Attachment III

Ecological Impacts of a Changing Climate

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Executive Summary

This roadmap provides a brief overview of the unique characteristics of California's ecosystems, the potential effects of global climate change on those ecosystems, and a discussion of the research areas that California should support in the next ten years to reduce the level of uncertainty in the estimation of the potential ecological consequences of climatic change.

In the short-term (1–3 years) this roadmap recommends addressing the objectives summarized in the table below:

Objective	**Projected Cost ($000 per year)**
Develop and implement ecological assessment and monitoring programs, using ecological indicators specific to climate change impacts.	1,100
Develop a more spatially resolved climate modeling approach. (Budget included in Regional Modeling Roadmap)	0
Develop a program to compile and analyze climate observations and model results rapidly.	300
Expand data inputs to improve ecosystem and species modeling in vegetation models, including non-native, invasive species.	1,000
Develop modeling program to understand future distributions of species assemblages in terrestrial, aquatic, and marine ecosystems.	1,000
Compile and analyze existing paleontological data to better understand past ecological responses to climatological change and to test models.	200
Develop an experimental and modeling research program to understand the impact of multiple global changes on ecosystem function and structure.	3,000
Study the response of non-native species to climate change.	3,000
Evaluate methods for using ecosystem and species data for conservation area decision making.	300
Total Short-term Cost per Year	**9,900**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure in dollars per year over the course of the short-term research.

The Public Interest Energy Research (PIER) Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, all of which build on the short-term work listed above. This roadmap outlines a comprehensive research agenda that would be necessary to fully address the research gaps identified in this document. PIER, however, due to the limited funding, will be able to support only some of the identified areas of research. PIER is currently examining all of the roadmaps to determine which projects should be supported with PIER funding.

Roadmap Organization

This roadmap is intended to communicate to a broad audience with varying levels of knowledge about the issue. The sections build upon each other to provide a framework and justification for the proposed research and development—both for stakeholders well-versed in climate change issues, as well as for those new to the issues.

Section 1 states the issue to be addressed. *Section 2: Public Interest Vision* provides an overview of research needs in this area and how PIER plans to address those needs. *Section 3: Background* establishes the context of PIER's climate change work as it relates to the ecosystem and species impacts of climate change. *Section 4: Current Research and Research Needs* surveys current projects and identifies specific research needs that are not already being addressed by those projects. *Section 5: Goals* outlines proposed PIEREA activities that will meet those needs. *Section 6: Leveraging R&D Investments* identifies methods and opportunities to help ensure that the investment of research funds will achieve the greatest public benefits. *Section 7: Areas Not Addressed by this Roadmap* identifies areas related to climate change research in this area that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being conducted to address climate change issues in this area.

Acronyms

Cal/EPA	California Environmental Protection Agency
DFG	California Department of Fish and Game
DGVM	Dynamic Global Vegetation Model
DOE	U.S. Department of Energy
EPIC	Environmental Protection Indicators for California
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautical and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
OEHHA	Office of Environmental Health Hazard Assessment
PFT	Plant Functional Type
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
SVAT	soil-vegetation-atmosphere-transfer model
TBM TB	Terrestrial Biosphere Model
USGCRP	U.S. Global Change Research Program
UV-B	Ultraviolet-B

1. Issue Statement

California's ecosystems provide essential goods and services that are being put at risk by climate change and other stresses. In order to prepare for and respond to this threat, we must better understand the potential effects of climate change on California's ecosystems.

2. Public Interest Vision

California supports an incredible array of natural and managed ecosystems, which in turn host flora and fauna of unparalleled diversity. These ecosystems provide a multitude of goods and services that have direct and indirect benefits to humanity, including marketable products, environmental services such as water purification, recreational opportunities and aesthetic pleasure. Despite this, California's ecosystems are being lost and degraded at an unprecedented rate. A steadily increasing number of people calling California their home have placed great pressure on natural systems. The result has been habitat destruction, non-native species introductions, community and species losses, and associated decreases in air and water quality and other health factors.

The challenge of responding to the existing pressures on ecosystems is exacerbated by a new threat to their structures and functions—global climate change. Among other things, increasing concentrations of greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide) in the Earth's atmosphere are expected to change the radiative balance of the planet, increase atmospheric temperature, and change the timing and magnitude of precipitation events.

Because climate is a major factor controlling the distribution of species and the structure and functioning of ecosystems, climate change has the potential to impact natural systems in novel, dramatic, and unpredictable ways. Ecosystem changes can have enormous economic consequences for California, including, for example, increased fire risk and decreased summer water supply. The serious nature of these impacts is cause for great concern.

To protect California's unique ecosystems, and the practical and aesthetic benefits these natural systems provide for Californians, a variety of research should be conducted in the short term. First, researchers need to build upon ecological assessment and monitoring efforts in California, by broadening and coordinating these efforts, which will enhance their usefulness and applicability. Second, researchers need to develop models capable of addressing regional climate modeling needs. Third, climate change researchers need to examine existing data, to identify its strengths and limitations. Fourth, researchers must develop a modeling program that will enable them to better understand the future distributions of species assemblages in terrestrial, aquatic, and marine ecosystems. And finally, researchers need to analyze existing paleontological data to better understand how different ecosystems and ecosystem types have responded historically to climate change.

This work will benefit Californians by providing public agencies, researchers, and decision makers with a better understanding of the impacts that climate change is likely to have on ecosystems, from a state, regional, and local perspective. More specifically, it will help the State develop public policy that will facilitate species and habitat survival and protect the ecosystem services that are vital to the State's economy and enhance the quality of life for all Californians.

3. Background

3.1 The Role of Climate in Ecosystem Distribution and Function

Climate change is not a new phenomenon. In the past 2.6 million years, the Earth has experienced a succession of glacial and interglacial cycles that have resulted in large fluctuations in climate. These dramatic climatic shifts have driven changes in species distributions, species diversity, and ecosystem functions. Because other environmental factors influence species distributions (e.g., soil types and inter-specific interactions), the persistence of ecosystems and survival of species under a changing climate is not merely a function of migration. In many cases, species require time for adaptation to a new set of conditions, resources, and biotic interactions. Past climate changes have occurred over hundred of years, giving species time to become established in new locations suitable for their growth and reproduction.

However, the climate is currently changing at an unprecedented rate. Measurements of historic global temperatures indicate that the global surface air temperature increased 0.9°F in the 400 years between 1500 and 1900 (Houghton et al. 1996) and another 1.1°F in the past century (IPCC 2001). This is a dramatic increase in the rate of atmospheric warming. This rapid pace may present an insurmountable challenge to a variety of California's plant and animal species, because geographic relocation and adaptation will not be possible. Human activities present an additional obstacle to successful redistribution of species across the landscape. Humans have altered land, fresh water, and ocean resources. In many regions, conversion of habitats from natural systems to "degraded" or "managed" systems has eliminated the natural resources or left them unable to respond to further perturbations.

In addition to its critical role in the persistence and distribution of ecosystems and species, climate is also important in determining ecosystem properties such as soil type and fertility, disturbance regimes (i.e. fire), net primary production, and carbon storage. With changes in climate, these, too, will undoubtedly be affected.

3.2 California's Current and Future Climate

There is more climatic variation in California than in any other area in the United States of comparable size. Total precipitation ranges from over 120 inches annually in the northwestern forests to periods of immeasurably low rainfall in the Mojave Desert. The range of temperatures in California is equally extreme. The high elevations in the Sierra Nevada can experience weeks of freezing temperatures; whereas, Death Valley can be above 100°F for comparable periods. California's coastal Mediterranean climate is unique in that the wet season coincides with the winter. Summers are dry. Total annual precipitation ranges between 15 and 40 inches per year. Temperatures are those of the subtropics moderated by maritime influence and fogs associated with the cold ocean currents.

Over the next century, California's climate will change dramatically. The U.S. Global Change Research Program (USGCRP), using models developed by the United Kingdom

Hadley Centre and the Canadian Centre for Climate Modeling and Analysis, projects annual average temperature increases of 8–11°F for the western United States (USGCRP 2000a). For California, these models also project significant increases in precipitation, especially during winter. Because a greater proportion of this precipitation will fall as rain, winter runoff is projected to increase, while snowpack in the mountains is projected to decrease (USGCRP 2000a). Little change or slight decreases in precipitation are projected for summer (Kim 2001). The amount of precipitation on extremely wet days will increase, especially in the winter and fall. In addition, there will most likely be an increase in the long, wet El Niño-like conditions and a decrease in the number of drought periods. Each of these changes will have a profound influence on the structure and function of California's ecosystems.

These projected changes subsume regional trends into statewide averages. Projecting climate change within different regions of California is difficult because of California's topographic diversity and proximity to the Pacific Ocean, and because global climate models are not sufficiently refined at present. The most advanced climate projections are generated by downscaling global climate change simulations from general circulation models to regional climate models (Wilby et al. 1998; Kim 2001; Chen et al. 1999). The results of these models, while state-of-the-art, do not produce precipitation projections with fine enough spatial and temporal complexity to adequately assess the impact of climate change on ecosystems. The models are also not able to simulate the infrequent but extreme events that play such an important role in shaping ecosystems. In addition, it is not yet known whether these changes in climate will follow a gradual or stepped pattern, or some other temporal pattern. The onset, timing, and magnitude of precipitation changes will all be important determinants of ecosystem trajectory.

3.3 California's Unique Species, Communities and Ecosystems

Californians enjoy a state that is highly diverse in its landscapes, from the spectacular coastal ranges to the Great Basin Desert. This rich and diverse landscape hosts more plant and animal species than any other state. These natural resources, described briefly below, provide goods and services that are the foundation of California's economy.

3.3.1 Terrestrial

California's terrestrial ecosystems are diverse, ranging from the cool, wet redwood forests of Northern California to the hot, dry Mojave and Colorado deserts of Southern California. The combination of diverse climate and topography results in a tremendous diversity of habitat types. The California Department of Fish and Game's (DFG's) Natural Diversity Data Base recognizes 275 vegetation series (Sawyer and Keeler-Wolf 1995). The California Wildlife Habitat Relationships System, also run by the DFG, lists 59 wildlife habitats (www.dfg.ca.gov/whdab/html/wildlife_habitats.html). The DFG utilizes a classification system with 178 major habitat types (Schoenherr 1992), the California Resources Agency classifies ten broad biological categories, or "bioregions" based on distinct and consistent climate zones, and The Jepson Manual identifies 10 floristic provinces (Figure 1) that are further divided into 24 sub-provinces (Hickman 1993). There are 5,057 native and nearly 1,000 exotic plant species. Of the native plant species, at least one third are endemic to California (Schoenherr 1992). There are almost 1,000 native vertebrate species, including 540 birds, 214 mammals, 77 reptiles, 47 amphibians, and 83 freshwater fishes (Schoenherr 1992). If one were to include insects and other invertebrates, greater than 50 percent of known species are endemic to California (Schoenherr 1992). Across the state, 215 plants and 148 animals are listed as threatened or endangered under the California Endangered Species Act of 1984 or the Federal Endangered Species Act of 1973 (DFG 2002).

