waters. This, in turn, reduces nutrient supply and productivity of the phytoplankton, which form the base of the food web.[44] The more variable runoff associated with climate change will increase the likelihood of this type of stratification and subsequent disturbances in the lakes' food web.[45]

In mountain lakes, there are a number of potential consequences from changes in the proportion of snow to rain and the volume and timing of runoff from snowmelt. These include alterations in flushing rates (the time required to exchange all the water), length of time of ice cover, amount of mixing, and the inflow of nutrients and other chemicals, including ones that cause acidification.[7] For example, the growth of algae in small mountain lakes often declines in years that have long periods of ice cover and above-average precipitation and subsequently high runoff.[46] Large lakes can be sensitive also. In Lake Tahoe, the peak in algae productivity is controlled partially by the depth of spring mixing, which, in turn, is influenced by the intensity of spring storms.[47]

Climate conditions can alter rain or wind-borne deposition of pollutants and nutrients, which acidify or cause excessive algal growth and murkiness (eutrophication) in normally clear, nutrient-poor mountain lakes. In the Sierra Nevada, rain transports much higher concentrations of these contaminants than does snow. Therefore, a warming trend that causes a shift to more rain than snow is likely to increase deposition of nutrients and pollutants. Computer models indicate that a doubling of deposition could begin to acidify California's high-elevation lakes,[48] and acidification will diminish the abundance of several species of aquatic organisms such as mayflies, an important food for trout.[49]

> Normally clear mountain lakes could turn murky as changing rain or wind patterns bring more pollution to the high country.

Another factor in changing the chemistry of mountain lakes is fires. Fires loft large amounts of material into the atmosphere, including nutrients that may fall into lakes. If climate change increases the incidence and/or severity of fires, algal growth and eutrophication in mountain lakes also may increase.

FIGURE 6
More Pollution in Formerly Clear Mountain Lakes

See page 26
for full-size full color image of this figure

Reductions in runoff could greatly degrade the wetlands that remain in the Central Valley. They now receive considerable runoff from agricultural fields, which contains numerous pollutants, often concentrated by evaporation.[34] These wetland ecosystems are harmed by the pollutants yet benefit from the runoff water. They are also highly vulnerable to reduced rainfall or policies that would divert more water from agricultural to urban uses. Moreover, these wetlands are important to migratory waterfowl, and the birds would be adversely affected by either elevated pollutant levels or loss of wetland area that would result from reduced runoff. The seasonally filled vernal pools of the Central Valley, which harbor an assortment of locally limited and endangered species, are especially sensitive to even slight increases in evaporation or reductions in rainfall because of their shallowness and seasonality.[50]

Plant Growth and the Water Cycle

Climate warming can either increase or decrease plant growth while elevated carbon dioxide spurs it. In California, which factor dominates will depend on the availability of water. Most California plants are highly sensitive to drought, and future changes in the summer dry period are likely to have impacts on plant growth that are at least as large as, and probably greater than, changes in temperature or carbon dioxide. Increases in winter precipitation may do little to increase summer soil moisture, however, unless a shift in timing extends the rainy season and the period of wet soils. Greater evaporation in a warmer climate is likely to cause greater drying of soils. Thus, summer drought stress may become increasingly important for plant productivity in California, unless the loss of soil moisture can be offset by the water-conserving responses of plants to elevated carbon dioxide.

Plant survival on land requires that the energy and carbon captured in photosynthesis be greater than that lost to respiration. This imbalance is fundamental. Plant growth, whether it occurs in a timber tree, a grape vine, or a grass used to revegetate a highway cut, fuels the cycle of life on the land and forms the foundation of the earth's food webs. Plant growth also provides an enormous subsidy to humanity in the form of carbon storage. Plants lock away in their tissues a substantial fraction of the carbon released by the world's economic activities—carbon that would otherwise be released to the atmosphere as carbon dioxide to intensify greenhouse warming. Carbon storage on land occurs when the uptake of carbon by green plant photosynthesis is greater than carbon released by respiration.

> For most of California, climate change probably means more evaporation and thus drier summer soils.

FIGURE 7
Redwoods in Fog

See page 26
for full-size full color image of this figure

The imbalance between photosynthesis and respiration is critically dependent on temperature. Respiration—the release of carbon dioxide by organisms as they burn carbohydrates to fuel life activities—generally increases with temperature.[51] Photosynthesis—the uptake of carbon dioxide and light energy by plants for the manufacture of carbohydrates—typically peaks at a point near what a plant experiences during the growing season, then drops off as the temperature rises.[52] Higher temperatures in the cool part of the year should usually increase plant growth or net primary production (total greenery produced), whereas warming in the hottest periods should decrease plant growth. Warming should always increase the rate of decomposition of dead plants and soil organic matter.

Other factors may counteract this effect, however. Plant photosynthesis can operate at higher temperatures in the presence of higher levels of atmospheric carbon dioxide—the same higher levels that are helping to drive global warming. Further, higher carbon dioxide levels have a fertilizer effect, increasing plant growth directly even as they increase the temperature optimum for photosynthesis.[53] The co-occurrence of warming and elevated carbon dioxide could lead to either increased or decreased plant growth, and which factor dominates will depend on the characteristics of individual species and the nature of their environment.

In California, the likely impacts of both warming and elevated carbon dioxide are intimately connected with the availability of water. California's Mediterranean-type climate (see *Current California Climate* on page 7), with its cool, wet winters and hot, dry summers, tends to create a separation between the time that water is available and the time that temperatures are appropriate for plant growth. As a consequence of the summer drought, many California species have been forced to adapt to growing during the winter, when the stress is more often from cold than heat.[54] Especially for winter annual plants that complete their life cycles before the onset of the summer drought, warmer temperatures may be beneficial. Species that grow year-round may be vulnerable to higher temperatures, depending on their individual characteristics, simply because they are physiologically active in summer.[21] Few plant species are killed by temperatures only a few degrees above those they are accustomed to, although unusual heat can decrease growth.

In contrast, most plants are highly sensitive to drought. Photosynthesis and growth completely cease when drought reaches a critical level. Even some of the region's most drought-tolerant desert shrubs suffer substantial mortality in unusual droughts.[55] In general, future increases in winter precipitation and any shifts in summer drought can be expected to have impacts on plant growth that equal and probably exceed those caused by changes in temperature or carbon dioxide.

Clear projections for future soil moisture, especially during the summer drought, are harder to make. The primary issue is that warming leads to increased evaporation, both because the atmosphere is warmer and drier and because of greater water loss (transpiration) by plants, and increased evaporation tends to dry the soil. The overall change in soil moisture, therefore, will depend on whether the increase in winter precipitation is greater than the increase in evaporation. We speculate that, for most of California outside the deserts, the increase in water lost to evaporation may dominate, leading to drier soils in summer. Because the soil now stays largely saturated through the winter rainy season over much of the state, additional rain in the winter will likely add to runoff rather than contribute to soil moisture. Computer simulations tend to support this reasoning, projecting substantial increases in winter runoff in major California rivers.[40]

If this scenario is correct, California's terrestrial ecosystems should, in general, be more affected by any changes in the timing of precipitation that extend the rainy season and the period of wet soils than by increases in the intensity of winter rains and thus the volume of winter runoff. In deserts, where the soil is rarely saturated, more precipitation in any season will increase local soil moisture and affect plant growth. In contrast, in extremely wet sites in the northwest corner of the state, where water is rarely limiting, any new precipitation will likely end up as runoff.

Another factor, however, may counteract drying of the soils by increased evaporation. Higher atmospheric carbon dioxide levels cause some plants to be more efficient in their water use. This water-conserving effect has been observed in California annual grasslands,[56] tallgrass prairie,[57] Australian grassland,[58] and cotton.[59] Unfortunately, it is far from clear that this effect operates in forests, especially conifer forests. Plants in some types of ecosystems, in fact, may respond to increases in soil moisture produced by this water-conserving mechanism by growing more greenery and consuming the additional water.[60] In some situations then, this response to carbon dioxide would not be adequate to counter the effects of climate change that favor increased summer drought. Drought stress may become increasingly important in California, unless the increased evaporative demand is offset by water-conserving responses of plants to elevated carbon dioxide.

FIGURE 8
Plant Responses to Warming

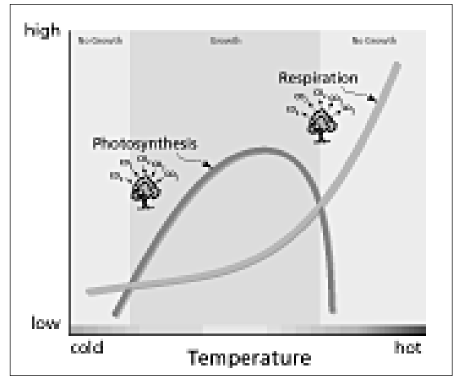

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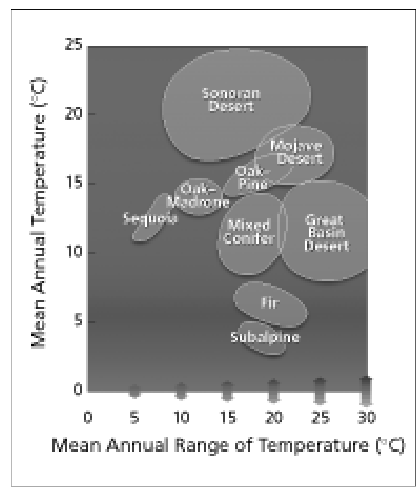
FIGURE 9
Distribution of Californian Plant Communities



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In the north coastal habitats of California, fog is a defining component of the water cycle. Coastal fog and coastal redwoods are partners, with redwoods effectively gathering their summer moisture from the fog. More than 30% of the water reaching the soil and more than 10% of the water annually lost to the air (transpired) by a redwood can come from fog that collects on the leaves and then drips to the soil.[61] If an increase in the frequency of El Niños or a decline in the upwelling of cold water near the coast caused a major decrease in coastal fogginess, the result could be stress and eventual elimination of the coastal redwoods. This remains a subject of great uncertainty. Under some climate change scenarios, coastal upwelling could actually increase and lead to increased fog.[62]

Recent evidence from Europe indicates an increase in the length of the growing season on that continent, perhaps linked to climate warming.[63] Any similar extension in the length of the warm period in California, however, would probably just intensify the severity of the summer drought.

Fire

Fire has long been a prominent force in California's forest and range ecosystems. Since 1850, California wildfire patterns have been altered by climate change, land-use change, and fire suppression, especially in pine and conifer forests. Computer simulations indicate that a combination of warming, drying, and increased winds could lead to large increases in loss to wildfires in the future. Great uncertainty remains in predictions of future fire patterns, largely because most fires in California occur under extreme rather than average weather and climate conditions, and climate models do poorly at predicting extreme events such as Santa Ana winds.

Fire has been a key ecological and evolutionary force in California's forest, shrub, and range systems for thousands of years. In the prehistoric Sierra Nevada, for example, ground fires recurred every 5 to 10 years in woodlands and grasslands, every 4 to 20 years in pine and mixed conifer forests, and every 15 to 40 years in higher elevation red fir forests.[64,65] Even in moist coastal redwood forests, the understory burned on average every six to eight years.[23] Although large, severe crown fires were rare in forest systems, they were characteristic of chaparral and coastal scrub systems, where they recurred every 20 to 80 years.[66,67]

Since 1850 fire patterns in virtually all upland ecosystems in California have been altered by climate change, land-use change, and—especially for the past 50 to 75 years—by fire suppression. Human ignitions now far outweigh lightning ignitions in shrubland fires, and human ignitions play an important role in forest fires as well.[68] Effects of fire suppression have been most dramatic in the pine and mixed conifer forests. Tree densities have increased as a result, and thick understories of white fir and other shade-tolerant species now promote the spread of fire up into the canopy, leading to catastrophic crown fires. The legacy of this management history will play an important role, along with climate change, in determining fire dynamics over the next century. Fire suppression has had less effect in chaparral, where the frequency of large fires has changed little over the past century.[66,69,70]

> Warmer, drier summers could mean hotter, harder-to-control wildfires, especially if the difficult-to-predict Santa Ana winds increase.

