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COMMISSION

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Climate Change Research, Development, and Demonstration Plan

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The Public Interest Energy Research (PIER) Program Environmental Area

The Public Interest Energy Research (PIER) program was created following the deregulation of California's electricity service industry (1996 Status, Chapter 854, hereinafter referred to as Assembly Bill (AB) 1890). Article 7 of AB 1890 was enacted to ensure that the benefits obtained from important public purpose programs, such as public interest energy research, development, and demonstration (RD&D), would not be lost in the newly deregulated environment. California's electric investor-owned utilities collect $62 million annually from electricity ratepayers to fund the PIER program. In September 2000, the Legislature passed, and Governor Gray Davis signed into law, Senate Bill (SB) 119 (Sher) and AB 995 (Wright), which extended the PIER Program surcharge to January 2012.

The PIER Program is organized in six PIER Program funding areas:

1. Residential and Non-Residential Buildings End-Use Energy Efficiency
2. Industrial / Agricultural / Water End-Use Energy Efficiency
3. Renewable Energy Technologies
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Energy Systems Integration

Each of these areas funds and conducts energy-related research in the public interest, for the benefit of California citizens.

The Public Interest Energy Research Energy-Related Environmental Research area (otherwise called the *PIER Environmental Area*, or *PIEREA*) is responsible for addressing the environmental impacts and beneficial uses of electricity in California. As defined by the PIER strategic plan, the overall mission of the PIEREA is to:

> Develop cost-effective approaches to evaluating and resolving environmental effects of energy production, delivery, and use in California, and explore how new energy applications and products can solve environmental problems.

1. Background and Overview

Climate change is no longer a hypothetical or distant possibility—it is occurring, and is likely to have a profound impact on human society and the natural environment over the coming decades. Climate change and its impacts on a global scale are the focus of an intense, broad-based international research effort in the natural and social sciences. Understanding the nature and potential consequences of climate change on regional scales, however, and for California in particular, is a challenge we have just begun to meet. This research plan has been prepared by the California Energy Commission to contribute to California's intensifying efforts to understand how climate change will affect the state's social, economic and natural systems, and to help provide policy-makers with the knowledge and tools they need to anticipate and plan for these impacts.

This opening section of the research plan discusses the role of CEC's PIER program in climate-related research, summarizes the development process for this plan, outlines the relations between PIER and other state agencies in conducting climate change research, and summarizes key benefits of the research proposed here.

1.1 The PIER Role in Climate Change Research

The scientific and analytical study of climate change and its potential impacts on California's economy and natural environment is one of the many areas of focus for the Energy-Related Environmental Research area of the PIER group (PIEREA). This *PIEREA Climate Change Research, Development, and Demonstration Plan* was prepared by PIEREA to provide a comprehensive vision of how it intends to support climate change research in California.

There are three primary reasons for a major PIER research effort on climate change. First, electricity generation in, or for import into, California is a major source of greenhouse gas (GHG) emissions. Therefore, PIEREA, according to its mission, must undertake climate change research at the state level, to evaluate and suggest means of mitigating the climate-related effects of electricity. Second, there is a high likelihood that climate change will have a significant, direct impact on the consumption of energy—and particularly electricity—in California because of changes in temperatures within the state. Accordingly, PIER must investigate how the state can prepare for and adjust to these changes in electricity demand. Third, by altering precipitation patterns across the West, climate change is likely to affect the supply and cost of hydropower, which represents about 20% of in-state electricity generation. Thus, it is necessary for PIER to determine how to accommodate these hydropower impacts, in order to maintain reliable and affordable energy flows to California's households and businesses in the context of a changing regional climate.

The research proposed in this Plan will build upon the long-standing contribution of the California Energy Commission (Commission) to climate change policy formulation

in California. In 1988, the California Legislature (Assembly Bill 4420, Sher) directed the Commission to begin a study of the potential impacts of global warming trends on the state's energy supply and demand, economy, environment, agriculture, and water supplies, and to develop policies for reducing these impacts. The Commission prepared a report in cooperation with other concerned state agencies and submitted this report to the Legislature on November 1991 (CEC 1991). Similarly, in 1997, the Commission staff prepared for the U.S. Environmental Protection Agency an inventory of GHG emissions and an evaluation of potential policies and strategies for reducing GHG emissions in the state (California Energy Commission 1998). Recently, SB 1771 and its subsequent revisions require, among other things, that the Commission update the statewide GHG emission inventory every five years and "...convene an interagency task force consisting of state agencies with jurisdiction over matters affecting climate change to ensure policy coordination for those activities." This bill also requires the Commission to establish a climate change advisory committee to make recommendations to the Commission on the most equitable and efficient ways to implement any national or international requirement on climate change (CEC 1998). There is a need for a strong, unbiased climate change research program that informs the policy debate without advocating a particular position on any issues. PIER climate change research will strive to play this role, which is in accordance with the PIER program's legislative mandate and in agreement with the adopted mission of the PIEREA area.