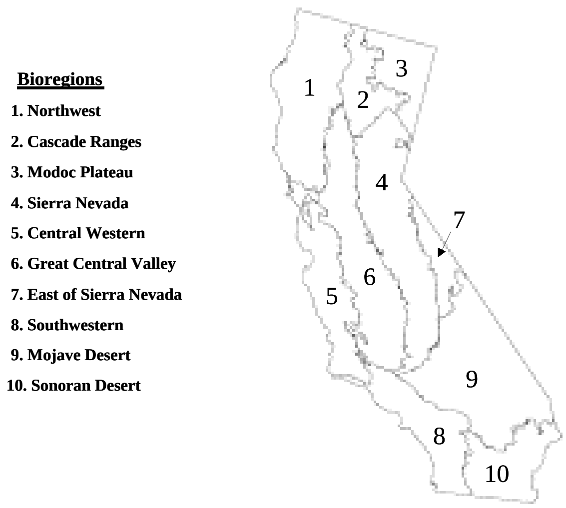

Figure 1. Bioregions of California

Climate and fire have played strong roles in the structure of California's terrestrial ecosystems. In general, there are wet, cool winters and hot, dry summers. As a result, the temperature and moisture optima for plant growth have little overlap. The plants have developed strategies and mechanisms for surviving under such conditions, including becoming physiologically dormant during the dry summer, developing taproots, or restricting growth to habitats that are wet enough to sustain growth year-round. These life strategies leave much of the landscape dry and fuel-rich during the summers and early fall, creating conditions conducive to the ignition and spread of wildfires. As a result, periodic fires have shaped California's landscape. These fires have been a necessary and regenerative force in many ecosystem types, such as the chaparral shrub and closed-cone pine communities (Schoenherr 1992). Both have adapted to periodic fires by evolving mechanisms that allow for survival, regrowth from stumps or reestablishment after fire. Many species in these ecosystems require fire for germination.

3.3.2 Coastal

California's coastline is 1,100 miles in length. The climate varies considerably along the coast as it spans a great range in latitude. Annual coastal water temperatures range from 50° to 60°F off the northern coast and 58° to 70°F off the southern coast. This pattern in water temperatures structures the coastal communities latitudinally. In addition, the cold ocean waters produce coastal fog leading to high humidity along the coast.

There are also patterns of zonation that exist vertically from the shoreline. The intertidal zone, where the land and ocean waters overlap, is influenced by the daily ebb and flow of tides. Because this zone is at the ocean-land margin, it maintains characteristics of both, creating one of the most diverse habitats in California (Schoenherr 1992). Below the intertidal zone are several vertical zones that are subject to the tidal action to a diminishing degree: the high-, mid-, the low-, and the sub-tidal. Each of these zones is distinct in its flora and fauna and each is structured by the timing and duration of its exposure to the atmosphere. Within the subtidal zone are the giant kelp forests that provide an abundance of habitat to marine vertebrate and invertebrate species. The kelp forests are comparable to tropical rainforests in their productivity and diversity of species.

3.3.3 Wetlands

California has approximately 454,000 acres of nonagricultural wetlands (Bertoldi and Swain 1996). To date, more than 90% of the State's wetlands have been drained to make way for agriculture and urban development. Before significant development occurred in the State, nearly 5 million acres of wetlands supported a great diversity of aquatic vegetation and provided habitat for hundreds of species of fish and wildlife.

California's wetlands have significant environmental and economic value for humans and wildlife. Wetlands provide temporary storage of floodwaters, reduce downstream damage, and serve as buffers against erosion. Marshes in the Sacramento-San Joaquin River Delta and many coastal marshes act as freshwater barriers to seawater intrusion of aquifers. Wetlands also trap sediment and absorb many waterborne pollutants and excess nutrients. Wetlands provide fish and wildlife habitat; inland wetlands are excellent habitat for bass, catfish, bluegill, sunfish, crappie, geese, ducks, wading birds, and many species of amphibians. Wetlands also offer recreational and educational activities.

3.3.4 Aquatic

California's inland waters are no less extraordinary in the diversity of species they host. Inland waters in California include freshwater lakes, saline lakes, vernal pools, freshwater rivers and streams, and marshes. There are 2,674 square miles of inland waterways that host a great diversity of aquatic habitats, including glacial, tectonic, volcanic, fluvial, solution basin, and shoreline lakes; and rivers and streams of consistent and intermittent flow (Schoenherr 1992). In general, the characteristics of the aquatic waterways have been shaped by climate, topography, and geology. Storm fronts from the Pacific Ocean release their moisture on the western slopes of the coastal and Sierra Nevada ranges, creating freshwater lakes in the valleys and alpine regions. The rain shadow of the eastern slopes helps to produce saline lakes such as Mono Lake.

3.4 Ecosystem Services Provided to Californians

Aside from the intrinsic value of natural and managed ecosystems, California's many ecosystems provide goods and services that are of great value to society and that form the basis of the fifth largest economy in the world (Costanza et al. 1997). California's ecosystem goods and services include marketable products, recreation, maintenance of species diversity and abundance, aesthetic experiences, spiritual experiences, and irreplaceable services such as the supply and recharge of clean water, regional climate regulation, removal of pollutants from air and water, control of erosion, control of pests and pathogens, the absorption of carbon dioxide, the production of oxygen, and long-term carbon sequestration (Pitelka 2000). Specific goods on which California's economy depends include seafood, timber, and foraged products. California's entire economy is also indirectly dependent on the services provided by its ecosystems because, although not extracted goods, they are essential to the economic health of the state of agricultural, forestry, tourism, and recreation sectors of the economy.

The quality and accessibility of these goods and services are dependent on the integrity and health of the ecosystem, and can be affected by human activity and climate change. An ecosystem that is stressed or changing rapidly is not able to provide the same quality and quantity of goods and services as its healthy counterpart. For example, a riparian zone that is stressed by encroaching development will not provide the flood protection, erosion control, spawning habitat, or water purification services on which we depend. Climate change can impact ecosystem services directly (e.g., more frequent and intense storms under climate change will lead to more flooding, resulting in increased soil erosion) and also indirectly, through impacts on ecosystem structure (e.g., a forest stand stressed from climate change may die out, contributing to slope instability, resulting in increased soil erosion).

Ecosystem goods and services are made possible by countless intricate interactions between the biotic and abiotic components of ecosystems. These processes, if disrupted, cannot be replicated adequately through technology or engineering (Field et al. 1999). Although the full value is not known, ecosystem goods and services in California may be worth billions, even trillions, of dollars annually (Field et al. 1999). Any threat to these valuable services is cause for substantial concern. There is a need, therefore, to identify and monitor ecosystem services crucial to the California economy so these basic, vital functions are maintained.

3.5 Ecological Consequences of Multiple Assaults

California is currently the most populous state in the United States, and is projected to be the fastest-growing state through 2025, when its population is expected to reach 49 million people (Campbell 1996). This increasing population will put further pressure on California’s natural resources, beyond that already expected from climate change alone, through human-induced changes in land use, water quality, air quality, species distributions and ecosystem services (Figure 2). As the figure shows, there are a variety of primary inputs from climate change, including increased precipitation, temperature, and atmospheric CO_2 concentrations. There are also many secondary impacts of climate change such as decreased soil moisture, a rise in sea level, and an increase in the intensity and frequency of extreme storm events. In addition to these climate-driven changes, other phenomena related to human activity are changing the structure and the functioning of California’s ecosystems, including land use change, loss of biodiversity, non-native species introductions, and air pollution. California’s ecosystems are already bearing these multiple stresses and are likely to be more vulnerable to climatic change. Their capacity for adaptation is likely to be limited. Although the central importance of considering interactions between multiple stresses is clear, present tools and methods for doing this are limited; this limitation points to an important set of research needs.

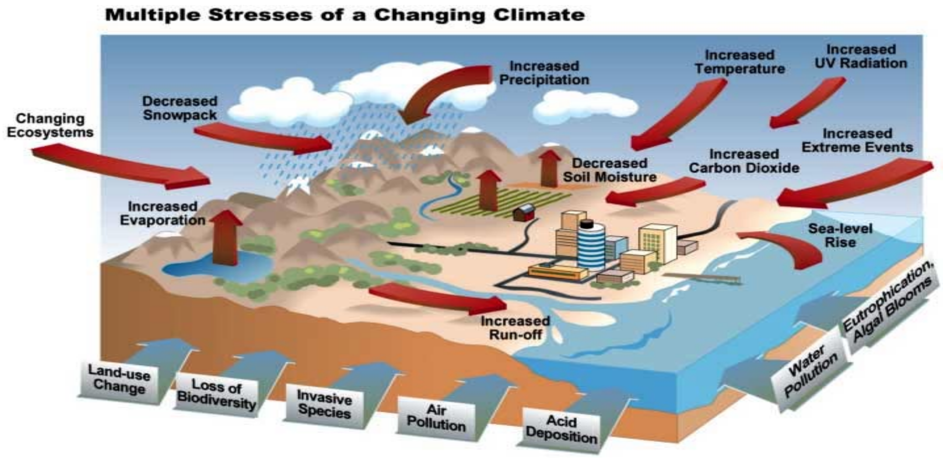

Figure 2. Multiple Stresses of a Changing Climate
Source: The Potential Consequences of Climate Variability and Change. Overview: Our Changing Nation. *P. 37.* The National Assessment Synthesis Team, U.S. Global Change Research Program. 2000.

Ecosystem responses to multiple stresses can be divided into two categories: ecosystem functioning and species change. *Ecosystem functioning* characterizes the manner in which energy, chemicals, and matter flow through natural ecosystems. Evaluating changes in ecosystem functioning includes the assessment of ecosystem interactions with the drivers of global change, given any state of the structure of an ecosystem. For example, this category includes changes in carbon storage, productivity, trace gas emissions and water holding capacity in direct response to climate change and in indirect response to changes in ecosystem structure. Species change evaluations deal with alterations in the state of an ecosystem. In particular, this category includes changes in the structure, composition, and diversity of species.