Several interacting factors control the pattern of wildfires in an ecosystem. One is climate, which controls vegetation growth and ignition patterns. Another factor is the vegetation itself, including how much fuel it produces and how flammable it is. A third factor is weather events, in particular the onset of extreme dry and windy conditions. Not surprisingly, fire histories reconstructed from tree ring records and fossil charcoal have shown that prehistoric forest and shrubland fire patterns in California were extremely sensitive to regional climate. For example, giant sequoia groves in the Sierra Nevada experienced fires every two to three years during the unusually warm period between 1000 and 1300 A.D., compared with every three to eight years during the cooler conditions between 500 and 800 A.D. and after 1300 A.D.[66] In the Santa Barbara region over the past 500 years, unusually wet decades have been followed a few years later by an increase in large chaparral fires.[63]

Fire behavior models predict a sharp increase in both ignition and fire spread under warmer temperatures combined with lower humidities and drier fuels.[71] One study, for example, combined a forest dynamics model and a fire model to look at Sierra wildfires under several different climate scenarios.[72] The results showed that the severest effects on fires would be provoked

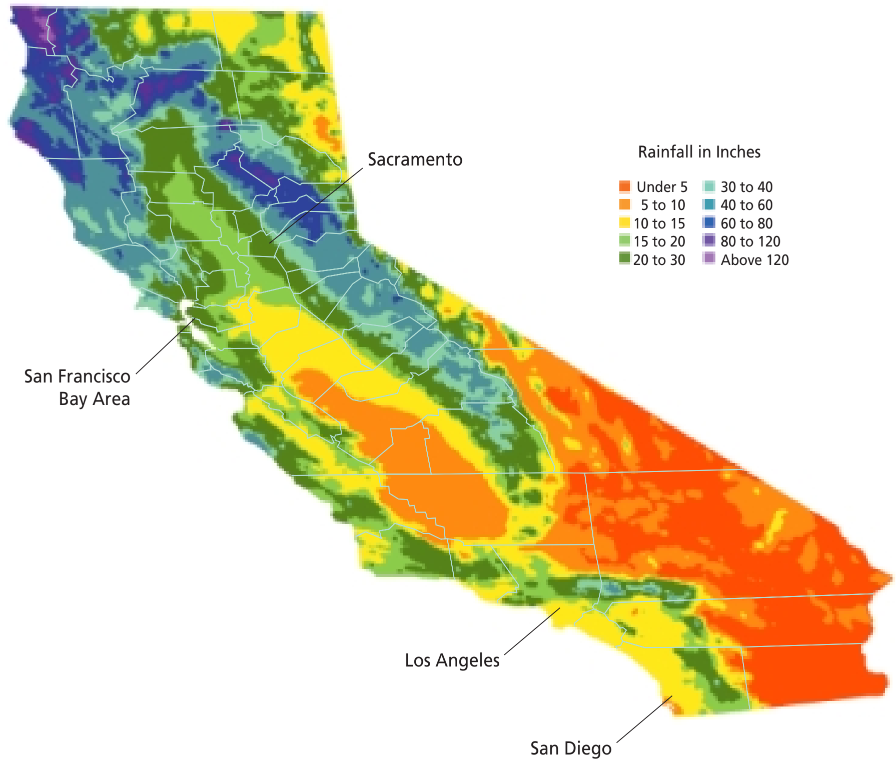
FIGURE 1

Map of Current California Precipitation

from page 8

The likely climate future for California is warmer and wetter winters and drier and hotter summers. Increased winter precipitation, particularly in the mountains, will more likely fall as rain than snow—resulting in greater winter runoff and less flow in summer streams. This cycle would intensify water demands in the state. Of course, rainfall varies tremendously across California, and climate change impacts will likewise be variable.

Credit: Christopher Daly, Oregon Climate Service, Oregon State University (http://www.ocs.orst.edu/pub/maps/Precipitation/Total/States/CA/ca.gif)



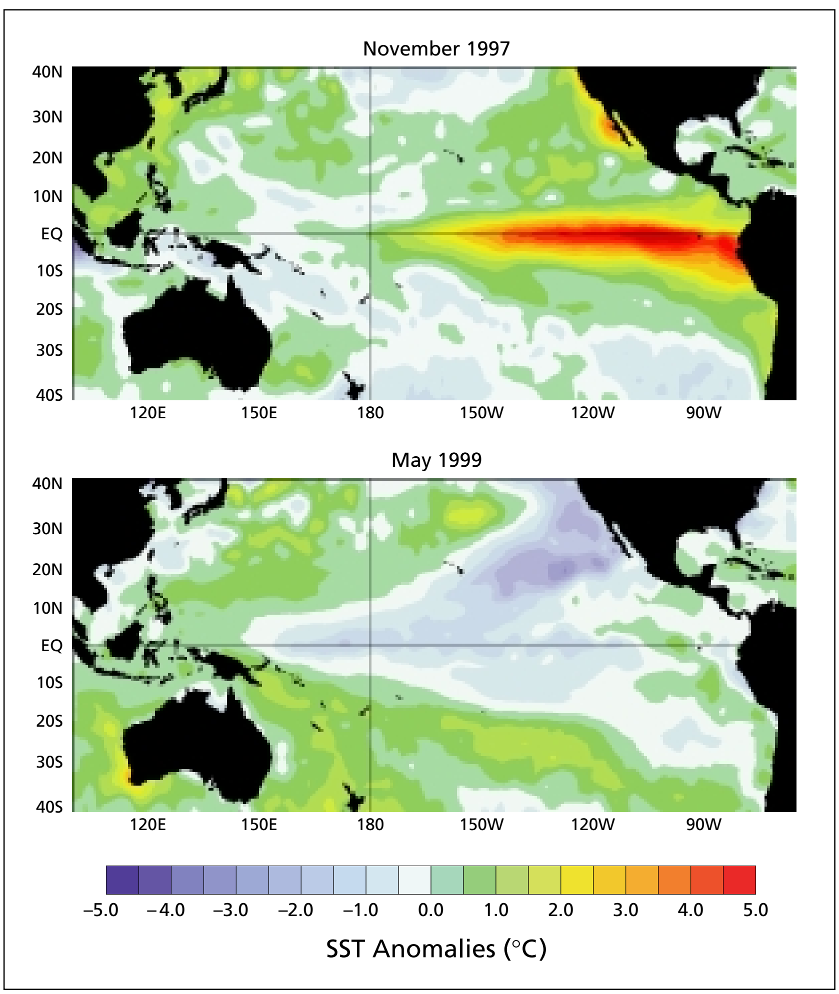


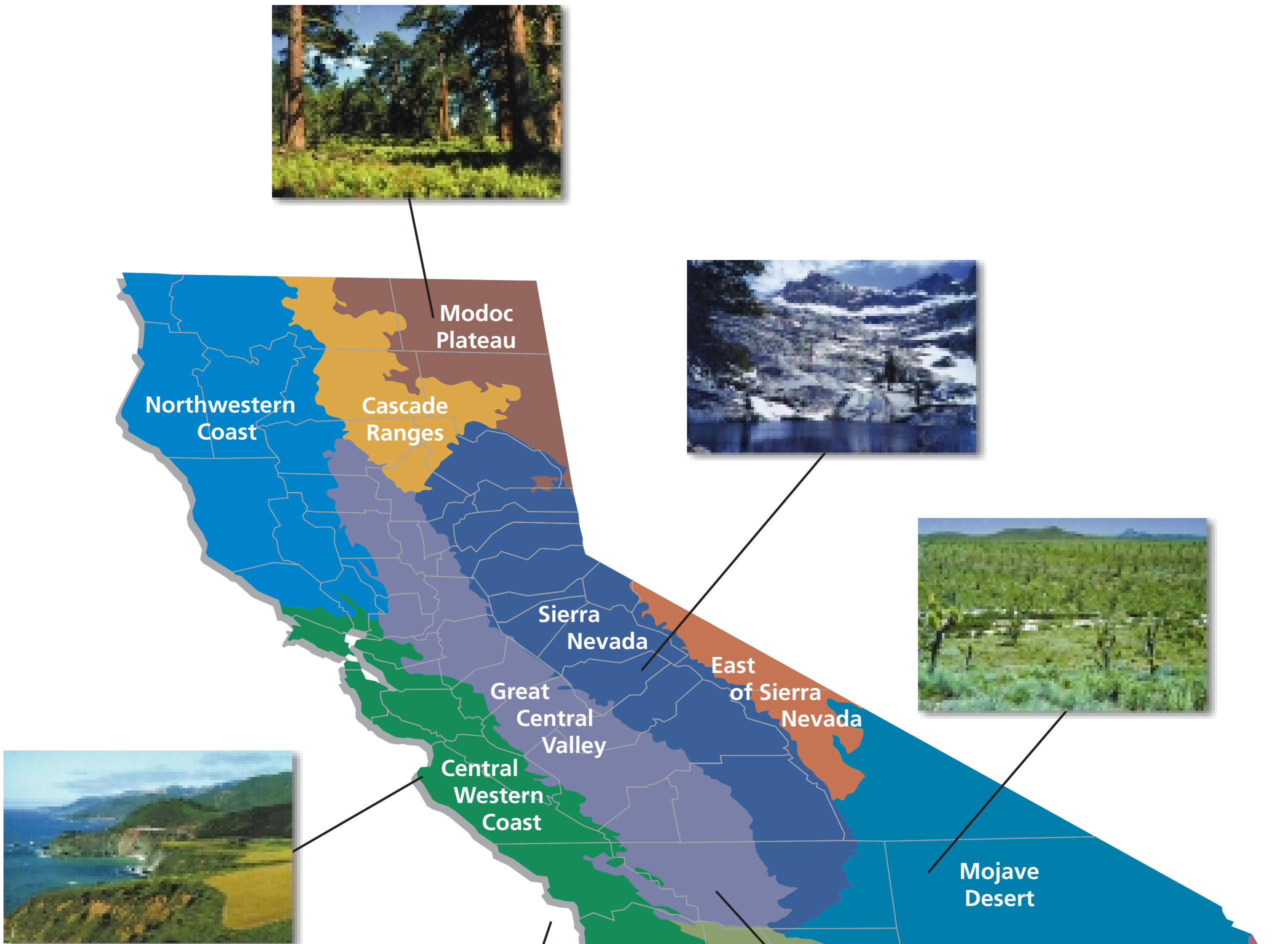
FIGURE 2

Sea Surface Temperatures—El Niño and La Niña Phases

from page 9

Much of California's year-to-year climate variation is linked to El Niño, and there is increasing evidence that El Niños may become more frequent as the climate changes. If so, Californians have had a taste of the future with the unusual frequency of El Niño since 1970, which brought costly floods, landslides, extreme tides, and power outages. These two sea surface temperature charts show the El Niño phase (above) and the La Niña (below).

Credit: Andrew F. Loughe, NOAA-CIRES Climate Diagnostics Center



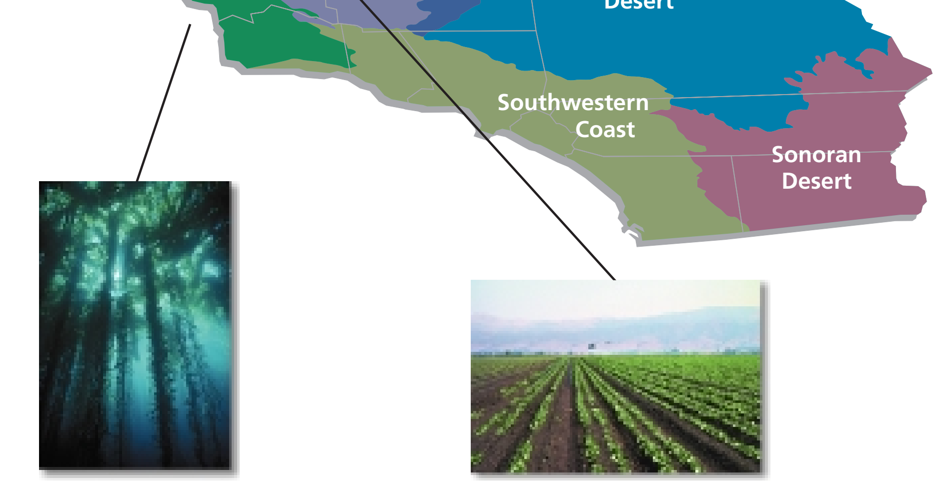


FIGURE 3

California's Distinctive Ecosystems

from page 11

California's landscape is dramatically diverse, encompassing 10 so-called "bioregions" on land as well as a highly productive coastline. In addition to this natural heritage, the 11% of California's landscape devoted to agriculture generates the highest state farm income in the United States.

Credit: Photos–clockwise from top: Eastside pine woodland, Frank Davis; a Sierra lake, John Melack; Mojave Desert, Kathryn Thomas; Farm field, American Farmland Trust; Kelp forest, Phillip Colla; Big Sur, Frank Davis. Jepson Ecoregions map–Frank Davis, California Gap Analysis Project

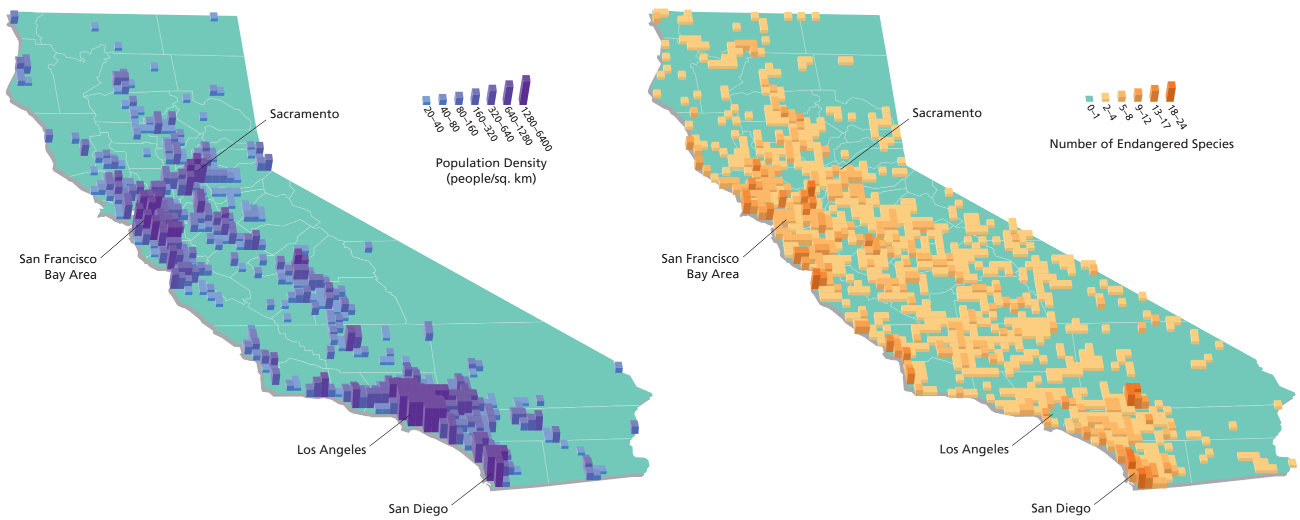


FIGURE 4

California Population Density Map/ Map of Rare and Endangered Species in the State

from page 15

With more than 30 million inhabitants, California's population density is nearly three times the U.S. average (shown at left). Human impacts on California's plant and animal species are pervasive. The maps above show that rare and endangered species are native to many of the most populous areas of the state. Indeed, Southern California hosts one of the four largest concentrations of endangered species in the United States

Credit: Michael Snow/Snow Creative Services, based on figures by Frank Davis.