1.2 Development of the PIER Climate Change RD&D Plan

Research on global climate change and its social and economic impacts is a very active and expanding focus at many universities, government agencies, and other institutions around the world. However, relatively little of this work addresses the significant scientific or policy questions related to climate change that are of unique importance to California. PIER is currently funding several studies that address climate change as it relates to California, to begin building the knowledge base needed by state policy-makers. (These studies and their implications for this plan are described subsequent sections.) To help determine how to expand upon and extend this work, PIEREA commissioned research roadmaps on various topics related to climate change, to identify research gaps that would be important to the state but would most likely not be addressed by existing national and international research efforts. Technical experts on climate change issues or closely related areas prepared these roadmaps with input from a large group of researchers from a range of disciplines.

The roadmaps are expansive, in the sense that they cover research topics well beyond those that could be addressed feasibly by the PIER program, but they were developed to identify and prioritize research areas based on their overall importance and relevance to PIEREA goals. The breadth of the roadmaps also allows the PIER program to more easily identify areas of common interest with other research programs. In some cases, other research entities are using these roadmaps to identify research opportunities. For example, the California Department of Water Resources (DWR) is using the roadmap on water resources to identify preliminary areas of work on climate change for

inclusion in the 2003 State Water Plan. The DWR plan is a major effort undertaken every five years that, for the first time, will take into account climate change concerns. The California Assessment Report (Wilkinson et al. 2002) also used these roadmaps to suggest research priorities to the national research program on climate change.

Although this research plan is based primarily on the roadmaps commissioned by the PIER program, the limited funds available for the implementation of the PIER program on climate change are not sufficient to fund all the research needs identified in the roadmaps. Thus, this plan identifies the areas of research that have been selected as priorities for PIER research funding according to the criteria of: (1) relevance to PIER objectives (i.e., concerning the energy sector), (2) likelihood of generating scientifically and/or policy-relevant results within no more than four-to-five years, (3) potential applicability to California policy-making related to climate change, (4) technical quality and potential to advance scientific understanding, (5) potential to generate "co-benefits" (i.e., in science or policy not directly related to climate change), (6) likelihood of eventually securing co-funding from other agencies, and (7) the clear need for state support to reach the level of funding necessary to address these issues adequately. The Plan emphasizes the following themes: cooperation with other agencies when conducting research; concentration on projects that will achieve multiple benefits and are policy relevant; advancement of science and knowledge; and identification of "no regrets" opportunities, which are actions that benefit California even in the absence of climate change considerations.

The following is a list of the roadmaps and the technical experts responsible for their preparation:

- Ecological Impacts of a Changing Climate (Rebecca Shaw, Stanford University)
- The Effect of Global Climate Change on California Water Resources (Maurice Roos, California Department of Water Resources)
- The Economics of Climate Change Mitigation and Adaptation in California (Alan H. Sanstad, Lawrence Berkeley National Laboratory)
- Modeling Regional Climate Change in California (Larry Gates, Lawrence Livermore National Laboratory)
- Developing Greenhouse Gas Supply Curves for In-State Sources (Mike Rufo, Xenergy, Inc.)
- Carbon Sequestration in California's Terrestrial Ecosystems and Geologic Formations (Ed Vine, University of California, Office of the President and Mark Wilson, Consultant)

These experts benefited from generous input from technical representatives of multiple state agencies (i.e., the California departments of Water Resources, Food and Agriculture, Forestry and Fire Protection, and the Air Resources Board); researchers from the University of California, California State University, and other universities; national laboratories; environmental groups; federal agencies; the Electric Power Research Institute; electric utilities; California irrigation districts; the California Climate

Registry; and the United States Global Change Research Program. The roadmaps are available from the California Energy Commission as separate documents. PIEREA may commission the preparation of additional roadmaps in other areas, such as the study of the potential impacts of climate change on public health, agriculture, and forested areas. This work will be conducted with the full cooperation with the relevant state agencies.

In addition to identifying priority areas for PIER funding, this document considers the interactions among different research areas to produce a comprehensive research plan. It presents a relatively long-term research agenda (20 years), but it focuses on the research activities that should be funded in the next two years. Individual products will be generated on a continuous basis, but PIEREA's goal is to produce an integrated report in four or five years, after all the elements identified in this plan have been executed. The plan is a living document that will be revised and updated regularly to reflect continuing scientific progress. In addition, since one of the goals of this plan is to identify policy-relevant research, this plan will be updated as needed to consider policy developments at the state, national, and international levels.

1.3 Coordination and Cooperation with Other State Agencies

A number of research activities are in progress at various state agencies that, while in most cases undertaken for other reasons, have implications for understanding climate change and possible policy responses. For example, the California Air Resources Board (ARB) efforts to understand the formation, transport, and deposition of aerosols (small particles) in the air is of relevance for climate change research, because aerosols are important drivers of climate change at the regional and global levels (Hansen 2001, Menon 2002). Aerosol research could have significant implications for climate policy because it indicates that black carbon (i.e., soot) should be considered a contributor to global warming; further confirmation of this finding would suggest that measures to reduce its atmospheric concentrations could be folded into climate change mitigation efforts. Similarly, the forest inventory work of the California Department of Forestry and Fire Protection is directly relevant to any efforts designed to estimate the amount of carbon stored in terrestrial ecosystems in the state. Other state agencies (e.g., the Department of Food and Agriculture and Department of Water Resources), state-federal partnerships such as CALFED, and funding programs such as the Kearney Foundation of Soil Science are also conducting climate-change-relevant studies that must be considered in the preparation and implementation of any research plan on climate change for the state.