3.5.1 Climate Change

Early investigations to determine species and ecosystem distributions under climate change have focused on the “climate envelope” approach (Malcolm and Pitelka 2000). Simple models, based on correlations between species distributions and climate, were used to simulate how ecosystems might shift with a given step-change in climate. The results suggested ecosystems would migrate to meet their optimal climate without disruption, which is now considered highly unlikely.

The next generation of models—dynamic global and regional ecosystem models involving transient changes in climate—suggest that ecosystems will not shift as intact entities. Instead, significant changes in the structure of the ecosystems are likely. Species richness is expected to decline with significant reorganizations of species community assemblages. Species will respond differently, depending on differences in competitive abilities, migration and dispersal rates, and recovery rates from disturbance. As a result, new combinations of species are likely to arise. Reorganization of ecosystem structure in California is likely to be particularly extreme because of the state’s topographic complexity that results in steep gradients in temperature and precipitation.

Climate change has already affected many species in California. For example, the recent expansion of mountain hemlock populations in Northern California is strongly influenced by climate (Taylor 1995). Along the coast, surveys of California's rocky intertidal systems indicate that fauna have shifted northward over the past 65 years (Barry et al. 1995; Sagarin et al. 1999). Similarly, climate change and climate variability have been implicated in changes in abundance and distribution of reef fishes and seabirds along the California coast (Holbrook et al. 1997; Oedekoven et al. 2001). Climate variability has also hastened redistribution and even extinction of some of California's terrestrial species (Parmesan 1996; Parmesan et al. 1999; McLaughlin et al. 2002).

These changes in the structure of ecosystems will have consequences for ecosystem function. For example, in parts of southeastern California, global climate and atmospheric changes are projected to lead to shifts in ecosystem type from desert to shrub land. Ecosystem dominance by woody plants and non-native annual grasses is projected to decrease biodiversity, increase ecosystem carbon storage, and accelerate the fire cycle (Smith et al. 2000).

3.5.2 Land Use Change

Land use is determined by a wide array of governmental, environmental, economic and cultural factors. In the last twenty years in California, land use changes have been driven mainly by a 44% population increase, a rapidly expanding economy, tax codes that favor sprawl, and land use planning at the local level. California's metropolitan areas and farmlands now cut deeply into natural ecosystems. Expanding acreage for agricultural, urban, industrial, and transportation systems has put ecosystem goods and services at risk through declines in the spatial extent and connectivity of forests, wetlands, open space, and wildlife habitat. In the last 50 years, land use changes in California have resulted directly in significant habitat loss, including a loss of 95% of wetlands (Fulton 1996), 70 to 90% of coastal sage scrub, 90% of native grasslands, 85% of coastal redwood forests, 32% of mixed conifer forests, and the imperilment of 66% of the State's threatened and endangered species (Doyle et al. 2001; Czech et al. 2000).

In addition to fragmenting the landscape, land use can affect ecosystems at a local level. For example, water quality can suffer as prime farmland is replaced by urbanization, and less suitable lands are put into production across California (Charbonneau and Kondolf 1993). "Urban avoider" birds are declining or disappearing from many areas within the state, as suburbs extend into their former habitats (Friesen 1998). Grazing can lead to changes in vegetation type and soil nutrient availability (Milchunas and Lauenroth 1993; Stromberg and Griffin 1996). Land use changes, including grazing, also have indirectly contributed to the alteration of basic habitat type by facilitating the introduction and establishment of non-native species. Successful non-native species have been quick to colonize disturbed habitats. Once established, the non-native species have often out-competed their native counterparts. This has led to further fragmentation of the original habitat, making reestablishment of native species difficult and sometimes highly improbable.

3.5.3 Nitrogen Deposition

Throughout California, high levels of ammonia and nitrogen oxides are emitted to the atmosphere by nitrogen fertilizer use in agricultural areas and combustion engines in urban areas. Although extremely patchy, nitrogen deposition rates in California are among the highest in the United States with up to 45 kilograms/hectare/year (kg/ha/yr) in the Transverse Ranges of Southern California (Bytnerowicz and Fenn 1996) and 16 kg/ha/yr in the Sierra Nevada Range of Northern California (Blanchard and Tonneson 1993). About 80% of the nitrogen enters ecosystems via dry deposition during the long, dry summers in Southern California (Bytnerowicz and Fenn 1996) and 75% as wet deposition in the North (Blanchard and Tonneson 1993). Because nitrogen limits primary productivity in terrestrial and aquatic ecosystems in California, nitrogen deposition is likely to alter basic ecosystem functions such as productivity, carbon storage, and nutrient retention. In southern California, nitrogen deposition threatens the quality of domestic water sources and has the potential to increase the vulnerability of mixed conifer forests to drought and disease (Takemoto et al. 2001).

3.5.4 Altered Disturbance Regimes

3.5.4.1 Non-native, Invasive species

Species native to areas outside the state have been purposely and inadvertently imported to California and are now a permanent feature of California's ecosystems. Once in California, many non-native species establish and disperse readily in the absence of any native biological controls, thus becoming invasive. Non-native, invasive species are now commonplace and have replaced native species as dominants in many ecosystems, including terrestrial, fresh water, estuarine, and coastal ecosystems (Mooney and Hobbs 2000). Non–native, invasive species threaten native species by competing with them for critical resources, preying on them, hybridizing with them, or changing the character of the environment.

Where climate changes more rapidly than species can become reestablished elsewhere or barriers to dispersal exist, native species may be less well adapted to establishing themselves in new climate regimes than non-native species. Thus, climate change could further facilitate biological invasions and decrease biodiversity in a state where 303 species are already federally listed as endangered or threatened.

Ecosystem processes, already impacted by climate change, will also be affected by the presence of non-native species. In some ecosystems, there is the potential for non-native species to affect ecosystem processes more strongly than changes in climate, even though in most cases, we do not know the full potential of many of the non-native species. Some species that have already dramatically altered ecosystem structure and function have the potential to do further damage under climate change in the future. For example, invasion of a deciduous shrub, Salt Cedar (*Tamarix* sp.), in Southern California has drastically altered ecosystem processes. Once established, it changes ecosystem dynamics by increasing: (1) soil salinity (Busch and Smith 1995), (2) water consumption (Sala et al. 1996), (3) wildfire frequency (Busch and Smith 1995), and (4) frequency and intensity of flooding (Busch and Smith 1995). The result is high density, monospecific stands (Cleverly et al. 1997). These impacts are considerable and, therefore, the combined impact of non-native invasive species and climate change may be devastating to many of California's native populations. Because of the nature and severity of these ecosystem impacts and a lack of information on how these impacts may be altered by climate change, there is a great need for research in the area (Table 1) (Mooney and Hobbs 2000).

3.5.4.2 Fire

Wildfires have helped to shape California's ecosystems over evolutionary time and are important in many ecosystems for species regeneration. Fire occurs at regular intervals, determining the type and structure of the vegetation, with consequences for all other species (Franklin et al. 2001). Historically, coastal scrub and chaparral ecosystems have experienced severe fires every 20 to 80 years. Ground fires have occurred every 5 to 10 years in grasslands and woodlands, 4 to 20 years in mixed conifer forests, 6 to 8 years in coastal redwood forests and 15 to 20 years in red fir forests (Skinner and Chang 1996; Swetnam et al. 1998; Brown and Swetnam 1994).

A number of important factors determine fire frequencies including climate, vegetation type, and extreme weather events such as drought or heavy winds. Reconstructed fire history shows that fire frequency is highly dependent on climate. Consequently, fire models project an increase in both ignition rates and fire spread with the warmer temperatures, lower humidity, higher winds and drier fuels that are expected under future climate scenarios (Torn and Fried 1992). In addition, elevated levels of atmospheric CO_2 are expected to increase growth of chaparral and similar vegetation, increasing fuel loads over time. Finally, if precipitation remains high, fire risk during dry years is likely to further increase, because fuel loads will increase in wet years as a result of increased plant productivity. This circumstance will lead to an increase in fire frequency with climate change.

Table 1. Important Topics in Invasive Species Research

• What is the nature of global change-elements and rates? • What kinds of land use change will either help or hinder the course of invasive species? • What sorts of scenarios will we see in the future in terms of land use patterns and the abundance of and movement of invasives? • How will climate change alter the balance between native and exotic species and crops and humans and their pests? • How will changes in atmospheric gases that directly affect metabolism including CO_2, ozone and nitrogenous compounds affect potential competitive outcomes between invaders and native vegetation or crops? • Will there be changes in biotic structure due to the continued use of pesticides and the development of herbicide resistant plants? • How can we utilize scenarios of global climate change, global land use change, and global atmospheric change to predict the changing success of invasive species? • The study of invasion biology has been hampered by the lack of experimentation. We need to develop approaches to experimentation in this field, and especially in examining the potential effects of global change

Source: Invasive Species in a Changing World. edited by H. A. Mooney and R. J. Hobbs. 2000.

Since the 1850s, fire patterns in California have been altered by human suppression, climate change, and land use changes. The history of fire suppression and changes in land use will play an important role in the character of the fires in a future climate. Even in the absence of climate change, fire management in California has led to larger fires that are more likely to occur in extreme weather (Minnich and Chou 1997). In the past, fire suppression has led to higher fuel loads, resulting in hotter, more widely spread, and more destructive fires in many ecosystems. Efforts at fire suppression in the future, therefore, could also result in a positive feedback to fire frequency. In addition, any increase in Santa Ana wind conditions, combined with warmer, drier summers, could escalate economic and environmental loss to wildfires.

California depends on successful fire management to protect its citizens and to enhance the economic, social, and environmental benefits that ecosystems provide to the state (California Department of Forestry and Fire Protection, **http://www.fire.ca.gov/**). A significant financial investment is required to fulfill this mission; in FY2001–2002, California is estimated to have spent $703 million on fire management and protection. The state has a clear interest in research that will advance understanding of interactions between climate change, human activities, ecosystem change, and fire behavior.

3.5.4.3 Pest and Pathogen Patterns: How Does the Pathogen Pool Change with the Climate?

Given the importance of pest and pathogens in structuring ecosystems, surprisingly few studies have assessed the interaction of pests and pathogens with a changing climate, and even fewer studies are region-specific. Most of the work relies on rule-based reasoning using data on the environmental requirements of organisms and their pathogens (Coakley et al. 1999). For example, data on climatic thresholds for various pest and pathogen species suggest the potential for range shifts in those species (Sutherst et al. 1995). Similarly, knowledge of pest and pathogen phenological responses to environmental conditions reveals potential for changes in the timing and duration of outbreaks (Coakley et al. 1999). Plant responses to climate change may also affect outbreaks. For example, changes in plant physiological and biochemical processes in response to climate change may affect pest behavior (Manning and von Tiedemann 1995). Plants are not the only organisms vulnerable to a changing pathogen landscape; for example, California sea otters have recently become accidental hosts for historically non-otter diseases (Lafferty and Gerber 2002).