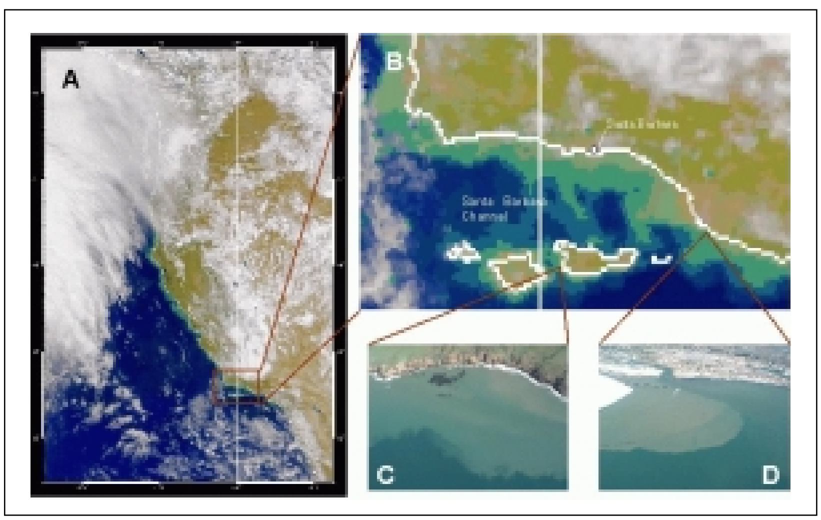


FIGURE 5

Greater Health Risks from Storm Runoff

from page 18

Many of Santa Barbara's popular beaches were closed in 1998 due to high bacterial counts from the intense El Niño storm runoff. Shifts in the amount or timing of freshwater runoff due to climate change can alter conditions in California's bays and estuaries. More winter runoff may bring larger sediment flows into coastal waters, while less summer stream flow would increase salinity and impact fish that use the bays as nursery grounds. True-color SeaWiFS images (A and B) show large areas of the Santa Barbara channel covered with El Niño stormwaters in 1998. These are also seen in the aerial photographs (C and D)

Credit: Figure produced by Prof. Leal Mertes and the Plumes and Blooms Project, ICESS/UCSB.

FIGURE 6
More Pollution in Formerly Clear Mountain Lakes
from page 19

Pristine mountain lakes, such as Emerald Lake in Sequoia National Park, could turn murky as a potential consequence of a changing climate in California. More pollution would be transported to the Sierra Nevada high country by an increase in the region's "convective storms"—the thunderstorms and other heavy rainfalls that occur in summer. These storms arise over land, trapping pollutants and nutrients that can acidify or cause algal growth in normally clear mountain lakes.

Credit: John Melack

FIGURE 7
Redwoods in Fog
from page 20

Northern California's storied coastal redwoods capture their summer water supply from fog. More frequent El Niños could greatly reduce coastal fogginess. It remains uncertain, however, whether fog will increase or decrease with climate change.

Credit: Gary N. Crabbe/Enlightened Images

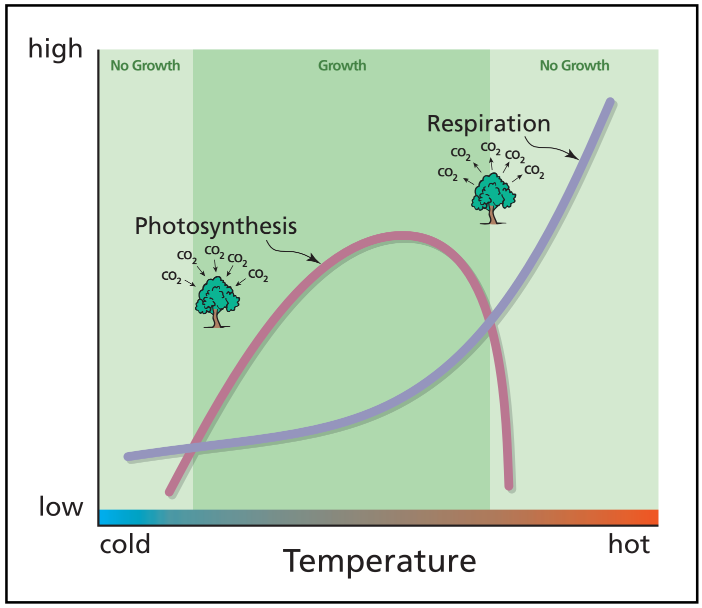
FIGURE 8

Plant Responses to Warming

from page 21

For plants to survive, the energy and carbon captured in photosynthesis must be greater than that lost to respiration—and temperature greatly affects this balance. As this chart illustrates, respiration rates generally increase as the temperature warms while the rate of photosynthesis typically peaks—usually at a temperature near what a plant experiences during the growing season—then drops off sharply. The shaded area represents the range in which plants grow. For example, higher temperatures in the cool part of the year should increase the lushness of plant growth, while warming in the California summer should decrease plant growth. Both carbon dioxide levels and water availability, however, could change the outcome.

Credit: Michael Snow/Snow Creative Services, based on schematic by Christopher Field



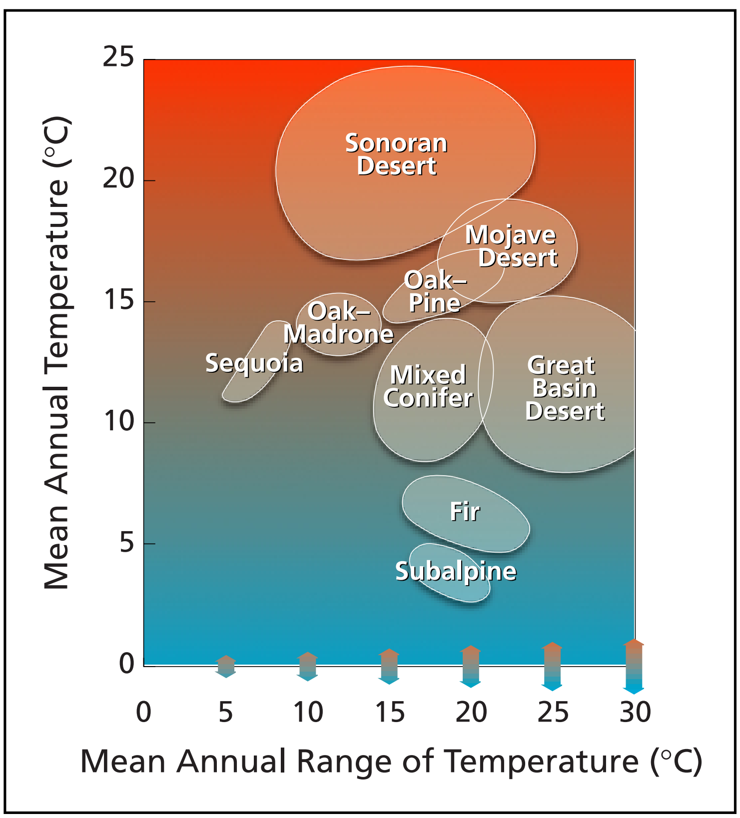


FIGURE 9

Distribution of Californian Plant Communities

from page 21

Plants are limited by the absolute temperatures and the range of temperatures in which they can survive. This figure shows the general mean temperatures and temperature ranges at which typical Californian plant communities exist.

Credit: Michael Snow/Snow Creative Services, Redrawn from S.C. Keeley and H. A. Mooney[18]

FIGURE 10
Fire in California Shrublands
from page 35

Warming, drying, and increased winds could mean hotter, harder-to-control wildfires, as seen in this night-time photo of the Romero Canyon fire in Santa Barbara. Future fire patterns in California remain difficult to predict, however, because most fires occur under extreme conditions—such as Santa Ana winds—and climate models are poor predictors of extreme, rather than average, conditions.

Credit: Frank Davis

FIGURE 11
California Vegetation Shifts
from page 37

The most likely scenario over the next century is an expansion of grassland communities at the expense of the shrublands in California's foothills. Shrublands in turn could replace the forests that now occupy the higher slopes. The top map shows the current distribution of vegetation types in California, while the map on the bottom shows a likely scenario for future vegetation shifts in the face of climate change as projected by a computer model called MAPSS, for the years 2070–2099.[149]

Credit: Michael Snow/Snow Creative Services, based on figure by Christopher Field and Ron Neilson

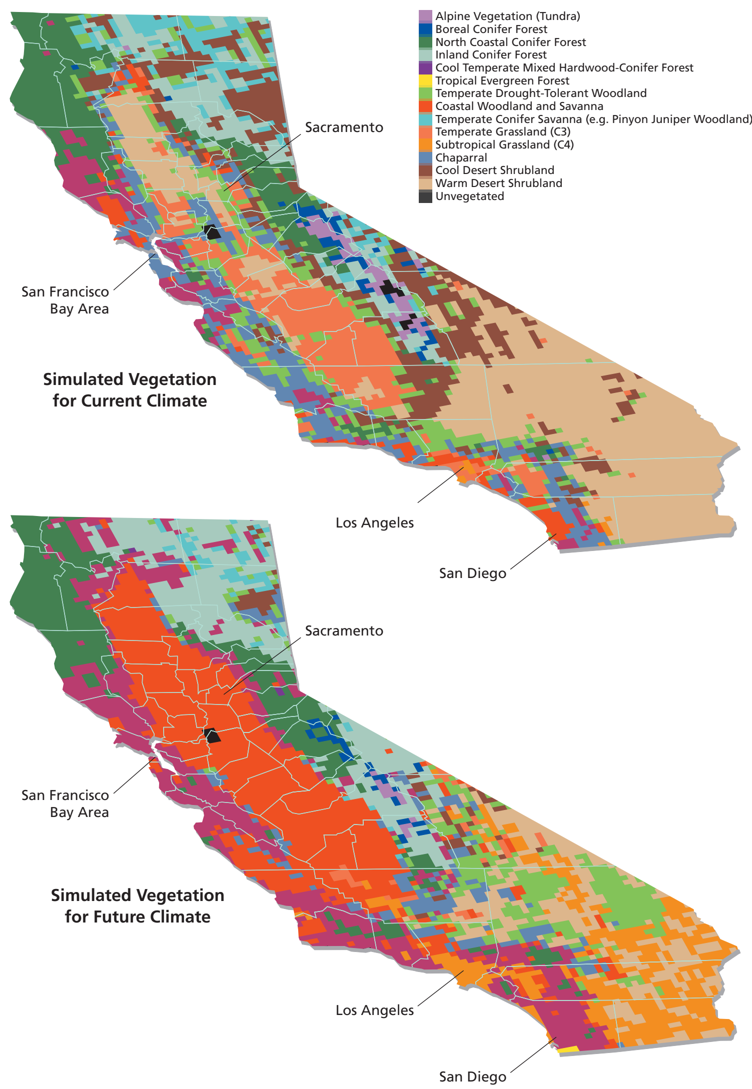


FIGURE 13

Obstacles to Finding New Habitat

from page 40

The abundance of invading species such as this starthistle (shown close-up in the photo at left) make it increasingly difficult for native species to migrate to suitable new habitats as the climate changes. Yellow starthistle is a noxious nonnative weed that infests 22 million acres of California grassland, rendering many areas useless for grazing and miserable for recreation, as seen in the photo at right. Nonnative species have already severely impacted many of California's ecosystems—especially freshwater systems and grasslands.

Credit: Jack Kelly Clark, printed with permission of the University of California Statewide Integrated Pest Management Project.

Credit: Steve Schoenig, State of California Dept. of Food and Agriculture Plant Health and Pest Prevention Services, Integrated Pest Control Branch

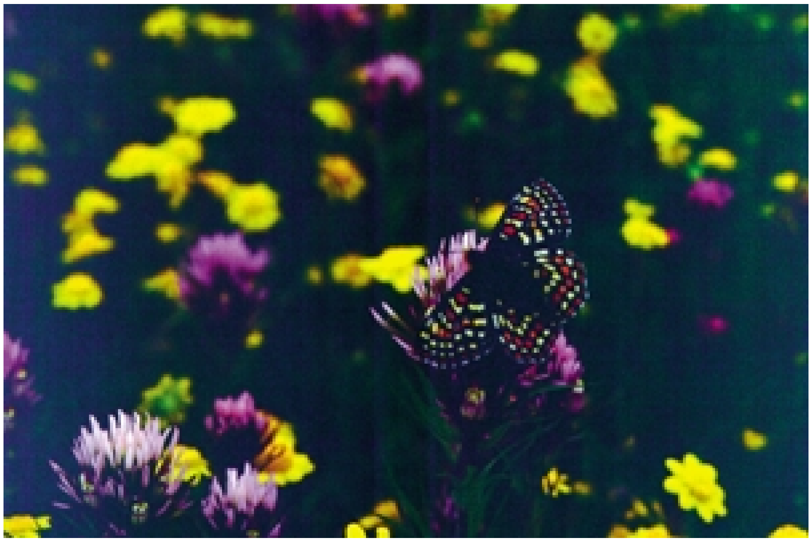


FIGURE 12
Plant and Animal Range Shifts
from page 39

Shifts in species ranges are already occurring, most likely in response to warming. At least one California butterfly species, Edith's Checkerspot, is shifting from the southern to the northern end of its range and from lower to higher elevations. A recent study found populations of the butterfly were about four times as likely to go extinct at the southern extreme of its habitat than at the northern extreme.

Credit: Larry LaTarte

FIGURE 14
Forests Under Attack
from page 41

This photo, taken at Mt. Meadows Reservoir near Chester, shows the devastation wrought by the Jeffrey pine beetle. Outbreaks of many stand-destroying tree pests tend to occur when the host trees are already stressed or weakened. Such pests could become more prominent if climate change stresses their hosts. However, climate change will affect pests, their target plant or animal species, and the natural enemies that prey on the pests in different ways, making it hard to precisely predict future pest and disease patterns.

Credit: Bruce Roettgering, photographer, Forest Service-USDA, Pacific Southwest Region

FIGURE 15

Increased Flood and Landslide Risk

from page 43

Wetter winters with more rain than snow—as well as any increases in the frequency or intensity of El Niños—should increase risks from floods and landslides in California, including higher flood peaks as well as large floods in winter rather than spring. This photo shows one of the many areas of the north-central valley that were inundated by the widespread flooding of January 1997.

Credit: Robert A. Eplett, California Governor's Office of Emergency Services

FIGURE 16

A Destructive Combination

from page 43

Timber harvests and fires also increase the likelihood of landslides during the wet season, as illustrated in these photos from Laguna Beach in Orange County (above) and this landslide along U.S. Highway 50 in El Dorado County (below). In both instances, the slope failed in a heavy rainstorm that was preceded by a vegetation-destroying fire.

Credit: Laguna Beach–Bill Dietrich; Highway 50–Robert A. Eplett, California Governor's Office of Emergency Services

FIGURE 17
California Water Resources at Their Limit
from page 44

More droughts could threaten California's productive agricultural regions. 87% of California's crop area is irrigated; and although future drought could theoretically be countered by more irrigation, virtually all of California's surface water is already allocated and further water imports are unlikely. In addition, irrigation can eventually become counterproductive, causing salt to accumulate in the soils, making them unproductive.

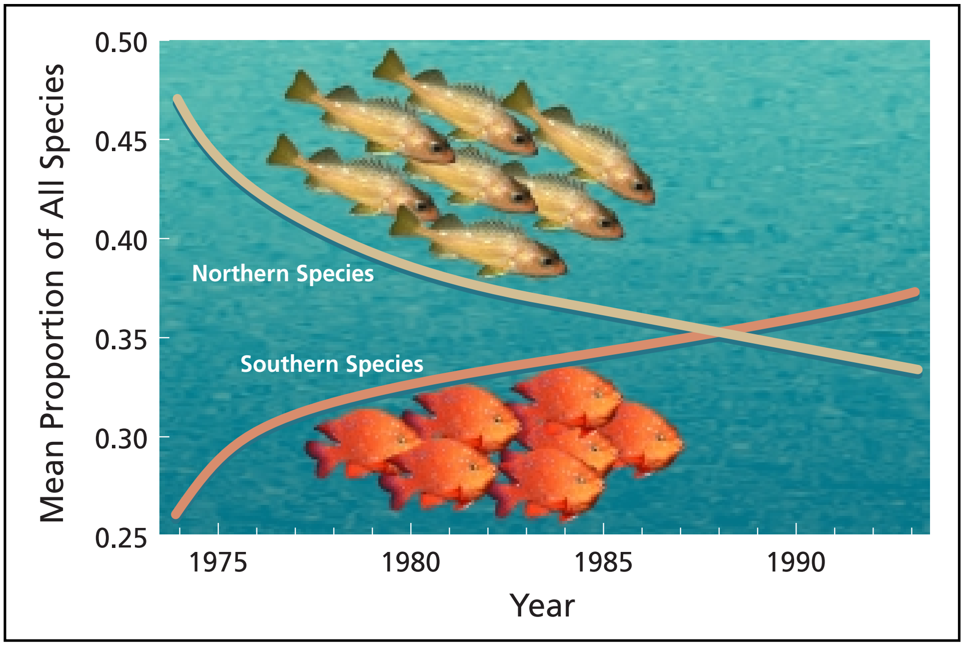
Credit: California Department of Water Resources

FIGURE 18
Growers Need Projections of Future Climate Conditions
from page 45

Many of California's most economically important crops—including fruit and nut trees and grapes—are perennial. Because trees and vines require several years to mature, growers cannot respond to changing climate conditions by simply planting new varieties and bringing them quickly to production.

Credit: American Farmland Trust

FIGURE 19
Changing Coastal Marine Ecosystems
from page 47



Since 1976–77, warmer ocean temperatures off the coast of Southern California have resulted in declining abundance of fish and lower productivity in this ecosystem. The proportion of cold-water, northern fish species (represented here by the greenspotted rockfish) in the reefs along the shore near Los Angeles has dropped by about half, while the proportion of southern, warm-water fish species (represented here by the Garibaldi) has increased by nearly half. In addition, future increases in the frequency or intensity of El Niño events could have severe impacts on the geographic distribution of viable fisheries off California.

Credit: Michael Snow/Snow Creative Services, based on diagram by Jeff Jones, University of California at Santa Barbara

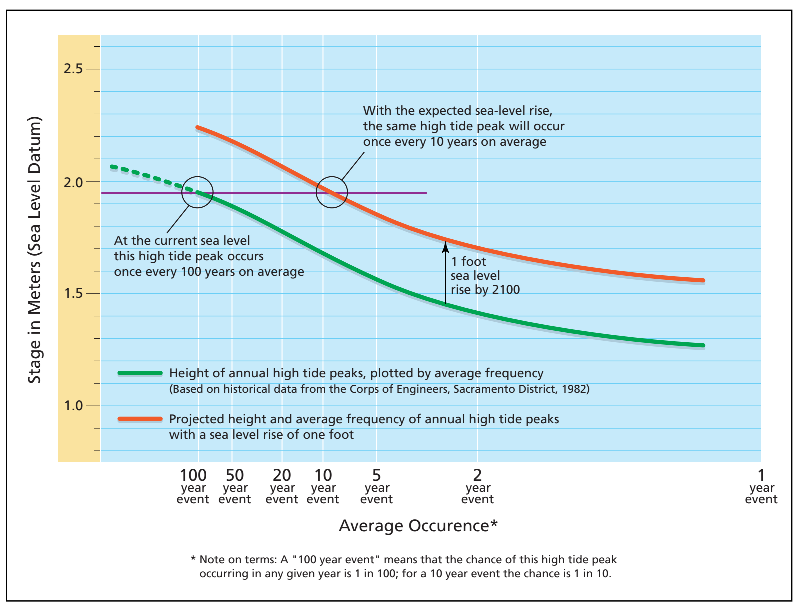


FIGURE 20
Sea-Level Rise and Delta Flooding
from page 49

1100 miles of levees protect rich farmland, small communities, highways, and utilities that have been built up in the Sacramento-San Joaquin Delta on land reclaimed from marshes. A one-foot rise in sea level resulting from climate change would transform the current high tide peak on the lower San Joaquin from an event that occurs every 100 years on average to one that occurs every 10 years—making the now rare event in the Delta a common one.

Photo Credit: Robert A. Eplett, California Governor's Office of Emergency Services
Credit: Michael Snow/Snow Creative Services, based on graphs by Maurice Roos and Herb Hereth

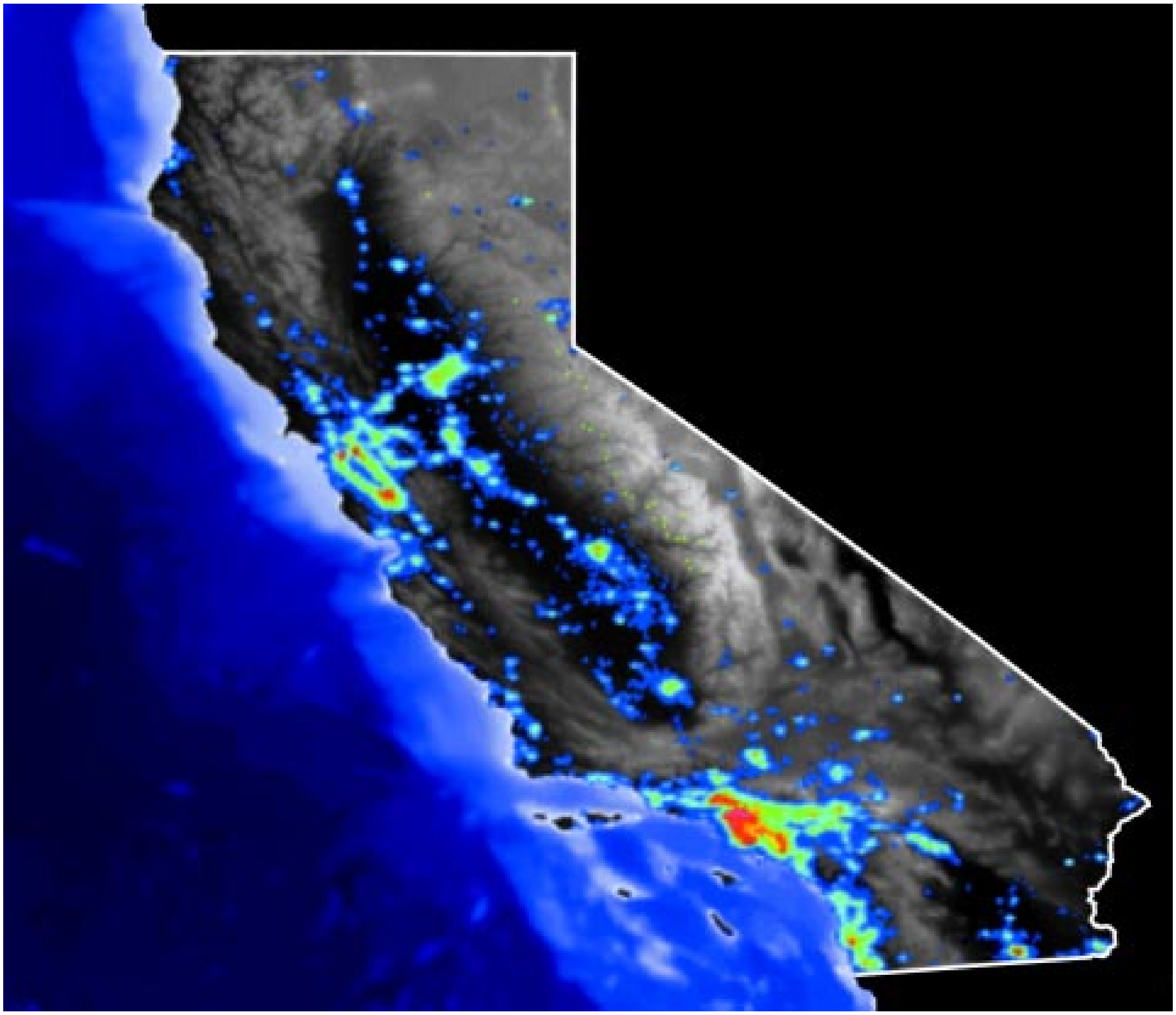


FIGURE 21

California at Night

from page 53

Shown here is a nighttime view of urbanization in California, clearly documenting the extent of human activity throughout the state. California, with the world's seventh largest economy, is responsible for about 2% of its fossil fuel use. Californians could be a model for the nation and the world by taking action to decrease their reliance on coal, oil, and gasoline—thereby reducing greenhouse gas emissions that lead to climate change.

Credit: Image created from the Defense Meteorological Satellite Program's Operational Linescan System by research sponsored by NASA's Earth Science Enterprise, NASA's Goddard Space Flight Center, and NOAA's National Geoscience Data Center. Image composite produced by Flashback Imaging Inc. .

by an expansion of the fire-prone mixed conifer forest and a corresponding reduction in the red fir forest that occupies the next higher elevation zone. This change in forest composition was accompanied by substantial increases in both fire frequency and area burned.

In another simulation that coupled a fire model with a climate model, the results showed that the combination of warming, drying, and increased winds could lead to large increases in loss to wildfires.[73] Because hotter fires generally spread quickly, they have a greater tendency to escape control and can release wind-borne embers that start fires at unconnected sites. This combination of intensity with difficulty of control led researchers to conclude that California wildfire losses would increase, even with increased expenditures for fire control. On the basis of this analysis, the greatest expansion in area burned and in fire losses would come in the grasslands and shrublands of California's coast and foothills.

The effect of increased winter or spring precipitation on the occurrence of wildfires is harder to predict. Increases in summer fuel moisture can more than offset the effects of increased summer temperatures on ignition and spread of fire in chaparral shrublands.[71] Any change in water balance would also affect changes in plant growth and canopy structure that could either promote or retard fire in different ecosystems.[74] Fire is limited by the amount and distribution of fuel in deserts, Great Basin woodlands, and grassland ecosystems, but fuel is a far less limiting factor in shrublands and forests.

FIGURE 10
Fire in California Shrublands

See page 28
for full-size full color image of this figure

It is important to emphasize the very great uncertainty in any predictions of fire patterns under future climate scenarios. Most fires occur under extreme rather than average weather conditions, extremes that are not well predicted by any climate models. Wind, for example, is a critical fire variable that is very poorly predicted with the use of current GCMs, especially in rugged terrain. Frequency and timing of Santa Ana events in Southern California and similar wind episodes in other regions may, at least in the short run, be far more important than changes in average temperature and rainfall. Finally, variations in the pattern of seasonal and year-to-year precipitation will have an important impact on changes in wildfire patterns across the state.