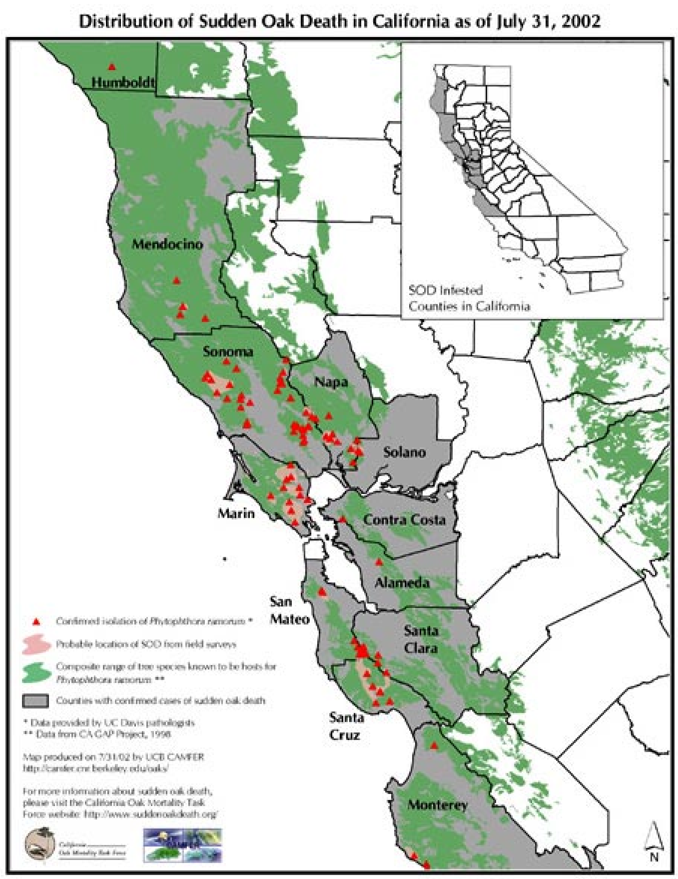

Figure 3. Distribution of Sudden Oak Death
Source: Center for the Assessment and Monitoring of Forest and Environmental Resources. UC Berkeley. (http://camfer.cnr.berkeley.edu/oaks/SOD_Calif_b&w07-31-02page.jpg)

A great deal more research is needed in this area, because changes in pest and pathogen outbreaks may exert considerable control over ecosystem structure. For example, one of the most visible and damaging pathogen outbreaks in California today is that of the fungus *Phytophthora ramorum* that causes Sudden Oak Death. Over five short years, tens of thousands of tanoaks (*Lithocarpus densiflorus*), coast live oaks (*Quercus agrifolia*) and black oaks (*Quercus kelloggii*) have been infected or killed in California's coastal counties (Figure 3). From its origins in Marin County, *Phytophthora* has spread rapidly to 11 other central coastal counties: Alameda, Contra Costa, Humboldt, Mendocino, Monterey, Napa, San Mateo, Santa Clara, Santa Cruz, Solano, and Sonoma. Although it is believed that the pathogen may have been introduced into California via importation of ornamental rhododendrons, it is unknown whether the fungus was recently introduced into California or if it is native and has only recently become fatal to oaks. *Phytophthora* can be spread by contact with infected wood, soil, rainwater, by human transplantation of infected plants, or through spores dispersed through the air under moist and windy conditions from the leaves of other infected species. Additional hosts, such as huckleberry (*Vaccinium ovatum*), bay laurel (*Umbellularia californica*), madrone (*Arbutus menziesii*), California buckeye (*Aesculus californica*), manzanita (*Arctostaphylos manzanita*), bigleaf maple (*Acer macrophyllum*), western azalea (*Rhododendron occidentale*), and California rhododendron (*Rhododendron macrophyllum*), carry the infection primarily on their leaves. The leaves provide a site for the rapid accumulation of *Phytophthora* spores and, therefore, function as a constant source of the infectious agent and facilitate rapid spread to mature oak trees. Today, an ever-growing percentage of mature oak trees are infected with the disease, and death often occurs within one year. High oak mortality is expected to have significant economic and ecological effects. For example, oaks increase property values and provide shelter and food sources for wildlife. In addition, large numbers of dead trees greatly increase fire risk.

Under a changing climate, there are a number of issues that will make this scourge (and other non-native infectious agents) particularly troublesome. Oak trees and other hosts are likely to be stressed as temperature and precipitation patterns change. Stress in host species compromises their vigor, making them more susceptible to deleterious pathogens. As a result, pathogenic outbreaks, like Sudden Oak Death, could become commonplace and act as a dominant force structuring California's ecosystems.

There are some fundamental questions that need to be addressed to reduce the uncertainty and to develop a management strategy for confronting these future threats: How is the pool of potential pathogens changed as the climate changes in California? What are these new pathogens likely to be? Are these pathogens native or introduced species? If the pathogen is introduced, what is its role in its native habitat? What is a host species' defense against an invading organism? How is that defense altered by a changing climate? Which species does the disease affect? Do some species have genetic resistance? How will a shift in dominant species affect the overall ecology of an ecosystem? What are the potential economic impacts of these changes in ecosystems? How does climate affect disease progression?

3.6 Areas of Uncertainty

3.6.1 Extreme Weather Events

As California experiences global change, some extreme climate events, like the frequency of heat waves and very heavy precipitation, are expected to increase. Widespread, extended periods of extremely high temperatures are projected to become more frequent with continued global warming. Higher temperatures lead to higher rates of evaporation and precipitation. Since the precipitation is likely to fall over shorter intervals of time, the frequency of extreme precipitation events is projected to increase (IPCC 1995; USGCRP 2000a; Easterling et al. 2000). The best evidence of increases in extreme and very heavy precipitation events comes from data for the United States (Figure 4). It is also expected that in many regions, including California, higher temperatures will accelerate soil drying, resulting in longer periods of low soil moisture and even droughts. This accelerated soil drying is expected to occur even as precipitation increases and extreme, intense precipitation events become more common.

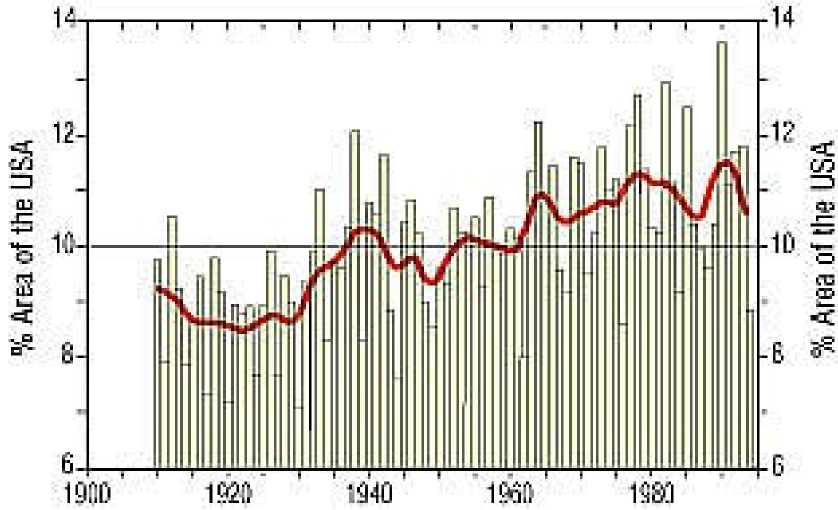

Figure 4. Extreme Precipitation Events in the United States
The area (expressed in percentage) of the United States, excluding Alaska and Hawaii, with an unusually large amount of total annual precipitation coming from extreme precipitation events (those with more than 5.08 cm {2 inches} of rainfall {or equivalent if precipitation is snowfall} in 24 hours) is displayed. The smooth curve shows the same data, but averaged over periods of about 10 years.
Source: World Meteorological Association.

3.6.2 Ecological surprises

Unfortunately, predictions based on general trends provide no insight into the magnitude or frequency of uncommon and extreme events. Climate change will likely include stochastic "surprises"—unanticipated events that differ from current expectations. These surprises will confound our ability to project impacts accurately, and therefore hinder our capacity to adapt to changes. Identifying these events will be difficult, if not impossible. Assessing the probability of these events and gaining a better understanding of their climatic, ecological, social, and economic consequences would be a fruitful topic of further research and assist the development of climate change policy.

Changes such as the loss of biodiversity, land use change, land cover change, hydrological disruptions, species shifts, and modified biogeochemical cycles will interact with climate change to alter California's ecosystems. Ecosystem impacts may be the continuation of trends that are gradual, predictable and ongoing. However, complex systems can respond to change in highly discontinuous ways that can catapult a system to a new state. These surprises and their ecological consequences are often readily interpretable after they occur, but difficult to anticipate. For example, in the early twentieth century, no one suspected that anthropogenic emissions of non-reactive chlorofluorocarbons would cause significant reductions in atmospheric ozone levels. This atmospheric "surprise" has impacted marine and terrestrial ecosystems. For example, in terrestrial ecosystems of South America, increased levels of UV-B radiation has driven changes in species composition and affected insect herbivory (Ballare et al. 2001).

The potential for similar large-consequence surprises in the future poses the greatest challenge for policy and research. In an effort to confront the impacts of climate change on ecosystem structure and function, some of our assessment effort should be devoted to identifying and characterizing potential low-probability, large-impact events.

3.7 Interaction Between Climate, Native Species Movement, Land Use Patterns, Fire, and Pest Outbreaks

Californians use and manipulate large areas of land—primarily for agriculture, forestry, and housing—and to a lesser extent for energy, recreation, transportation, and industry. These practices have created a mosaic of different land uses and ecosystem types, resulting in fewer remaining large contiguous areas of a single type of habitat than existed in the past. Many of California's ecosystems are essentially trapped on small islands, cut off from one another or connected by a limited and shrinking number of bridges. Because of these obstacles, it will be often difficult for plant seeds and individual animals to reach and become established in suitable areas, even if they are able to cover the required distances quickly enough. Over time, more species are likely to be stranded in an environment in which they cannot survive or reproduce. As this occurs, species will be more susceptible to air pollution and pest outbreaks. In forests, fast-growing, non-native species are likely to replace dominant, slow-growing tree species. Often, these non-native species provide lower quality habitat for other native species, further disrupting ecosystem biodiversity and integrity. In addition, as large woody individuals die, the risk of fire will increase as fuel loads increase.