Future Distributions of California Ecosystems

As climate conditions change, the map of vegetation types will shift. Tracking where ecosystems will move in a warming climate is not straightforward, because species move individually, and their fate may be altered by changes in the availability of water and nutrients or patterns of fire, drought, or pest attack. Computer models suggest that the arid shrublands on California's foothills may give way to grassy savannas while shrubs replace forests on higher slopes. Trees, in turn, may gain ground upslope. In many parts of California, fragmentation of the landscape by human developments, invasions by non-native species, and air pollution may limit the reestablishment of native ecosystems.

The world's ecosystems are astonishingly diverse, containing perhaps 10 to 30 million different kinds of plants, animals, and microbes. In spite of this diversity, the distribution of the major vegetation types according to climate zones is relatively consistent throughout the world. Tropical forests, grasslands, shrublands, deciduous forests, and conifer forests all tend to occur in similar zones of temperature and precipitation on every continent. The fossil record supports the idea that plants move as climate changes.[75] Analysis of pollen captured in lake sediments, for instance, shows that even relatively small changes in climate such as the 1° F cooling that occurred during the Little Ice Age in the 17th century are followed by a change in plant species.[76]

A simple starting point for mapping the fate of California ecosystems would be to suggest that they will move northward or upslope as the climate warms so that they track the movement of their preferred temperature zone. Yet abundant evidence illustrates the danger of overemphasizing a simple model like this:

- Species clearly move as individuals and not as complete communities.
- Increased temperature can lead to changes in the availability of water or nutrients—changes that benefit some species and stress others.
- Extreme events such as severe droughts are often more limiting to plant survival than average conditions, so average temperature may not be a good predictor of where plants would move.
- Warming could alter the risk of fire, disease, or pest attacks that affect the fate of species and their ecological communities.

Because of such complexities, early models such as the Holdridge life zones that predicted vegetation zones as a function of altitude or annual temperature and precipitation[77] have given way in recent decades to models built on a wealth of field and laboratory data that take into account the role of seasonality, soils, altered carbon dioxide, and other factors.[78,79] The most highly developed and widely tested computer models in use today for predicting the redistribution of plant communities in response to climate change (equilibrium biogeography models) still have major limitations. One is that they see only a natural world, with grasslands where the climate and soils are suitable for grasslands, and so forth, without regard to the fact that in California and elsewhere much of the landscape has been converted to subdivisions, golf courses, citrus groves, or rice. Second, they also see only the end point, the equilibrium stage, in the musical chairs of climate change and ecosystem reshuffling: if it's 2100 and 4° F warmer, this must be shrubland. Yet ecosystem distributions over the next century will certainly not reach any final equilibrium, and current models tell us little about the ecological and economic upheavals that may occur in natural or agricultural areas during the transition. Still, the models provide a valuable starting point.

Two equilibrium biogeography models, MAPSS[79] and BIOME3,[80] have been widely used to assess potential changes in vegetation distributions with climate change. Projections from these models differ substantially, depending on which climate change scenario and which ecological processes are represented in a particular experiment.[81]

Among all the model projections, the most likely scenario over the next century or so is an expansion of savanna communities at the expense of the shrublands in California's foothills. Shrublands and grassy savanna often occur in close juxtaposition to each other, especially in the Coast and Peninsular Ranges but also throughout much of the western foothills of the Sierra Nevada. In these areas, fire, timber cutting, topography, and soil types have all interacted to produce mosaics of savanna, shrublands, and forests. Even as shrublands contract across much of the foothills, shrubs could replace the forests that now occupy the shadier north-facing slopes in these settings. In this scenario, the relatively drought-adapted broadleaf and conifer tree species in these foothills would decline or disappear at lower elevations and on relatively dry sites but could become more competitive upslope.

> Over the next century, California's ecosystems will tend to shift north and up the mountains, except where appropriate habitats do not exist or have been replaced by human development.

Shrublands are interspersed among broadleaf and conifer forests throughout California's mountains. Also, trees and shrubs intermingle in many coastal oak woodlands and in the pinyon-juniper woodlands of the Modoc Plateau, the eastern Sierra Nevada, and at high elevations in the Mojave Desert. A modest shift to a warmer climate, especially one with drier soils in summer, could facilitate a gradual increase in the abundance of the shrubs at the expense of the trees. This tendency would be reinforced if climate change were accompanied by an increase in fire frequency. In fact, potentially slow transitions from one vegetation type to another could be greatly accelerated by climate-driven increases in the occurrence of fire, pests, or disease.

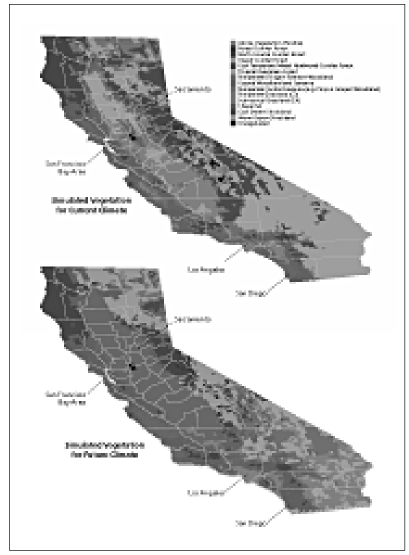
One important and largely unanswered question concerns reshuffling of vegetation types: What happens in the interim if the rate of future climate change exceeds the maximum speed at which organisms can disperse? This problem has three aspects: the fate of species already present, including changes in their growth, reproduction, and survival; how long it takes new species to migrate in from distant sites;[82] and the distances involved in migrations. "Outpost" populations scattered through the areas to be colonized could keep the distances small. But if plants begin to die out on a site before new, better adapted species move in, the result could be degraded systems that fail to provide ecological goods or services.

The question of whether species can move quickly enough to keep up with climate changes has an important counterpoint, especially in the time frame of a century or so. Many of California's most spectacular and revered ecosystems are dominated by trees such as coast redwoods, Giant sequoias, and bristlecone pines that have individual lifespans of several centuries or even millennia. In these cases, persistence of the forests over the next century requires only that environmental conditions remain appropriate for adult survival. The range of conditions that allows for adult survival, however, is typically much broader than that required for seed production, seedling establishment, or the progression from seedling to adult. Thus, continued survival of adult individuals is no guarantee that a species is maintaining or perpetuating itself. For a species like the Giant sequoia, adults could persist for thousands of years, leaving us with "museum ecosystems" dominated by spectacular individuals long after these trees have ceased to reproduce. On the positive side, this provides Californians with ample time to find and try solutions that might allow these important species to persist. On the negative side, if effective action is not taken, massive ecological losses will be transmitted, almost invisibly, to future generations.

What happens if climate changes faster than plants and animals can migrate?

On the other hand, not all long-lived species need to reproduce every year. Even when the climate is shifting toward average conditions too dry for such a species to reproduce, for instance, the species might persist for long periods, or even indefinitely, if there are occasional wet periods that allow successful reproduction. The indirect effects of climate change on fire, pests, and disease, however, may be as important as successful reproduction for the persistence of such ecosystems. For example, seedlings and saplings of Giant sequoia are quite sensitive to fire, and successful passage to adulthood requires an interval of several decades without fire. If fire return intervals were to shorten and fires raged too often to allow passage to adulthood, the sequoias would be unable to persist at the site, even if the adults were thriving and setting abundant seed.

FIGURE 11
California Vegetation Shifts



See page 28
for full-size full color image of this figure

Plants whose seeds persist for long periods in the soil can also take advantage of occasional favorable conditions in a changing climate. Such species need appropriate conditions for germination to occur only with great enough frequency that some seeds will remain viable.

In the face of intensive human modification of the landscape, however, species survival and dispersal abilities often will be rendered moot by the fractured nature of California's landscapes. Human developments and managed landscapes, from crop fields to highways and shopping malls, create barriers to dispersal that can turn isolated patches of natural habitat into ecological prisons. Not only seeds but also insect pollinators and animals with limited mobility may be trapped, unable to reach more favorable sites. Even in the absence of climate change, habitat fragmentation tends to have negative effects on the success of plants[83,84] and animals.[85]

In California, habitat isolation often results from fragmentation of a once-extensive ecosystem. In some cases, however, habitat patches existed as islands even before development, with plants restricted by microclimatic conditions or soil chemistry. These islands, especially those defined by soil chemistry such as Northern California's Serpentine outcrops and the seasonally wet vernal pools of the Central Valley, are often ecologically rich, with high proportions of species that exist nowhere else. As more of a given type of habitat is lost to development, the remnant islands are left farther apart and may eventually be unable to serve as "stepping stones" to enable migration during climate change or natural recolonization after a disturbance.

Other human influences will complicate the reshuffling of ecosystems. For example, the composition of communities in the face of ongoing climate change will depend as much on invasions by non-native species as on the ability of native species to survive or migrate. When an unusual weather event, disturbance, disease, or gradual climate change decreases the success of a native organism in any California habitat, it is increasingly likely that, if a replacement takes advantage of the opening, that replacement will be a non-native species.

Air pollution also can have major confounding effects on plant responses to a changing climate. In the southern Sierra Nevada, serious ozone injury has been documented in Jeffrey and Ponderosa pines, affecting their susceptibility to bark beetles. The impacts of ozone and bark beetles depend strongly on the water balance of the tree and are thus closely tied to climate.[86] In Southern California, damage from ozone and nitrogen oxides may interact with changing climate and fire patterns to cause expansion of exotic grasslands at the expense of shrublands in Riverside and San Diego counties.[87]

Biodiversity

When suitable habitat disappears, species disappear. One study reports that 5% to 10% of California's native plants would no longer find suitable habitat within the state if temperatures warmed 5° F. At least one California species, Edith's Checkerspot butterfly, is already shifting to the coolest parts of its range, most likely because of warming. Changes in the abundance of particularly desirable or noxious species are difficult to predict, yet these may be responsible for some of the largest ecological impacts of climate change. California's current system of protected areas is not representative of the state's environments or its biological diversity, and many reserves are very small. Even an expanded and more representative system of reserves will not necessarily protect the state's rare and endangered plants and animals against climate change unless a concerted effort is made to link isolated reserves and to keep suitable migration corridors open. Finally, climate change may create indirect threats to biodiversity by disrupting vital interactions between species, from predation to pollination.

Biological diversity or biodiversity refers to the richness of our living heritage at many levels —genetic diversity within populations, the number of species within ecosystems, the mosaic of ecosystems within regional landscapes. California's biodiversity is extremely rich and distinctive across all of these levels *(see Chapter Two).*

Predicting the impacts of future climate change on biodiversity is a major challenge, but one guided by key principles. Perhaps the most important of these principles is known as the species-area relationship. This is the trend for the number of species to decline as the size of available habitat decreases or its isolation increases.[88] When suitable habitat disappears, species disappear. The area occupied by a species could contract or expand with climate change, depending on which geographic zones still offer a suitable climate. Climate change will cause a shift in the distribution of species toward the most favorable habitats. Their expansion into new habitat will be controlled by the combination of their own dispersal ability and the barriers they face, both natural and human-created. The large, slow-growing organisms that dominate many ecosystems may persist as non-reproducing adults for extended periods, but they will, at least in theory, be the species most likely to disappear over time as patches of available habitat shrink.[89]

One study has predicted that 5% to 10% of California's native plant species would no longer find suitable temperature conditions within the state if average temperatures warmed 5–6° F.[90]

We are already beginning to see shifts in species ranges, with at least one California species shifting from the southern to the northern end of its range and from lower to higher elevations. Populations of Edith's Checkerspot butterfly were about four times as likely to go extinct at the southern extreme of its habitat than at the northern extreme, according to a study that compared current surveys with museum collection records.[91] Further evidence for the role of climate comes from the observation that the fraction of populations that disappeared was lowest in sites at the highest elevations. Perhaps as important as the results of this study was the researcher's finding that about one third of the original survey sites could no longer be used for comparisons because they had become too degraded to qualify as suitable habitat.

The example set by Edith's Checkerspot butterfly in California appears to be typical of habitat shifts of other butterflies. A recent study of 35 European butterflies concluded that, in the past century, 63% shifted ranges to the north, whereas only 3% shifted to the south.[92] Although these habitat shifts are stark evidence that impacts of climate change are already being felt at the ecological level, they are also an encouraging indicator of the potential mobility of species. In this study, northward habitat extensions in the past century ranged from 20 to 150 miles (35 to 240 km), shifting the animal's ranges by about the same distance as the 75-mile (120-km) average shift in the isotherms or zones of equal temperature.

Possible changes in the abundance of particularly desirable or undesirable species will be very difficult to predict. Yet such changes may be responsible for some of the largest impacts of climate change on ecosystem goods and services. For example, if Pacific yew trees and their associated fungus, *Taxomyces andreanae*, had been lost from the North Coast forests, there would have been no discovery of the cancer drug taxol.[93] Loss of charismatic or highly revered species such as the remaining Giant sequoias would be a spiritual and cultural affront to many Californians. On the other hand, a dramatic increase in the abundance of a noxious weed such as yellow star thistle, which already infests 22 million acres of California, can render annual grassland useless for grazing and miserable for recreation.[94]

> If climate change affects the timing of plant or animal life stages—such as when buds burst, when flowers bloom, or when eggs hatch—then vital interactions between species, from pollination to predation, may be disrupted.

Many of California's rare and endangered organisms occur only in remnant or isolated habitats. In many cases, these plants and animals are unusually picky about their habitat, slow to reproduce, ineffective at colonizing new sites, or a combination of all three. In the absence of climate change, appropriately designed preserves may be an effective strategy for protecting such species.

FIGURE 12
Plant and Animal Range Shifts

See page 30
for full-size full color image of this figure

However, California's current system of protected areas is not representative of the state's environments or its biological diversity. Although 18% of the state is in formally designated public or private reserves, much of this land is at high elevation in the southern Sierra Nevada or in the desert regions; low elevations and coastal areas are underrepresented. Thus, of 194 mapped plant community types, 73 types—including many very widespread shrubland and forest types—have less than 10% of their current distribution in reserves.[95]

Even an expanded and more representative system of reserves will not necessarily protect the state's rare and endangered plants and animals against climate change unless a concerted effort is made to physically link isolated reserves and to keep suitable migration corridors open. Otherwise, even modest changes in climate could substantially degrade the effectiveness of small or isolated preserves, and many of California's reserves are very small. More than half of 1,019 individual reserves mapped by the California Gap Analysis Project occupy less than 500 acres (200 ha).[95] The difficulties of migrating from isolated reserves to suitable new habitats could be further aggravated by an abundance of alien invading species, most of which are successful invaders precisely because they are excellent colonists.[94] Increasingly, rare and endangered species are held almost as prisoners by alien invaders in limited and sometimes deteriorating habitats.

FIGURE 13
Obstacles to Finding New Habitat

See page 29
for full-size full color images of this figure

Climate changes that affect the timing of plant or animal life history events such as leaf emergence, flowering, and egg hatching could also threaten biodiversity by disrupting vital interactions between species, from predation to pollination. There is some evidence, for example, that climate change could disrupt plant-pollinator relationships and dispersal of seeds by animals in Mediterranean-climate ecosystems, including California.[96] Pollination by bats, bees, beetles, birds, butterflies, and other animals is required for the successful reproduction of most flowering plants, including both wild and crop species. In California agriculture, pollinators are critical to production of many orchard, field crop, and forage plants, as well as the production of seed for many root or fiber crops The continued availability of pollinators depends on the existence of a wide variety of habitat types needed for their feeding, successful breeding, and completion of their life cycles.[97] Pollination services may already be in decline in important crop-growing regions, but this apparent trend has been detected only recently and remains poorly documented.

> Endangered plants and animals will not be protected against climate change unless we make a concerted effort to physically link isolated reserves and to keep suitable migration corridors open.

Pests and Pathogens

The impact of climate change on pest and disease outbreaks is difficult to predict because it involves changes in both the vigor of the predator and the vulnerability of its prey. Warming speeds up the life cycles of many insects, suggesting that insect pest problems could increase. Yet plant-eating insects also could grow more slowly as they feed on the typically protein-poor leaves produced under conditions of elevated carbon dioxide. On the other hand, if warming stresses trees such as pines, pine bark beetles would find them easier to attack. In California, public health policy and access to medical services will have more influence on the future of human diseases than will climate change. Yet the environment plays a large role in some vector-borne diseases. Warming could make tick-borne Lyme disease more prevalent, although a drier climate might counter that. More intense El Niños could complicate the control of rodent-vectored hantavirus on land and toxic marine algae along the coast.

Pests and pathogens can play important, even dominant, roles in regulating the workings of ecological communities, yet only a few studies have assessed the interactions of pests and pathogens with climate change. Predicting changes in pest and disease outbreaks under a warming climate remains exceedingly difficult because it requires an assessment of the shifting vulnerability or vigor of two or more interacting species—for instance, pests, their target plant or animal species, and the parasitoids and other natural enemies that prey on the pests.[98,99]

There are several possible impacts of climate change on insects themselves. For instance, many insects can complete their life cycles more quickly under warmer conditions, suggesting that insect pests may become more problematic.[98] Elevated carbon dioxide levels in the atmosphere, however, may counter that effect, at least for plant-eating insects. Leaves grown under higher carbon dioxide concentrations generally contain a smaller proportion of protein, and a number of studies have found that plant-eating insects consume more when they are fed such leaves, presumably to meet their protein needs.[100] Despite eating more, insects typically grow more slowly on a diet of leaves grown under elevated carbon dioxide.

Climate change also will have impacts on target species that may make them more vulnerable to pests. Many stand-destroying tree pests, for instance, invade more successfully when harsh conditions limit tree growth. Pests such as pine bark beetle could be expected to become more prominent or more destructive if climate change stresses their hosts. None of the studies to date have examined what happens when a full suite of predatory insects, parasitoids, and other significant actors in the ecological web are allowed to interact under changed climatic conditions.

Plant pathogens are largely unstudied in the context of climate change. Some researchers suggest that increased plant growth stimulated by elevated carbon dioxide may create a denser leaf canopy that evaporates more water and generates more humidity. A more humid canopy, in turn, could encourage fungal pathogens such as rusts, powdery mildews, leaf spot, and blights.[101] But canopy humidity could also decrease on average, especially if water availability declines or elevated carbon dioxide triggers water-conserving tactics that cause plants to lose less water to evaporation. One study with barley yellow dwarf virus concluded that elevated carbon dioxide made infected plants less sensitive to the infection.[102] If infected plants are at less of a disadvantage under the elevated carbon dioxide, however, they are also larger targets for the aphids that spread the virus, potentially leading to faster spread of infections.

> Pests such as the pine bark beetle could become more prominent or destructive if climate change stresses the trees they attack.

Despite the uncertainties, these scenarios emphasize an important point: A number of poorly known ecological interactions have the potential to exert strong control over the magnitude and direction of changes in plant communities, as well as other ecosystem responses to climate change. These include the ecological impacts of physiological processes such as water-conserving responses of plants or changes in their protein content under elevated carbon dioxide. Yet such processes have the potential to completely reverse the nature of ecosystem responses to climate change, a fact that should provoke healthy skepticism about highly specific projections at this stage.

FIGURE 14
Forests Under Attack

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The impact of climate change on the potential for shifts in the geographic range and spread of human diseases has received considerable attention. In an economically developed region such as California, changes in public health policy and access to medical services are likely to have more influence on the future of human diseases than will climate change. Yet the environment does play a large role in some diseases, especially vector-borne diseases, where an arthropod or a small mammal serves as a carrier or vector.

Mosquito-borne diseases such as malaria and dengue fever once occurred across much of the United States. Their potential range could expand northward with warming, but the diseases would not become problems in California without changes in other aspects of the public health system.[103] Lyme disease, which is transmitted by ticks, is increasingly prevalent in California, with 142 cases reported in 1998. Tick development is accelerated by warmer temperatures, although ticks fare best in humid conditions.[103] Thus, warming might make Lyme disease more prevalent. Changes in soil and atmospheric moisture, however, could either counter or reinforce this tendency. Hantavirus outbreaks may also be linked to climate. Years with heavy rain provoke increases in the density of the rodent hosts, and the prevalence of the virus in the mice population seems to increase in response over several years.[104] If the California climate future includes more frequent or more intense El Niños, the control of hantavirus may become increasingly difficult and costly.

Prevalence of water-borne diseases could also shift with climate change. Floods and heavy runoff are frequently implicated in contamination of drinking water, especially cases involving cryptosporidiosis that originates in agricultural waste products.[103]

Offshore, warmer waters favor the growth of several toxic marine organisms, including some that cause shellfish poisoning. Northward extensions in these diseases have been linked to El Niños, suggesting that either gradual warming or increased frequency or intensity of El Niños could lead to increased problems with toxic marine algae.[105]

A warmer climate could mean more favorable conditions for insects and rodents that carry dengue fever, Lyme disease, or hantavirus—making control of these diseases more difficult and costly.

Floods and Landslides

A large swath of California's coastal and mountain regions is vulnerable to flooding and landslides. Specific forecasts are not possible, because the occurrence of floods and landslides depends on very local conditions and on extreme weather events, both of which are predicted poorly by climate models. Yet if climate change brings increasing winter precipitation, a decreasing fraction of the precipitation in snow, and any increases in the frequency or intensity of El Niños, the result will be increased risks from floods and landslides. Throughout the state, development and land-use practices that encourage building in flood plains and on scenic but slide-prone slopes magnify the risks.

Much of California is vulnerable to flooding, landslides, or both—and both become more likely when precipitation is high, storms are frequent, and above-normal precipitation continues for several years. In low-elevation coastal watersheds, flooding is most common when a wet winter results in frequent storms.[106] In higher elevation watersheds, where surface water is stored as snow, flooding can result from unusually warm winter storms, a fast warming of the air, or springtime melting of the snow. In both kinds of habitats, landslides and slope failures are partly the result of precipitation and partly the result of land-use practices that allow or even encourage building in scenic but risky areas.

Floods and landslides will probably increase with more winter precipitation, especially if it comes as rain rather than snow.

Numerous coastal mountain watersheds in northern California have rivers that flow over their banks once or twice every ten years. The Russian River exceeded flood stage (39 feet) six times between 1900 and 1950 and eight times between 1950 and 1990. In 1995 and 1997, Russian River floods created large economic losses, which were amplified by the presence of many housing developments within the 10-year flood plain. Similar flood events occur in southern California coastal watersheds during strong precipitation events. Mountainous watersheds often generate floods during the spring melt season. The 1997 flooding in the Central Valley was triggered by a warm, late-winter storm. This storm's legacy included not only direct effects but also increased future risks because of the damage it caused to the existing levee system.

Predicting the future trend of floods and landslides is an uncertain proposition because both depend on very local conditions and on extreme weather events, and both of these are predicted poorly by climate models. Still, several kinds of considerations point to the likelihood of increasing problems with floods and landslides. Increasing winter precipitation, a decreasing fraction of the precipitation in snow, and any increases in the frequency or intensity of El Niños should all act to increase risks from floods and landslides. Unfortunately, current estimates for the magnitudes and impacts of historical floods and landslides are based on a relatively short period of observations, and these may fail to reveal the full range of potential risks, including the size of the flood plain in unusually intense floods.

Landslides and erosion have a variety of ecological effects, and many of these effects can be amplified by other factors. Generally, landslides bring additional sediment into river systems, degrading water quality and silting reservoirs.[107] Timber harvests and fires that remove interwoven root mats increase the incidence of landslides and the probability of slope failure during the wet season. Floods are a major force in shaping waterways, sometimes providing vegetation-free sites for plant invasion, but in other cases sweeping away the bars that serve as islands for invasion. Often, scouring by a flood creates the potential for further erosion. Away from riparian habitats, landslides create bare ground that is subject to erosion and to invasion by non-native species.

FIGURE 15

Increased Flood and Landslide Risk

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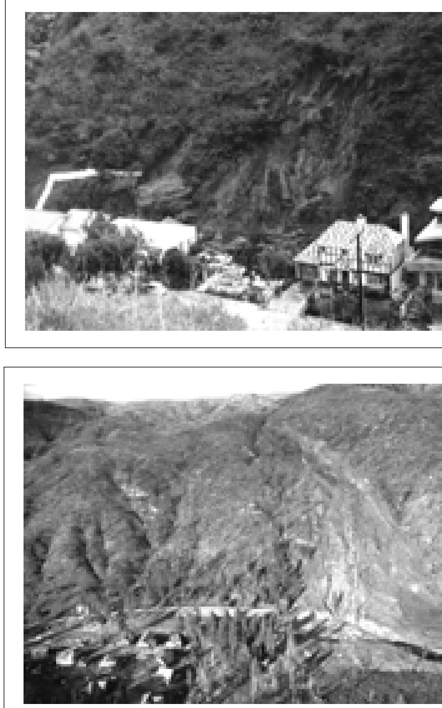
FIGURE 16

A Destructive Combination



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Agricultural Ecosystems

Warming generally hinders crop yields, although the beneficial effects of elevated carbon dioxide in fertilizing plant growth may cancel out the effects of warming. If warming is accompanied by increased drought, however, the detrimental effects would be intensified. In California, 87% of the crop area is irrigated, and increased drought could be countered by human management. Yet there are severe constraints on increased irrigation. Growers of perennial crops, including fruits, nuts, and grapes, cannot shift quickly to new cultivars as conditions change; they are most vulnerable to shifts in climate and to extreme events such as drought or pest outbreaks. If California agriculture were to lose one or more crops to climate change, it would most likely be crops that use large amounts of water to produce crops of limited economic value. The economics of producing and selling crops will depend, in turn, on the impacts of global climate change on worldwide agricultural markets.

California's agricultural ecosystems cover 11% of its landscape. State farm income in 1996 was $24.8 billion, the highest in the United States and nearly twice that of the number two producer, Texas. Farm products yielding revenues in excess of $1 billion per year include almonds, grapes, lettuce, cotton, cattle and calves, milk, and cream. Grapes and dairy products form the largest sectors, contributing about 25% of the total revenue. Cotton, grapes, wheat, corn, and rice are each planted across more than half a million acres.[108]

> Any crops propelled off the California agricultural stage by climate change are likely to be those that use large amounts of water but have relatively limited economic value.

How will California crops fare under a changing climate? The overall effect of climate change on crop yields has four major components: effects of warming; effects of elevated carbon dioxide; effects of potential water-conserving responses of plants, along with any changes in water supply; and effects of changes in market forces.

FIGURE 17
California Water Resources at Their Limit

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In general, plants grow slowly at low temperatures. Growth rate increases with temperature up to some threshold, above which growth declines again (see earlier section, *Plant Growth and the Water Cycle*). The temperature range for maximum growth often differs substantially among varieties of a single crop. Most crop plants follow this general pattern, but with one important twist. Even with faster growth under warmer temperatures, many crop plants fail to achieve the maximum size reached by the same crop species grown more slowly under cooler conditions. In essence, the schedule of development is accelerated more than the schedule of growth. Warming is generally detrimental to crop yields, with the best yields often realized in the cooler parts of a crop's range.[109]

If warming is accompanied by increased drought, the detrimental effects are intensified. In California, where 87% of the crop area is irrigated, future increases in drought in agricultural regions could be countered by human management, although this would be subject to major constraints. First, in a state where 100% of the surface water is already allocated and where water imports are unlikely to increase, irrigation cannot be increased without limit. In addition to the limits on the availability of water, ecosystems can tolerate only a limited amount of additional water input. Beyond that, soils tend to accumulate salts that make them unproductive. Also, increased irrigation in coastal regions such as the Salinas Valley is already causing widespread saltwater intrusion into aquifers,[110] a consequence that threatens continued agricultural production. Changes in the demand for water by cities and other users could also place severe constraints on the cost and availability of supplies for irrigation.