3.8 The PIER Focus

Although the specific effects of climate change on California's water resources are still uncertain, it is clear that climate changes will affect the already-stressed ecosystems of California. To ensure that these ecosystems continue to provide habitat for the State's myriad flora and fauna, and that these natural systems continue to provide services to California citizens, it is essential that the State assess potential impacts from climate change on its natural environment and act to mitigate those impacts. Further, to ensure a rapid and informed response (and to leverage state resources), this data must be readily accessible to researchers in a wide variety of disciplines.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Examining the impacts of climate change on the State's ecosystems, and potential responses to those changes, is one such issue. PIEREA aims to address this topic through its own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmap chapters address other ecological, technical, and economic aspects of climate change effects California. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

At present, research needs to focus on developing a comprehensive assessment and monitoring plan by deciding what is important to monitor, establishing ecological indicators, and then developing a coordinated plan among various agencies to focus on relevant data sets. The State would then need to conduct a "gap analysis" of existing programs to determine where and how often additional monitoring would be necessary.

The second goal is to refine the spatial and temporal resolution of climate and vegetation models, while collecting data to validate the models' capabilities.

The following discussions outline the status of current work in these areas and identify scientific and research gaps. This roadmap addresses the areas of vegetation modeling; experimental field work to understand the impacts of simultaneous, multiple global changes on ecosystem dynamics; and understanding the impacts of invasive species. Other areas of research need attention in the future but are beyond the scope of this present report.

4.1 Ecological Assessment and Monitoring Using Ecological Indicators

The essential goods and services provided to society by California's ecosystems are threatened by climate change and other stresses. To better manage ecosystems in the face of multiple stresses, it is essential to begin monitoring the status of California's ecosystems. Long-term monitoring, using appropriate ecological indicators, can help identify emerging problems and determine which actions are most appropriate, based on accumulated experience of how environmental changes and human interventions have affected systems in the past. At this time, the data that would serve as a baseline in this effort are inconsistent, incomplete, and poorly integrated. As a result, our abilities to assess the impacts of multiple stresses on ecosystem biodiversity, structure, and function that have already occurred are limited.

It is necessary to begin to collect data on important ecosystem attributes. Much of the framework for such an effort is already in place. The California Resource Agency's California Legacy Project is working to standardize, integrate, and expand ecosystem assessment programs across the state, and to make data easily accessible to interested parties. These assessment efforts are intended primarily to support conservation decisions. The Legacy Project does not, however, explicitly consider climate change or its potential effects on ecosystems. There is a need, therefore, to increase communication and coordination between the California Legacy Project and the climate change community, so that the work of each group will mutually support the efforts of the other.

Successful monitoring programs rely on measures of ecosystem status. The National Research Council (NRC) has developed a checklist for evaluating potential ecological indicators (NRC 2000):

1. General Importance: Must provide information of general importance about changes in ecological or biogeochemical processes.
2. Conceptual Basis: Must be based on accepted conceptual model of the ecosystem.
3. Reliability: Must have evidence that demonstrates its reliability.

4. Temporal and Spatial Scales: Must provide information at the appropriate scale of interest.
5. Statistical Properties: Must be statistically robust in practice.
6. Data Requirements: Must know how much and kinds of data to be gathered for calculation of indicator.
7. Skills Required: Must know the skills and technical skills required of the data-collecting technicians.
8. Data Quality: Must ensure that the data are of high quality and reliable.
9. Data Archiving: Must have stringent requirements for data archiving and data sharing.
10. Robustness: Must be able to yield reliable data in and during external perturbations.
11. Intergovernmental Compatibility: Must be compatible with data being collected at other spatial scales.
12. Costs, Benefits, and Cost-Effectiveness: Must be efficient with respect to limited resources.

With these guidelines in mind, the NRC suggested national indicators in three categories that meet the previous criteria:

1. Indicator of extent and status of ecosystem: *Land cover and land use.*
2. Indicator of ecological capital: *Total species diversity, native species diversity, nutrient runoff, and soil organic matter.*
3. Indicators of ecological functioning: C*arbon storage, production capacity, net primary production, lake trophic status, stream oxygen, nutrient-use efficiency, and nutrient balance.*

The California Resources Agency is implementing the Environmental Protection Indicators for California (EPIC) program in collaboration with the Office of Environmental Health Hazard Assessment (OEHHA) that will regularly report environmental indicators. These indicators include some of those listed above (e.g., land cover and land use) (Cal/EPA 2002) However, indicators of ecological capital and ecological functioning are either non-existent or inconsistent in type across ecosystems. These parameters are fundamental to the provision of ecosystem goods and services and are likely to be linked strongly to climate change. Appropriate indicators of ecological capital and ecological functioning must be identified, and monitoring programs using these indicators must be implemented.

Research Needs

Research will need to define criteria for evaluating indicators, based on the NRC criteria. However, the NRC indicators were developed for the United States as a whole, so researchers should determine if these are the best indicators for California and how to best coordinate the indicators with those at the national level. Indicators that should be developed immediately for the 10 major biomes defined by the California Resources Agency are those listed under “Indicators of ecological capital” and “Indicators of ecological functioning.” Only a few of these indicators are currently being implemented by the EPIC program. During the next decade, researchers will need to be funded to develop informative environmental indicators.

Once ecological indicators are defined, California must establish and coordinate monitoring programs across the state. Great strides in this area have been made by the California Legacy Project. However, the goals of that project do not include explicit consideration of climate change and its effects on ecosystems. Work should begin immediately to integrate climate change concerns into statewide ecosystem assessment efforts, and to foster links between the Legacy Project and climate change researchers. Part of this work could be accomplished through a series of workshops, with representatives from the California Legacy Project, various state monitoring programs, and the climate change research community in attendance.

Once researchers have defined ecological indicators that provide information on ecosystem status and possible responses to climate change, California must make a consistent and long-term investment in monitoring programs. The result of this effort will be a vital baseline of data for many ecological parameters that will be used to assess ecosystem impacts from climate change. Results could be used by any persons interested in assessing the long-term impacts of climate change on ecosystem structure, function, and biodiversity. The payoffs from this straightforward approach will be enormous but will take several years to accrue.

This work should be funded immediately and continued on an ongoing basis. The level of funding will be determined by the level of interest on the part of the funding agencies and will determine the scope and depth of the effort.

4.2 Develop a More Spatially Resolved Climate Modeling Approach

Climate modelers generally agree on the likely rise in the average global temperatures over the next century. Unfortunately, projecting the change in particular regions is more difficult. The spatial structure of the climate in California is very fine. Climate modelers are unable to say whether particular regions within California will receive more or less rainfall, although they predict more winter variability and potentially drier summers. In sum, we are unable say whether a wetter or a drier climate is more likely for many California regions. It is not yet known if the change in climate will be gradual, stepped, or an iterative combination of both. In addition, since nighttime temperatures have been shown to have an impact on plant growth (Alward et al. 1999), it will be important to know how nighttime average, minimum, and maximum temperatures will change.

Modeling efforts must be supported with field-based measurements of fluxes of energy and materials between ecosystems and the atmosphere. As part of the USGCRP's nationwide AmeriFlux network, five eddy flux sites have been established in California, covering grazed and ungrazed grassland, savanna, chaparral, and mixed evergreen and conifer forest systems. The data from these sites provide valuable information about regional fluxes and can be used to improve soil-vegetation-atmosphere-transfer models (SVATs), which integrate climate and ecosystem processes at larger scales.

The AmeriFlux program is a solid start in the effort to understand interactions between climate and ecosystem processes within California, and should continue to receive strong support. However, the modeling efforts that are so intimately tied to eddy flux work need further funding. Currently a few federal agencies sponsor this type of research, including the National Science Foundation (NSF), the National Oceanic and Atmospheric

Administration (NOAA), the National Aeronautical and Space Administration (NASA), and the Department of Energy (DOE), but the funding is sporadic and not comprehensive. The USGCRP, which integrates research from many of these agencies, is also well-positioned to support increased climate modeling efforts. If California is to make great strides in this area, there must be a concerted and consistent effort to do so.

Research Needs

Because understanding climate is crucial for understanding of both ecosystem structure and function, it is important to continue to: (1) develop a more spatially resolved climate modeling approach, and (2) ensure that researchers in all fields of study have ready access to results of climate model studies.

This work should be funded immediately and on an ongoing basis. The level of interest on the part of the funding agencies, which will determine the scope and depth of the effort, will determine the level of funding. This research would provide the data necessary to begin to examine potential consequences of climate change for California's ecosystems.

4.3 Development of Modeling Efforts to Map Future Climate with Species Assemblages, Soil/Substrate Type, Dispersal Rates, and Migration Corridors for More Informative Scenarios of Ecosystem and Species Impacts

All of California's ecosystems will be affected by climate change, which will interact with present-day environmental stresses (e.g., changes in land use, nitrogen deposition, invasive species). Although important, it will not be possible to assess the full extent of ecosystem responses to global climate change through experimentation alone (Aber et al. 2001). Ecosystem responses to multiple global changes can be explored using ecosystem models that utilize critical information from field experiments.

During first attempts, models designed to assess the responses of ecosystems to climate change used a step-increase in temperature to project future species distributions. These models did not incorporate transient states, species migration patterns, or dispersal capabilities. Consequently, these models have very limited value in predicting ecosystem distributions, because species move as individuals and not as ecosystems. Clearly, increased temperature can lead to changes in the availability of basic resources (including water and nutrients) that will affect species differently, extreme climatic events such as drought or El Niño are likely to determine species' migration and establishment, and climate change will alter the frequency of major disturbances such as fire, pests, and pathogens (Field et al. 1999). Each of these factors will have a significant impact on future species and ecosystem distributions, but they were not included in early models.

For terrestrial research, a new generation of models—Dynamic Global Vegetation Models (DGVM)—is being developed to help address these shortfalls. The DGVMs combine the functionality of existing Terrestrial Biosphere Models (TBMs)—which contain modules for processes affecting carbon pools and fluxes such as photosynthesis, autotrophic respiration, and heterotrophic respiration—with existing Biogeography Models that capture the biological processes that determine long-term plant population dynamics. Currently, these models use plant physiological and ecological traits to categorize vegetation into Plant Functional Types (PFTs) and establish life history characteristics for each type. The models parameterize the physiological processes and climate-sensitivity associated with each PFT. The models also establish the competitive interactions that take place when two different PFTs occupy the same physical space.