Most crop species respond positively to growth under doubled atmospheric carbon dioxide, with yield increases in the range of 10% to 50%.[111] Most of these growth increases, however, were measured on isolated plants in pots, and the actual enhancements might be smaller under field conditions.[112,113] Over much of the United States, a number of crop models indicate that the beneficial effects of elevated carbon dioxide come close to canceling any detrimental effects of warming.[109] This generalization is likely to hold at least approximately for California, where most farmers have access to modern and constantly changing crop varieties, tools for pest control, and nutrient supplements.

In California, the abundance and economic importance of perennial crops, including fruits, nuts, and grapes, could have major implications for overall impacts of climate change on agriculture. First, it is not possible for growers of these crops to shift quickly to new cultivars as conditions change. A farmer needs a reasonable projection of future conditions throughout the productive life of the plants, which can be several decades for trees and vines. Second, the consequences of an extreme event can persist for many years. A severe drought or a pest outbreak that kills a farmer's fruit trees, for example, eliminates production not just for the year of the drought or outbreak but for several successive years until a new crop of trees bears fruit. For these reasons, California farmers who specialize in tree and vine crops will need to plan carefully and insist on the best available information when making decisions about cultivars intended to bear fruit decades from now.

California agriculture has the resources to overcome most of the likely challenges of climate change in the next century. Given these resources, it seems unlikely that Californians will lose the ability to produce any crop locally. Yet climate change could raise production expenses, especially the cost of providing water. If one or more crops are to decline or disappear from the California agricultural scene with climate change, it is likely to be those that use large amounts of water to produce crops of limited economic value. California's three largest water users are alfalfa, cotton, and grapes. Together, these three crops use approximately one third of the irrigation water applied in California.[114] Alfalfa, which generated 1996 revenues of less than $1 billion, consumed more than 10% of the combined agricultural and urban water in the state. In contrast, vineyards are heavy water consumers yet constitute one of the most productive sectors in California agriculture.

FIGURE 18
Growers Need Projections of Future Climate Conditions

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The economics of produc–ing and selling a particular crop will depend heavily on impacts of global rather than regional climate change on worldwide agricultural markets. A number of studies have examined the impacts of climate change on U.S. agriculture in the context of global markets. Factoring assumptions about future markets into assessments adds another layer of uncertainty, but it also changes the results in fundamental ways. Specifically, agricultural production sometimes follows the direction one might predict from assessing the basic physiological responses of the crop to a changed climate. Yet sometimes the results go against biology, such as when demand from other regions rises more than the costs of production and when profits from producing a given crop are greater than from alternative uses of the land. After considering a number of studies that integrate both biological and economic approaches, researchers concluded that risk and vulnerabilities vary regionally, and the greatest risks to agriculture are found in areas where options for alternatives to farming are limited and where key crops are already at their limit for heat or drought tolerance.[109]

Forestry

In regions such as the Sierra Nevada, where neither water nor nutrients are severely limiting to plant growth, elevated carbon dioxide is likely to enhance forest production. In places where warming leads to increased drought or where soil nutrients are limiting, however, forest production may not be stimulated, and it could decline. As in other California ecosystems, changes in the pattern of fires, disease, or pest outbreaks have the potential to modify or conceivably even reverse the predicted responses of forests to elevated carbon dioxide and warming.

Commercial forestry is a substantial industry in California, with a 1996 harvest of 2.2 billion board feet that generated revenues of nearly $1 billion. Most of the harvest comes from national forests, which cover 20.5 million acres of California. Only 13% of the 1996 revenue came from forests on private land. The state's dominant timber species are mixed conifer (Ponderosa pine, sugar pine, Jeffrey pine, red fir, white fir), Douglas fir, and redwood. Redwood breaks the pattern of primarily federal ownership, with more than 85% of that forested area privately owned.

The responses of California forest species to climate change will depend critically on changes in drought and in the availability of mineral nutrients in the soil. If water and nutrients are sufficient, elevated carbon dioxide is likely to enhance forest production. The lack of studies on mature trees makes it difficult to predict increases in growth rates, but it would not be surprising to see growth increase under doubled carbon dioxide by approximately 25%.[115] Even if this level of stimulation persisted for only a few years after seedlings are established,[115] the cumulative nature of plant growth ensures that the stimulation could still have a dramatic effect, either on the time it takes the trees to reach harvestable size or in their ultimate size at maturity. In the Sierra Nevada, modeling experiments have predicted small increases in the total plant material produced per year.[81]

In places where warming leads to increased drought or where mineral nutrients are limiting, however, forest production may not be stimulated, and it could decline.[117] Several model simulations indicate decreased net primary productivity in northwestern California. In some parts of the world, the human-generated rain of nitrogen pollution could at least partially alleviate soil nutrient shortages.[118] Nitrogen deposition could be important in California, although current rates of deposition are too low to play a dominant role in nutrient budgets.

In forests, as in other California ecosystems, fires, pests, and pathogens have the potential to greatly affect how ecosystems respond to climate change, conceivably even reversing the predicted responses to elevated carbon dioxide.

Intertidal and Marine Ecosystems

Coastal marine ecosystems can change character much more quickly than California's terrestrial habitats as shifts in climate and ocean circulation redistribute the larvae of invertebrates and fish along the coastline. Many decades of monitoring in the California Current System have revealed a gradual warming of sea surface temperatures as well as a corresponding increase in the dominance of southern species of kelp forest fish and a northward range expansion of sardine populations. In addition to this gradual warming, coastal waters also experienced an abrupt jump in temperatures in the late 1970s that persists. The warmer temperatures of the past two decades have been accompanied by reduced mixing in the water column, reduced upwelling of nutrients, and widespread declines in algal productivity along the California coast. The decline in productivity has been followed by equally large changes in other levels of the food web, including declines of sea birds and an accelerated decline in yields of commercially fished species. Year-to-year variations in temperature and in ocean productivity and accompanying ecological changes caused by the natural El Niño phenomenon parallel those that have persisted since the abrupt temperature rise of the 1970s, but are much shorter lived.

Coastal marine ecosystems can change character in response to climate shifts much more quickly than California's terrestrial habitats. The dominant species in marine habitats are typically much shorter lived and include larval life stages that drift in the plankton and can be moved great distances by ocean currents.[119] As a result, shifts in ocean circulation could rapidly redistribute individuals and species along a coastline. Increasing evidence suggests this is already happening along the California coast.

California's marine ecosystems have already changed dramatically, likely in response to recent warming.

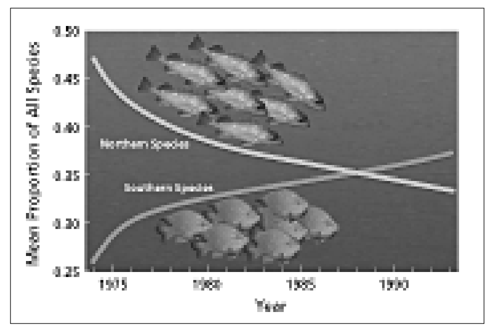
Although long-term studies of ocean ecosystems are rare globally, the coast of California is one of the best studied. California is bathed by the California Current System, a predominantly southward flowing current. Monitoring of physical and biological characteristics of the California Current dates back many decades at a number of locations.[120] The physical data suggest gradual changes over the last century, including an increase in average sea surface temperature in Pacific coastal waters. Complicating these long-term trends, however, are more abrupt temperature changes over years and over decades. Although the biological data address a limited number of organisms and sites, it is increasingly clear that pronounced changes have also been taking place in marine ecosystems and that these appear to be coupled to climatic shifts.

One of the studies that documented ecosystem changes associated with warming took place at a rocky intertidal community at the southern end of Monterey Bay. Researchers revisited sites that had been mapped and studied in 1931–1933 and found that southern animal species are increasing as native northern species decline.[121,122]

During the 60 years since the first survey, the annual mean ocean temperature along the shoreline has increased by 1° F, and mean summer maximum temperatures are higher by 4° F. Comparable shifts to dominance by southern species have been noted in kelp forest fish from two sites in Southern California.[123] Since the early 1970s, the proportion of species in fish assemblages that are cold-water, northern species has dropped by about half, whereas the proportion of southern, warm-water species has increased nearly 50%. Similarly, data from California Cooperative Oceanic Fisheries Investigations (CalCOFI) document population increases and northward range expansion of sardine populations over the last 25 years.[124] Collectively, these patterns suggest an ongoing redistribution of marine species along the coast of California that is consistent with predictions for northward shifts in species' ranges in response to ocean warming.

In addition to the gradual warming trend, marine ecosystems off California showed a large, abrupt shift in surface temperatures around 1976-77.[125] The average temperature of a large area of the coastal northeastern Pacific increased abruptly and has continued at elevated averages for more than two decades. In Southern California, for example, average temperatures increased nearly 2° F above the average of the previous decades. Although the causes of this shift are not fully understood, the changes in ocean temperature are associated with a shift in position and intensification of the Aleutian Low Pressure area and its associated westerly winds. Therefore, this persistent warming pattern appears tightly linked to large-scale atmospheric and ocean processes. How it will persist, and whether it reflects human-driven climate change or natural climate variability, is unknown.

FIGURE 19
Changing Coastal Marine Ecosystems



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Besides its direct impacts on marine ecosystems, sea surface warming off the coast of Southern California is associated with other widespread physical changes in the ocean that magnify its impacts on ecosystems. Among these physical changes are corresponding increases in stratification of the water column,[126] which decreases the mixing of nutrients from the cooler, deep waters into the shallower waters where life is more abundant. These nutrients are critical for phytoplankton (algae) production in surface waters, and their reduction has led to widespread declines in ocean productivity along the Southern California coast since 1977.[120]

Declines in ocean production, in turn, appear to have caused widespread biological changes in Southern California's marine populations. The depression of phytoplankton production is associated with equally large changes in other levels of the food web. Zooplankton, which feed on the phytoplankton, declined in abundance by more than 70% in parts of the California Current beginning with the temperature shift of 1977.[126] Correspondingly large declines have occurred in several other levels of the food web, including sea birds,[127,128] attached algae (which are generally called seaweeds),[129] sea-bottom invertebrates, and fish.[122] Indeed, the shift in dominance from northern to southern fish fauna in Southern California kelp forests is largely the result of differential declines in both groups of fish species since 1977. The abundance of both southern and northern species declined, but the declines were greater among the northern ones.

Increases in El Niño's frequency and/or intensity could have severe impacts on fisheries' geographic distribution.

The abrupt temperature shift also appears to have affected economically important species. Although the yield from commercially fished species was declining before 1977, the declines accelerated after that point.[130,120] Populations that have been reduced by fishing pressures commonly have lower resilience to environment change than natural populations.[131]

Different regions of the California coast may respond differently to climate change. For example, despite declines in ocean productivity in Southern California associated with warming of surface waters, trends in Central and Northern California may differ. The coast north of Pt. Conception, for example, is a classic wind-driven upwelling system. In spring and summer, northerly winds drive surface waters offshore, and cool, deep waters, laden with nutrients, well up to replace them. This wind-driven circulation is a key source of essential plant nutrients in coastal waters. The strong winds along shore that drive this circulation are generated in part by pressure gradients between low-pressure cells over land and high pressure over the cooler ocean. Climate warming driven by greenhouse gases should intensify this pressure gradient, leading to stronger along-shore winds and upwelling.

Forty years of wind records off Northern California show a strong increasing trend in winds favorable to upwelling.[132] The extent of these wind changes has probably had important effects on the productivity of Central and Northern California marine ecosystems; however, corresponding data on changes in productivity or species abundances are not available. Nonetheless, the competing effects of enhanced winds and upwelling versus surface warming and stratification mean that the responses of ocean productivity to climate change are likely to be complex and perhaps as regionally specific as impacts on land.

The driving force for year-to-year variation along the California coast is the El Niño Southern Oscillation. Large, rapid warming events in the California Current System are linked to equatorial El Niños. This century, there have been more than a dozen warm El Niño events and a corresponding 10 cold La Niña events. Physical changes off California during these events can be dramatic. Ocean temperature rises an average of nearly 2.7° F during El Niño events and declines an average of 1.8° F during La Niña events.[120] Extreme events can drive even larger changes. The warming during El Niño shares many other characteristics with the decade-scale shifts of the late 1970s. Stratification of the water column increases, nutrient delivery to surface waters declines, and phytoplankton and kelp productivity drop. In addition, increases in storm frequency and intensity are usually dramatic, magnifying disturbance of coastal communities through larger waves and increased runoff from terrestrial watersheds that causes greater turbidity and sedimentation. Unlike changes that have persisted since the abrupt temperature shift of 1977, however, physical changes associated with El Niño are short lived. On average, El Niño conditions in this century have persisted for 6 to 12 months, although occasional extreme events have lasted for two years.

Although El Niño events are part of natural climate variability, many have argued that they may provide a proxy for climate warming.[133] Also, as discussed earlier, there is some evidence that El Niño events may be changing in intensity, frequency, or both. Although the range of physical changes that occur during El Niño makes it difficult to pin down the causes of specific biological changes, the biological responses of California's marine ecosystems to El Niño events are dramatic and widespread. Zooplankton biomass commonly declines precipitously during El Niño events.[134,135] In addition, the structure of the plankton community is completely rearranged[120] as new groups come to dominance during El Niño. Larval fish are one of the key groups that show large declines in abundance, and this may contribute to the abrupt drops in some commercial fisheries that follow a large El Niño event.[136] Commercial salmon fisheries off the coasts of California, Oregon, and Washington were hit especially hard by the 1982–83 El Niño.