The newest generation of DGVMs has made great progress in incorporating the complexity of ecosystem dynamics into the analysis of responses to a changing climate. For example, the DGVM called *MC1* simulates vegetation succession at large spatial scales through time while estimating variability in the carbon budget and responses to episodic events such as drought and fire (Lenihan and Neilson 2002). Although these model simulations cannot be viewed as predictions of the future, they give important indications about trends that may be important in California as the climate changes. For example, the model calculates that rising temperatures will cause a shift from conifer-dominated forest to mixed conifer and evergreen hardwood forests in northern California.

However, there are still crucial drivers of ecosystem dynamics that are not adequately addressed by the DGVMs. Four drivers deserve immediate attention:

1) **Land use.** The current models do not address the impact of current land use, land use change, land cover fragmentation, and the history of land management on ecosystem dynamics. These elements are critical for understanding ecosystem structure and function in a changing world. It is necessary to know the trajectory of land use change for the model to produce a realistic vegetation age structure. Future land use will be a function of both human population growth and vegetation change. In addition, it will be important to understand the distribution of the physical barriers to species migration that may be imposed by land use change.
2) **Age structure of vegetation.** In the current DGVMs, spatially variable age structure of the vegetation is simulated by the model. Although there are efforts underway to compare constructed vegetation age structure with observed age structure, it is unknown how well the simulations replicate observed patterns. Because initial age structure of the vegetation is important for understanding the trajectory of ecosystem structure, it will be advantageous to the success of future model predictions to accurately portray observed age structure at the onset of the model run.
3) **Dispersal rates and modes.** Dispersal rates and modes of different species are not considered in the DGVMs. The models need to incorporate the varying dispersal abilities of species in California to adequately assess the impact of a changing climate on community composition of California's ecosystems. Most likely, the inclusion of such information for all species would be cost-prohibitive, but it is essential that the models be able to incorporate information from a few key target species into the model runs with the goal of understanding species-level responses to future threats.
4) **Invasive species.** The DGVMs are not currently considering the impact of non-native, invasive species. The introduction and spread of invasive species can cause disruption in an ecosystem's successional trajectory. Non-native species pre-adapted to disturbance could easily colonize altered sites before native species become established. Non-native species can alter disturbance regimes so that further establishment by native species is highly unlikely. For example, the spread of *Bromus tectorum*, a non-native invasive grass to Western shrublands, alters the frequency of fires, which in turn suppresses the establishment of native shrubs.

Mechanisms involving invasive species, therefore, have a tremendous potential for altering ecosystem structure. Any progress made toward incorporating species-specific dispersal traits from activity (3) will aid this effort as well. The impact of introduced pest pathogens that cause such diseases as Sudden Oak Death should also be considered for incorporation into the new generation of models.

Efforts to address these shortfalls receive limited funding from the National Science Foundation. There is a need for leadership in this area.

Research Needs

Specifically, it is important that future aquatic, terrestrial, and marine ecosystem and species modeling efforts take into account the following factors:

1. **Successional state of ecosystem.** Researchers should assess the status of the ecosystem and its age structure to help determine its response under climate change.
2. **Transient states.** A transient change in climate must be used to assess the transient changes in ecosystem structure and function and their impact on outcomes.
3. **Substrate types.** Maps of substrate types of the existing range and future range must be used to understand if survival at a new geographic location is possible.
4. **Dispersal modes and rates.** Researchers should incorporate information about individual species' dispersal modes and rates to determine whether species are capable of becoming established in new areas on temporal and spatial scales relevant to climate change.
5. **Disturbance regimes.** Researchers should use information about the changing nature of disturbance regimes when modeling ecosystem impacts.
6. **Migration corridors.** Species may not be able to redistribute if there are no corridors, or if major physical obstacles (both natural and anthropogenic) exist. Potential corridors must be used to determine migration probabilities.
7. **Land use.** Researchers should examine past, present, and future land uses.
8. **Physiological and ecosystem process responses to climate responses to increasing CO_2.** It is possible that there will be a CO_2-fertilization effect on productivity. Modelers should run sensitivity analyses to determine the significance of such a mechanism (Aber et al. 2001).

This work should be funded immediately and on an ongoing basis. The level of interest on the part of the funding agencies, which will determine the scope, and depth of the effort will determine the level of funding. This research would provide the data necessary to begin to simulate ecosystem and societal impacts on California, and could be used by any persons interested in assessing the long-term impacts of climate change on ecosystem structure, biodiversity, and services.

4.4 Development of a Program to Better Understand Past Ecological Responses to Climate Change

Researchers can learn a great deal about potential impacts of future climate change by studying how ecosystems have responded to past climate changes.

The two main sources of funding for this area of research are the NSF and NOAA. Increased support of paleoclimate research would allow us to better predict the direction and magnitude of ecosystem response to climate change parameters.

Research Needs

By compiling and analyzing existing paleontological data, researchers could better understand ecosystem responses to basic climate changes such as temperature and precipitation. Important research outcomes would include how the rate and timing of species movements change, how basic water flows change, and how tides and near-shore processes are altered.

This work should be funded immediately and on an ongoing basis. The level of interest on the part of the funding agencies, which will determine the scope, and depth of the effort will determine the level of funding. Results could be used by any persons interested in assessing the long-term impacts of climate change on ecosystem structure, biodiversity, and services.

4.5 Understanding Multiple, Simultaneous Impacts

In addition to baseline ecological data and improved climate and vegetation models, empirical field studies are absolutely critical in the effort to understand the ecological impacts of climate change. The experiments used to study ecological responses to climate change generally address only a single factor—or at most two—yet, multiple factors are operating concurrently. Moreover, most experiments address only a subset of the scales of time and space that ecosystems respond to during real changes. Many lines of evidence suggest the importance of understanding longer-term processes, but these have been very difficult to study directly.

Field experimental studies should include treatments that will help in the understanding of ecosystem impacts of multiple global changes. These experiments should be designed to include combinations of the following treatments and to understand the mechanisms of change in species composition and basic ecosystem processes:

1. Atmospheric CO_2 increases
2. Atmospheric temperature increases
3. Precipitation variability
4. Nitrogen deposition increases
5. Invasive species introductions
6. Fire disturbances

Few studies of long-term ecosystem responses to multiple global changes are currently underway in California. These projects rely on intermittent funding from a variety of institutions. For example, Drs. Walter Oechel and David Lipson of San Diego State University; John Gamon of California State University, Los Angeles; Mike Allen of University of California, Irvine; and others have examined the long-term responses of southern California chaparral ecosystems to interactions between elevated CO_2 and variable rainfall and temperature. Funding for this project has come from a diversity of sources, including the NSF, the National Institute for Global Environmental Change, and the U.S. Department of Energy (DOE).

A second project, under the direction of Dr. Christopher B. Field of the Carnegie Institution of Washington and Drs. Harold Mooney, Peter Vitousek, and Brendan Bohannan of Stanford University, examines the long-term impacts of elevated CO_2, warming, nitrogen deposition, and increased precipitation on California grassland ecosystems. The Jasper Ridge Global Change Experiment has been supported by grants from the Terrestrial Ecology and Global Change program, the Packard Foundation, and the NSF's Biocomplexity and the Environment Initiative.

No other comprehensive, large-scale experiments are underway at this time in California.

Research Needs

Understanding and integrating these long-term components requires a broad research agenda. One of the keys to rapid progress will be experimentation on model systems in which the long-term responses occur over a period of years, rather than decades or centuries. Ideally, climate change field research projects should meet five objectives:

1. Be designed to address processes fundamental to California ecosystems.
2. Focus on ecosystem responses that are likely to be important but are poorly represented in existing models.
3. Incorporate multiple, simultaneous, interacting impacts known to be important to ecological systems such as climate, nitrogen deposition, non-native invasive species introductions, fire, and others.
4. Provide a clear path for generalizing results to a range of ecosystems.
5. Provide results that can be readily incorporated into regional climate and vegetation models.

Field experiments conducted under this program should provide information to both ecosystem-modeling efforts and to ecological indicators monitoring. This effort should be funded immediately and continue for 10 years.

4.6 Interaction with Invasive Species

There are few studies of potential invasive species' responses to changing climate. This endeavor is hampered by the fact that not all invasive species will respond the same, nor will a single invasive species respond the same in different bioregions or under different climates scenarios.

Invasive species research in California receives support through a variety of state and federal agencies, including the University of California Statewide Integrated Pest Management Project, the United States Department of Agriculture, the Bureau of Land Management, and the National Park Service. However, this research is generally focused on agricultural and rangeland pests at the expense of wild land pests. In addition, very little work is being done at the interface of invasive species and climate change research in California.

Research Needs

To approach this complex problem, researchers should establish programs in each of the 10 bioregions identified by the Jepson Manual (Hickman 1993) and the California State Resources Agency and should include the coastal marine system as an eleventh bioregion.

For the terrestrial research, the University of California Integrated Pest Management Project is well positioned to support such an effort. Each program should identify the three most aggressive biological invaders in terrestrial, aquatic, and marine habitats in the region. Researchers should conduct field experiments to understand the impact of the invaders on ecosystem structure and function.

Because of its potential importance to the understanding of future ecosystem dynamics, this work should be funded in the first year of this research program. The results would help to establish a database of potential responses of exotic invader to a changing climate. Results from the terrestrial ecosystems would be valuable in further developing the dynamic vegetation models. This research would allow us to better predict the direction and magnitude of ecosystem response to climate change parameters.

4.7 Development of a Program for Rapid Dissemination of Modeling Results to Field Ecologists, to Be Used in Experimental Efforts

Currently, there is not adequate communication between modelers, experimental researchers, and policy makers. Climate change impacts will manifest themselves in a variety of ways across California's landscape on historically short timescales. It will be extremely important in the coming decades that scientists (experimentalists and modelers) and policy makers have an efficient flow of information between them.

Research Needs

A Web site and a state coordination office should be established to serve this purpose. It should coordinate the collection and dissemination of up-to-date information about the most current research findings. This endeavor could be hosted by a university with extensive ongoing research in this area. All climate change researchers and policy makers could use this Web site and office as a primary resource.

4.8 Incorporation of Climate Change in Land Use and Conservation Planning

It is not enough to simply know where species may be able to survive under a changing climate. In a human-dominated landscape, species' abilities to become established in new areas may become secondary to overcoming habitat fragmentation in an altered landscape. Human developments, including cities, roads, agricultural fields, dams, and harbors—as well as natural isolating mechanisms such as soil type, microclimate, and topography—create significant barriers to large-scale species dispersal. The result is a more precarious future for important California ecosystems, even in the absence of climate change. The potential effects of human activities and climate change on issues of conservation concern are not being addressed sufficiently to aid land use and coastal planning in California.

Research Needs

With information about potential species and ecosystem distributions from current modeling studies, efforts should begin to develop techniques that include scenarios of future climate in the establishment of new conservation areas. These conservation techniques should be developed to conserve native species, ecological communities, and important ecosystem functions. This effort will also benefit land use planning, as climate change affects processes such as fire behavior. Research in this area includes:

1. incorporation of dynamic species model outcomes to conservation planning,
2. incorporation of biological and climatological models into land use planning,
3. adaptive management research for important California ecosystems, and
4. assessing the feasibility of applying conservation planning techniques.

Research programs focused on the development of effective conservation planning for an unknown future climate are rendered useless if no strategies are developed to implement the findings. Currently, research in this area is nearly non-existent. Professor Frank Davis at the University of California at Santa Barbara has begun some work in the area, but it is currently not funded.

5. Goals

The goal of the Ecosystem Impacts portion of PIER Global Climate Change Research Plan is to provide information about potential consequences of climate change for California's ecological and social systems. With such information, the State can take action to help protect vital goods and services.

The achievement of that goal depends on the success of a broad data-collection effort, as well as being able to develop and validate climate and vegetation models so that their resolution in time and space is improved.

The PIEREA program recognizes that much work is currently under way in these areas and seeks to draw from, build upon, and broaden the focus of those efforts. Whenever possible, PIEREA will identify existing efforts and form partnerships to leverage resources**.**

5.1 Short-term Objectives[1]

In the short term, this effort should develop a comprehensive assessment and monitoring research plan. This process would include deciding what is important to monitor, establishing ecological indicators, and then working with the California Legacy Project to develop a coordinated plan among various agencies to focus on relevant data sets. Next, researchers would need to conduct a "gap analysis" to determine where and how often additional monitoring would be needed. This effort would be very data-intense, and would involve workshops. Short-term work should also focus on refining climate and vegetation models so they are more highly resolved in time and space—while at the same time collecting data to validate their performance.

5.1.1 Establish Good Baseline Data

A. Develop and implement ecological assessment and monitoring programs, using ecological indicators specific to climate change impacts.

Activities needed (Monitoring): (1) Conduct a literature search to identify useful long-term data sets and gaps. (2) Develop a monitoring plan that specifies monitoring

[1] S*hort-term* refers to a 1–3 year time frame; *mid-term* to 3–10 years; and *long-term* to 10–20 years. The activities specified in the roadmap are projected to begin sometime within the designated time frames, and the duration of actual projects may be less than the entire term specified.

locations, monitoring methods, criteria/ecological indicators that the data must meet, and how the data will be stored and disseminated. (3) Establish monitoring sites and begin monitoring. Whenever possible, this work should be coordinated with the structure and activities of the California Legacy Project.

Activities needed (Ecological Indicators): (1) Establish a broad-based Advisory Committee to provide guidance and consensus on developing useful ecological indicators. (2) Using the National Research Council checklist for evaluating potential ecological indicators, evaluate the ecological indicators already developed by the NRC, California Resources Agency, and California Office of Health and Safety. (3) Based upon the evaluation in #2, develop a mutually agreed upon set of ecological indicators that address California's unique ecosystems. Give priority to developing *indicators of ecological capital* and *indicators of ecological functioning* for the 10 major biomes defined by the California Resources Agency. (4) Determine how to best coordinate the indicators with those at the national level. (5) Implement these ecological indicators in the monitoring programs described in the monitoring portion of this objective. Again, whenever possible these activities should be done in coordination with the California Legacy Project's existing structures.

Critical Factors for Success:
- Agreement among pertinent stakeholders on monitoring locations, methods, and ecological indicators.
- Adequate funding for monitoring.

5.1.2 Development of More Accurate Regional Climate Models

A. Develop a more spatially resolved climate modeling approach.

Activities needed: (1) Establish a broad-based Modeling Advisory Committee (composed primarily of modelers) to provide guidance and consensus on developing more accurate regional climate models. (2) Evaluate existing regional climate models to determine their capabilities and inadequacies. (3) Leverage the strengths of the existing models to develop a new model that can adequately address the needs of regional climate modeling for California.

B. Develop a program to compile and analyze climate observations and model results rapidly.

Activity needed: Convene a series of workshops in which climate change researchers assemble and analyze existing results to identify strengths and limitations of available data.

Critical Factors for Success:
- Ability to develop reliable regional dynamic vegetation models and marine species distribution models on an appropriate regional scale.
- Collaboration among stakeholders.
- Adequate funding for these activities and the modeling approaches outlined in the Regional Climate Modeling Roadmap.

5.1.3 Develop More Effective Vegetation Models.

A. Expand data inputs to improve ecosystem and species modeling in vegetation models including non-native, invasive species.

Activities needed: (1) Incorporate model inputs that account for the successional state of the ecosystem, transient states, substrate types, dispersal modes and rates, disturbance regimes, migration corridors, land use change and CO_2 fertilization. (2) Conduct modeling using the additional criteria. (3) Disseminate the results.

B. Develop a modeling program to understand future distributions of species assemblages in terrestrial, aquatic, and marine ecosystems.

Activities needed: (1) Incorporate model inputs that account for the successional state of the ecosystem, transient states, substrate types, dispersal modes and rates, disturbance regimes, migration corridors, land use change, and CO_2 fertilization. (2) Conduct modeling using the additional criteria. (3) Disseminate the results.

Critical Factors for Success:

- Collaboration among stakeholders.
- Consensus among users as to how information should be disseminated.

5.1.4 Develop a Program to Better Understand Past Ecological Responses to Climate Change.

A. Compile and analyze existing paleontological data to better understand past ecological responses to climatological change and to test models.

Activities needed: (1) Conduct a literature search of sound paleontological data that can illustrate past ecological responses to climatological change. (2) Analyze the data to determine associations between ecological variables (e.g., species movements, water flows, and tidal change) and historical climatological changes. (3) Disseminate the results.

Critical Factors for Success:

- An adequate amount of sound paleontological data that can be compared across various studies.

5.1.5 Develop an Experimental Research Program to Understand the Impact of Multiple Global Changes on Ecosystem Function and Structure.

A. Study the interactions of multiple impacts.

Activities needed: (1) Establish field and modeling studies that address multiple and simultaneous global change impacts on ecosystems.

B. Study the response of non-native species to climate change.

Activities needed: (1) Establish research programs in the 10 bioregions identified by the *Jepson Manual*. This program would identify the most important invading species in each of the 10 bioregions, use DGVMs with the new species module, and run the models to understand the long-term impact. (2) Establish experimental field studies that manipulate the invasive species simultaneously with other climate change variables.

Critical Factors for Success:

- Adequate funding for field studies and modeling.

5.1.6 Evaluate Methods for Using Ecosystem and Species Data for Conservation Area Decision Making.

A. Determine the feasibility of applying ecosystem and species data to conservation planning.

Activities needed: (1) Convene a workshop to identify the best approach to designing conservation areas in a rapidly changing climate. (2) Establish a timeline for research in this area after the workshop.

Table 2. Short-term Budget

Objective	**Projected Cost ($000 per year)**
5.1.1.A Develop and implement ecological assessment and monitoring programs, using ecological indicators specific to climate change impacts.	1,100
5.1.2.A Develop a more spatially resolved climate modeling approach. (Budget included in Regional Modeling Roadmap)	0
5.1.2.B Develop a program to compile and analyze climate observations and model results rapidly.	300
5.1.3.A Expand data inputs to improve ecosystem and species modeling in vegetation models, including non-native, invasive species.	1,000
5.1.3.B Develop modeling program to understand future distributions of species assemblages in terrestrial, aquatic, and marine ecosystems.	1,000
5.1.4.A Compile and analyze existing paleontological data to better understand past ecological responses to climatological change and to test models.	200
5.1.5.A Develop an experimental and modeling research program to understand the impact of multiple global changes on ecosystem function and structure.	3,000
5.1.5.B Study the response of non-native species to climate change.	3,000
5.1.6 Evaluate methods for using ecosystem and species data for conservation area decision making.	300
Total Short-term Cost per Year	**9,900**

Note: An asterisk (*) indicates a high probability that the work will be leveraged with other ongoing efforts. The figure given is the California Energy Commission's projected expenditure in dollars per year, over the course of the short-term research.

5.2 Mid-term Objectives

5.2.1 Develop a program for rapid dissemination of modeling results to field ecologists

A. **Design a set of mutually agreed upon methods for disseminating data via a Web site, implement the site, and staff a state coordination office.**

Activities needed: (1) Establish an advisory team of modelers, experimentalists, researchers, and policy makers to guide the data dissemination process. (2) Hold workshops to discuss issues and design workable methods. (3) Based on the results of those discussions, design a Web site to disseminate modeling data. (4) Develop and implement the Web site to be hosted by the California Resources Agency. (5) Establish a state office to coordinate these activities.

5.2.2 Incorporate Data on Climate Change's Potential Impacts on Species and Ecosystem Distributions into Land Use and Conservation Planning Using a GIS Database.

A. **Develop techniques for including scenarios of future climate in the siting and establishment of new conservation lands.**

Activities needed: (1) Incorporate model outcomes of dynamic species models to conservation planning. (2) Incorporate biological and climatological models into land use planning. (3) Research adaptive management for important California ecosystems.

5.3 Long-term Objectives

5.3.1 Develop a More Spatially-resolved Climate Modeling Approach.

A. **Continue improving regional models.**

Activities needed: *(1) Continue the iterative process of improving the regional models.*

6. Leveraging R&D Investments

6.1 Methods of Leveraging

Much of the work identified in this roadmap would be collaborative with other entities; PIEREA would either co-fund projects by other entities, or use outside funds to support PIEREA efforts.

Specifically, this roadmap seeks to:

- provide PIER funds for co-funding existing or planned work by entities yet to be determined, and

- solicit funds from entities yet to be determined, to build upon their efforts, or to co-design new projects at the Energy Commission.

6.2 Opportunities

No co-sponsored efforts are under way at this time. Co-sponsorship opportunities are likely with the organizations listed below. Each of these organizations is interested in addressing climate issues. The following specific collaborative opportunities have been identified:

Ecological Assessment and Monitoring

Monitoring could be administered through a number of different state agencies. State agencies could hire technicians to conduct monitoring that is consistent across park units and fish and game management regions. In addition, PIER could award state grants to researchers at universities and research institutes.

Ecological Indicators

Currently the California Office of Health and Safety is conducting an effort to establish ecological indicators for the state of California, so PIER could team with those researchers.