Forests of giant kelp are seriously damaged during El Niño as a consequence of nutrient depletion, warmer water, and intense winter storms. The damage to the kelp is especially severe in Southern California.[135,137] The catastrophic effects of El Niño on giant kelp cascade through much of the food web as many other groups either decline in abundance or have poor reproductive success. That includes reef fish,[122] seabirds,[138] seals, and sea lions .

Marine species of fish and invertebrates are redistributed along the coastline during El Niño events. As far back as the 1920s, there were observations of large expansions in the northward range of California species during El Niño.[139] Widespread observations of similar range shifts were noted during the 1982–83 El Niño,[136] including observations of major shifts in fish spawning grounds for some species. For some fish species off California, such as sheephead, their successful reproduction is totally dependent on pulses of larval recruitment that occur during El Niño, and some invertebrates such as sea urchins get many more larval recruits during El Niño events.[140,141] Future increases in the frequency or intensity of El Niño events could have severe impacts on the geographic distribution of viable fisheries.

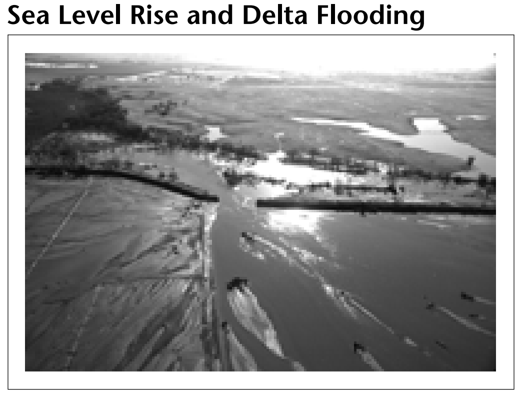
Sea Level

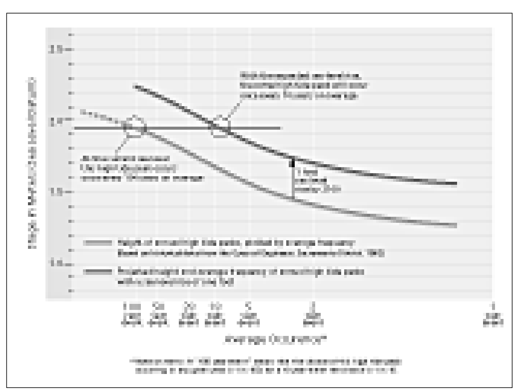
Sea level is projected to rise 8 to 12 inches along the California coast in the next century. A higher sea level will intensify the impact of storm surges on coastal developments and wetlands and put increasing stress on California's vital levee system.

Global models project that sea level in California will rise by 8 to 12 inches by 2100.[142] That represents a doubling or tripling of the sea level rise seen in recent history. To put this in perspective, the sea level at San Francisco has risen by only about 4 inches since 1850.[143]

The potential impacts of rising sea level are coupled with changes in the intensity of storm surges. This intensity already has increased since 1970. If this trend continues, the combination of rising sea level and more intense storm surges will increase coastal erosion and create greater stress on vital levees and inland water systems in California. For instance, with a 12-inch rise in sea level, the current 100-year high in the storm surge felt on the levee system of inland San Francisco Bay and Delta would become

FIGURE 20
Sea Level Rise and Delta Flooding





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the 10-year high—that is, so-called 100-year events would increase 10-fold.[135] An indirect effect of this threat could be further loss of wetlands and riparian habitat as Californians respond with bulkheads, riprap, revetments, and other engineering works to protect coastal homes, roads, and other developments.

Rising sea levels also can have adverse effects on agriculture in coastal areas, especially the low-lying Sacramento-San Joaquin Delta. The California Energy Commission estimates that, with the expected warming of climate, Delta farmers could need an additional 700,000 acre-feet of fresh water from runoff to offset saltwater intrusion into areas protected by the levee system. This problem could be exacerbated if the combined effects of sea level, tides, runoff, and winds increase the risks of failure of the Delta levees.

> A one-foot rise in sea level means the current 100-year high tide peak on the levee system of inland San Francisco Bay would become instead the 10-year high—thus a rare event would become common.

How Confident Can We Be About Future Trends in Climate and Ecosystems?

No one can predict the future with certainty. Yet the scientific community that seeks to understand the earth-atmosphere system has learned a great deal about the past, about the trends that are shaping the future, and about the mechanisms that will control how climate and ecosystems respond to those trends. This understanding provides us with a sound basis for assessing the level of certainty associated with each of the trends we discuss.

Uncertainties in future projections are sometimes expressed with probabilities—for instance, a 20% or a 50% chance of rain. For the projections discussed in this report, however, assigning specific probabilities is usually neither feasible nor informative. This is because each projection spans a range of possible outcomes, each with a different probability. For example, a warming of 4° F by 2100 is much more likely than a warming of 8° F, but both outcomes fall within the climate projection we simply label as "warmer." It is possible, however, to use the scientific insights available to us to project the most likely outcomes, and to assign to them broad confidence levels. This is the approach taken in this report, as summarized in the table below.

We consider climate changes highly certain if they are supported by more than five computer modeling studies, including studies based on a range of modeling approaches. We judge ecological impacts to be highly certain when both models and numerous observations indicate that such changes will occur in response to highly certain climate changes and associated human pressures.

Climate changes and ecological responses with medium certainty are those predicted by several modeling studies and confirmed in direct observations, especially long-term observations that span past changes in climate.

Finally, climate changes and ecological responses listed as lower certainty are those predicted by at least one state-of-the art model or set of observations. It is important to remember that certainty reflects current understanding. Being "lower certainty" does not imply that a change is unlikely or that the impact of a change will be small. Instead, it means that our current understanding is still too limited for us to be confident about the magnitude of changes that could occur over the next century or so. Nevertheless, several of the changes listed below as lower certainty are critical to consider because they will have major impacts on California if they come to pass.

It is also important to remember that the assessments in this report are based on the assumption that current trends in global greenhouse-gas emissions and human pressures on California ecosystems will continue. If California and the rest of the world were to adopt aggressive measures to minimize climate changes and human degradation of ecosystems, many of these impacts could be avoided.

How Confident Can We Be About Future Trends in Climate and Ecosystems?

Here in tabular format are the confidence levels we assign to some of the projected changes in California's climate and ecosystems highlighted in this report:

Confidence Levels

	High Certainty	Medium Certainty	Lower Certainty*
Predicted Changes in California's Climate	Warmer, with more warming in winter than in summer	Increased winter precipitation Higher snowlines and increased fraction of precipitation as rain rather than snow	Stronger or more frequent El Niños over much of the Pacific, including California More convective storms
Predicted Impacts on California's Ecosystems	Higher sea level Decreased summer stream flow Increased summer salinity in San Francisco Bay Northward shifts in the ranges of many marine species Decreased suitable habitat for many terres-trial species as climate change intensifies human impacts Increased competition for freshwater among urban, agricultural and natural ecosystem uses	Increased winter runoff Northward and upslope shifts in the ranges of many terrestrial species Increased summer drought Expansion of grasslands into foothill forests, shrublands into Sierran forests, and forests into tundra.	Increased floods and landslides Decline in arable land in the Sacramento delta More wildfires Increased losses of forest trees to pests such as pine bark beetles Increased prevalence of vector-borne diseases such as hantavirus. Increased problems with toxic marine algae

* "Lower certainty" does not imply that a change is unlikely or that the impact of a change will be small. *(See page 51 for details.)*

CHAPTER

Five

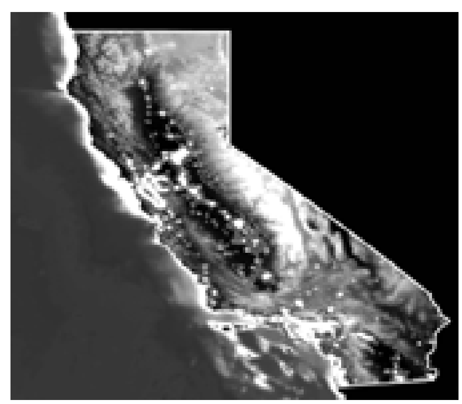
Meeting the Challenges of Climate Change

The challenge of minimizing the disruptive impacts of climate change on California ecosystems encompasses actions on two fronts. One involves minimizing the pace and intensity of the change in climate. The other entails direct actions to strengthen and protect vulnerable ecosystems.

Although the driving forces behind greenhouse warming are global in scale and the state cannot act alone to stabilize its climate, Californians are better positioned than most of the world's population to contribute to the global solution. Californians make up only 0.5% of the earth's population yet consume about 2% of its fossil fuel–emitting, in the process, over 400 million tons of CO_2 a year.[145] Their individual actions as consumers can be globally significant. Perhaps more important, however, is the fact that California has long served as a leader in attitudes, aspirations, and innovative practices, including many that help to reduce emissions of greenhouse gases. As a consequence, today's Californians could become models for the nation and the world by encouraging and embracing the development of novel energy, transportation, and land-use solutions to the problem of global climate change.

When it comes to minimizing the impact of climate change, California citizens and policy makers can take direct actions now to stabilize or even improve ecosystems and reduce their vulnerability to warming. Because the effects of climate change will interact with continuing human pressures on ecosystems, the opportunities for meaningful contributions are great. Yet so are the risks of inaction or unwise actions. It is critically important to take a cautious approach, emphasizing actions that provide a range of benefits, reevaluating the situation often, and making adjustments as necessary.[16]

FIGURE 21
California at Night



See page 34
for full-size full color image of this figure

Fortunately, many of the actions that would be most effective in shielding vulnerable ecosystems from the risks of climate change would also yield immediate benefits for public safety, recreation, agriculture, fisheries, and the state's unique natural heritage. The following actions are low-risk, high-payoff investments that would be well justified even without climate change.

Limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides, is probably the most important action Californians can take. It is also one of the most challenging, in light of the expectation that the state's human population will double by 2040.[36] Limiting the area of human infrastructure can preserve habitat, maximize the size of habitat patches, and avoid severing the connections among natural areas in the landscape. Restoring degraded habitats can also be a vital complement to limiting the footprint of development.

> Modest investments now can help secure both ecological and economic options over many future generations.

In California's coastal marine and freshwater ecosystems, effective actions include minimizing inputs of waste products while minimizing extractions of water from streams and rivers. Strategies such as managing the dynamics of water releases from dams can also contribute to lowering overall human impacts.

Nature reserves should be designed to accommodate future climate changes and necessary range shifts and migrations of plants and animals. Design improvements could include larger size, layouts that encompass a greater range of local habitats and environmental conditions, and locations that maintain or enhance connectivity among habitat remnants. Marine reserves should be designated and managed in tandem with protected areas on land to reflect the vital links between healthy watersheds and wetlands and the continued productivity of coastal waters.

Restoration ecology is making major strides in developing theory and practice to support rehabilitation of degraded ecosystems, especially wetlands.[146] As this field advances, it will be increasingly possible to use such ecological engineering to help ameliorate the impacts of climate change. It is too early to know whether these efforts should include deliberately moving species or entire ecosystems. Restoration should be viewed as one component of a larger picture, used to reverse damage rather than to justify further damage to California ecosystems.

Limiting and controlling biological invasions should be a top priority. The overwhelming evidence on invaders is that they degrade ecosystems and displace native species. Without dedicated action, the negative impacts of biological invaders will increase as the climate changes.

Learning to recognize and fairly value the many subsidies and services our society receives from healthy ecosystems will help to ensure their protection in the face of a changing climate. Human societies preserve and protect what they value, and nature's subsidies in the form of pure air and water, fertile soil, and rich and productive ecosystems have been taken for granted too long. By acknowledging the economic and societal value of the services we receive from natural and managed ecosystems, we will be able to assign more realistic priorities to stabilizing and nurturing these systems in the face of climate change.[147]

Finally, it is important to take the long view. Climate change and ecosystem responses to it will unfold rapidly in relation to the history of the earth but may seem slow in relation to human perceptions. Humans and human societies can adjust to a broad range of physical and ecological environments. The adjustments generally involve costs as well as benefits. As we face the prospect of climate-driven ecological changes that may persist for centuries, it is worth taking time to consider seriously how modest investments over the next few years might secure both our ecological and economic options for many generations.

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This report represents the consensus reached by a panel of seven scientists selected to provide a broad array of relevant expertise. The report was peer-reviewed and approved by a Steering Committee convened by the Union of Concerned Scientists and the Ecological Society of America. The authors' institutional affiliations and areas of expertise are described below.

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Serving as the report's lead author, Dr. Field worked with the other authors, the Steering Committee, and a range of other scientists to insure that the report is up-to-date and accurate. He was the senior author for the report's sections on California's ecosystems, California's climate, and the responses of terrestrial biogeochemistry and species distributions to climate change.

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A national Steering Committee provided guidance and oversight to ensure the scientific review and integrity of the report. The Steering Committee members were:

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Confronting Climate Change in California

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UNION OF CONCERNED SCIENTISTS

The Union of Concerned Scientists (UCS) is an independent, nonprofit organization dedicated to advancing responsible public policies in areas where science and technology play a critical role. Established in 1969, UCS has created a unique alliance between many of the nation's leading scientists and thousands of committed citizens. Augmenting rigorous scientific research with public education and citizen advocacy, this partnership addresses the most serious environmental and security threats facing humanity. For more information, visit the UCS website at http://www.ucsusa.org.

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