Development of More Spatially-Resolved Regional Climate Models

Currently a few federal agencies fund this type of research including NSF, NASA, and DOE, but the funding is sporadic and not comprehensive.

Development of Modeling Efforts to Map Future Climate with Species Assemblages, Soil/Substrate Type, Dispersal Rates, and Migration Corridors for More Informative Scenarios of Impacts.

This area of research receives sporadic funding from the NSF and NASA.

Develop a Program to Better Understand Past Ecological Responses to Climate Change

This area of research receives a small amount funding from the NSF.

Understanding Multiple, Simultaneous Impacts

This area of research receives some funding from the NSF and the Packard Foundation.

Study the Response of Invasive Species to Climate Change

This area of research receives sporadic funding from the National Science Foundation.

Develop a Program for Rapid Dissemination of Modeling Results to Field Ecologists

No leveraging or co-funding opportunities exist to date.

Incorporate Data on Climate Change's Potential Impacts on Species and Ecosystem Distributions into Land Use and Conservation Planning.

No leveraging or co-funding opportunities exist to date.

Evaluate Methods for Using Ecosystem and Species Data for Conservation Area Decision Making

No leveraging or co-funding opportunities exist to date.

7. Areas Not Addressed by This Roadmap

This roadmap was intended to focus solely on the direct impact of climate change on ecosystems in California. Except where specific examples were given, it was intended to be broadly written to encapsulate multiple impacts on a wide array of ecosystem types from marine to terrestrial. Of course, there is a great deal that was not addressed specifically in this report that requires and deserves further discovery. In particular, it will be vital for any research program that is implemented to be designed to integrate the environmental and economic impacts simultaneously. Below is list of important research areas that should be considered for future elaboration of this report:

- Impacts on key ecosystem services
- Impacts on forestry
- Impacts on agriculture
- Use of forestry practices to mitigate global climate change (see the *Carbon Sequestration in California's Terrestrial Ecosystems and Geologic Formations* roadmap)
- Impacts on fisheries, in particular, the salmon runs.
- Impacts on riparian ecosystems and implications for flood control
- Impacts on watershed restoration
- Impacts on fire management
- Impacts of ecosystem degradation on public health
- Impacts on grazing practices

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Appendix A
Current Status of Programs

This section outlines those efforts that most closely address climate change and its impact on California ecosystems.

Current Status: California

California Energy Commission (CEC)

- The California Energy Commission administers the Public Interest Energy Research (PIER) Program. PIER funds will soon become available for investigating the impacts of global climate change on California's ecosystems. http://www.energy.ca.gov/pier/energy/index.html

California Air Resources Board (CARB)

- The California Air Resources Board funds research on the environmental impacts of air pollution; however, it does not currently fund research on the impacts of climate change. CARB's current environmental research activities are shown at: http://www.arb.ca.gov/research/research.htm

California Department of Fish and Game (DFG)

- The Department of Fish and Game (DFG) is currently addressing the issue of adaptation to climate change with regional conservation planning, watershed planning, fisheries management and restoration, and biological assessment. http://www.dfg.ca.gov/

California Department of Forestry (CDF)

- The CDF does not currently have a research program on the mitigating the impacts of climate change, but its Fire and Resources Assessment Program (FRAP) monitors the area vegetation cover and timberland of California, allowing CDF to assess carbon storage capacity of the state. http://www.fire.ca.gov/index.html

California Department Water Resources (DWR)

- The California Department of Water Resources' California Water Plan Update 2003 will look at impacts of climate change on water resources in California, and potential strategies for adapting to these changes. Although this plan does not address the environmental impacts of climate change, results from the plan will be important for understanding effects of climate change on aquatic habitats and species. http://www.waterplan.water.ca.gov/b160/indexb160.html

California Environmental Protection Agency (Cal/EPA)

- Cal/EPA is addressing climate change through its assessment of environmental indicators in the Environmental Protection Indicators for California (EPIC) project. EPIC was created to develop scientifically based measures that convey complex information on environmental status and trends in an easily understandable format. http://www.oehha.ca.gov/multimedia/epic/index.html

- Cal/EPA is addressing new threats in their Emerging Environmental Challenges program. This program is not currently designed to address the impacts of climate change specifically. http://www.oehha.ca.gov/multimedia/epic/index.html

Current Status: Regional and National

U.S. Global Change Research Program (USGCRP)

- At the national level, the U.S. Global Change Research Program (USGCRP) coordinates the world's most extensive research effort on climate change. The USGCRP coordinates a broad agenda of research on global change. The program enables the integration of knowledge produced in different agencies and disciplines to provide useful information about how to prepare for and adapt to global and regional environmental changes. The USGCRP coordinates the research of ten federal departments and agencies with active global change programs and provides liaison with the Executive Office of the President. Participants include: Department of Agriculture (USDA), Department of Commerce/National Oceanic and Atmospheric Administration (DOC/NOAA), Department of Defense (DOD), Department of Energy (DOE), Department of Health and Human Services/National Institutes of Health (HHS/NIH), Department of the Interior/U.S. Geological Survey (DOI/USGS), U.S. Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and Smithsonian Institution.
- The USGCRP budget included $1.7 billion in FY2001 for research and observations under seven program elements, including: (1) Understanding the Climate System, (2) Understanding the Composition and Chemistry of the Atmosphere, (3) Global Water Cycle, (4) Global Carbon Cycle, (5) Understanding Changes in Ecosystems, (6) Understanding the Human Dimensions of Global Change and (7) Paleoclimate: The History of the Earth System (USGCRP 2000b). The elements most pertinent to this report are elements (4) and (5). In FY2001, the Global Carbon Cycle element received $221 million and the Understanding Changes In Ecosystems element received approximately $224 million (USGCRP 2000b). Distributions of these funds are discussed within the department from which they are administered. (www.usgcrp.gov/)

Department of Agriculture (USDA)

- The U.S. Department of Agriculture (USDA) was awarded ~$29 million under the USGCRP's Understanding Change in Ecosystems element (primarily for impacts on managed ecosystems) and ~$37 million under the Global Carbon Cycle element.
- The Forest Service Global Change Research Program (FSGCRP) within the USDA is designed to address the impacts of global change on forest ecosystems. Currently, there are no projects funded in California, but this program is a possible source for research funds. http://www.fs.fed.us/ne/global/fsgcrp/
- The Agricultural Research Service Global Change Research Program funds research projects on the impacts of climate change on agroecosystems. Some topics, such as the carbon cycling program, have relevance to natural ecosystems.

Currently, there are no programs funded in California. http://www.nps.ars.usda.gov/programs/programs.htm?NPNUMBER=204

Department of Commerce/National Oceanic and Atmospheric Administration (DOC/NOAA)

- USDA was awarded $9.9 million under the Global Carbon Cycle element. This source would provide resources for understanding carbon cycling and storage only.
- The Office of Global Programs (OGP) leads the NOAA Climate and Global Change (C&GC) Program. OGP assists NOAA by sponsoring focused scientific research aimed at understanding climate variability and its predictability. Researchers coordinate activities that jointly contribute to improved predictions and assessments of climate variability over a continuum of timescales.
- The OGP also leads the effort to fund the Global Carbon Cycle Program (GCC) that investigates the impacts of global change on carbon cycling. http://www.ogp.noaa.gov/

Department of the Interior/U.S. Geological Survey (DOI/USGS)

- DOI/USGS was awarded $13.9 million under the USGCRP's Understanding Change in Ecosystems element (primarily for impacts on managed ecosystems) and $3.5 million under the Global Carbon Cycle element. There was approximately $25 million in USGS's Global Change Research Program in FY2001. This source could provide resources for research for understanding the impacts of global change on California ecosystems.
- USGS's Global Change Research Program included fund for understanding the impacts of global change on biogeochemical cycling, terrestrial and coastal ecosystems, coastal wetlands, and fish and wildlife. http://geochange.er.usgs.gov/

Environmental Protection Agency (EPA)

- EPA was awarded $3 million under the USGCRP's Understanding Change in Ecosystems element (primarily for impacts on managed ecosystems). Including this source, EPA's Office of Research and Development (ORD) had approximately $23 million for understanding the impacts of consequences of global change on climate variability and biology and biogeochemistry of ecosystems. This source could provide resources for research for understanding the impacts of global change on California ecosystems.
- Still, there is $3 million/year for research on the impacts of global change research on the natural environment.

National Aeronautics and Space Administration (NASA)

- NASA was awarded ~$134 million under the USGCRP's Understanding Change in Ecosystems element primarily for impacts on managed ecosystems and ~$150 million under the Global Carbon Cycle element in FY2001. Including this source, NASA had approximately $39 million for understanding the impacts of consequences of global change on ecological processes. This source could provide resources for research for understanding the impacts of global change on California ecosystems.

- Much of the research funded at NASA is for space-based observations, but there are small programs that fund ecological research. http://www.nasa.gov/research.html

National Science Foundation (NSF)

- The National Science Foundation was awarded $29 million under the USGCRP's Understanding Change in Ecosystems element (primarily for impacts on managed ecosystems) and $13 million under the Global Carbon Cycle element. This source could provide resources for understanding the impacts of global change on California ecosystems.
- Although NSF's budget for environmental research for FY2001 was ~$188 million, competition for these funds is highly competitive and program-specific. http://www.nsf.gov/geo/egch/about_nsf_gcrp.html

Smithsonian Institution

- The Smithsonian Institution was awarded $3.8 million under the USGCRP's Understanding Change in Ecosystems element (primarily for impacts on managed ecosystems) and $0.3 million under the Global Carbon Cycle element. This source could provide little or no resources for understanding the impacts of global change on California ecosystems.

Current Status: International

European Union

- The European Union has taken the lead in its funding of climate change research. Although resources are not available for research in the United States, there is much to be learned by their approach to research on global climate change. http://europa.eu.int/comm/environment/climat/eccp.htm

Intergovernmental Panel on Climate Change

- The IPCC's latest document on mitigation, *Climate Change 2001: The Scientific Basis*, http://www.ipcc.ch/ provides a synthesis of current scientific data on global climate change and its impacts.

Global Change and Terrestrial Ecosystems (GCTE)

- Global Change and Terrestrial Ecosystem (GCTE) (http://gcte.org/) is a Core Project of the International Geosphere-Biosphere Programme (IGBP) (www.igbp.kva.se/cgi-bin/php/frameset.php), an international scientific research program established in 1986 by the International Council of Scientific Unions (ICSU).
- The scientific objectives of GCTE are: (1) to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including (i) agriculture, forestry, soils; and (ii) biodiversity; and (2) to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. http://www.gcte.org/about.htm