As noted earlier, PIEREA is also already funding some studies on climate change and has engaged different state agencies on these studies. For example, technical staff from the Department of Water Resources (DWR) and the Department of Food and Agriculture have provided invaluable technical support for a study being conducted by researchers with the University of California at Davis looking at the potential impacts of climate change on water resources and hydropower production in particular. In fact, DWR will consider this study in the preparation of its 2003 State Water Plan.

PIER's role in climate change research will be one of cooperation and coordination with other state and federal agencies, research programs, and funding agencies to avoid duplication of efforts, to leverage limited resources, and to ensure the production of high-quality, policy-relevant research for California and the nation. PIEREA will fulfill this role by seeking the input of different stakeholders in the execution of this research plan, and by organizing regular scientific workshops and conferences on climate change where the work funded by PIEREA and others will be presented, with the goal of sharing results and seeking cooperation. PIEREA will continue to work with other state agencies to develop joint research projects as much as possible, as has been done so far with the California Department of Forestry and Fire Protection (CDF) and DWR. Finally, PIEREA will actively seek cooperation with other research programs and funding agencies to enhance research on climate change in California. For example, PIEREA is currently in contact with the Kearney Foundation, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Energy (DOE) in order to develop projects of common interests that are also compatible with this research plan.

1.4 Key Benefits

The research outlined in this plan is an interrelated group of projects whose ultimate benefits not only address climate change issues in California, but also improve the overall health and vitality of the state's citizenry, environment, and economy. Some projects yield these benefits directly; whereas, others serve as inputs to other efforts that deliver direct benefits. All research efforts were evaluated on their ability to deliver benefits beyond those associated with climate change.

The lists below identify some key benefits in each subject area. Each topic's subsection in Section 3 discusses benefits in more detail.

Climate Change Sensing and Modeling

- Greatly improved and comprehensive understanding of likely regional climate changes that will affect California's hydrology, agriculture, and natural ecosystems
- Better snow-level forecasting and detection of subtle climatic changes
- Improved models based on higher-quality and more comprehensive data
- Better understanding of energy consumption patterns and climate, including the effects of urbanization
- Standardization of modeling protocols

Impacts of Climate Change on California Water Resources

- Improved understanding of important hydrological processes and capacity for early detection and interpretation of climate change signals
- Projections of the impacts of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes in California

Impacts of Climate Change on Ecological Resources

- Increased representation (in dynamic vegetation models) of interactions among critical ecosystem factors, improving understanding of the impacts of climate change on each factor and of the interrelated systems
- Enhanced capability for identifying and interpreting ecological trends

Carbon Sequestration in Terrestrial Ecosystems and Geological Formations

- An economic assessment of forestry and agricultural soil carbon sequestration strategies to help decision makers prioritize those strategies, and also to help agricultural and forestry specialists allocate resources among competing alternatives
- A comprehensive understanding of the feasibility and economic factors involved in bioenergy use in California, and potential solutions for overcoming barriers to the use of bioenergy in the state
- Identification and quantification of the feasibility, economics, and potential of various strategies for sequestering carbon in geological formations, to help decision makers prioritize options

Inventory Methods and Supply Curves

- Accurate data in a form that researchers can use to improve estimates of energy consumption and CO_2 emissions from the combustion of fossil fuels in California, and for use in economic analyses
- Standardized methods to estimate non-CO_2 emissions, based on more comprehensive, California-focused data

The Economics of Climate Change Mitigation and Adaptation in California

- A first assessment of the possible aggregate economic impacts of climate change and GHG policy on California, and analytical and empirical benchmarks for further study
- An integrated modeling framework for incorporating results of PIEREA research on water and agriculture, energy demand, technological change, and other key areas
- Tools to enable California policy-makers to develop robust strategies in response to uncertain climate, economic, and technological change
- Improved understanding of the costs and benefits of increased energy efficiency in reducing GHG emissions in California
- Identification of multi-GHG reduction strategies that could also generate air quality benefits, at a lower overall cost
- Assessment of potential for regional GHG trading markets in California

1.5 PIEREA Climate Change Research Plan Organization

This research plan is organized as follows: Section 1 has outlined PIER's role in climate change research, the plan's development process, and key research benefits. Section 2: *Climate Change and California* provides a brief overview of facts regarding global climate change, key mechanisms of climate change in California, possible impacts, and a profile

of the state's GHG emissions. Section 3: *PIEREA Research Agenda and Benefits* outlines PIEREA's proposed research activities and the benefits that will accrue from their implementation. Section 4: *Bibliography* lists the references used to prepare this plan.

2. Climate Change and California

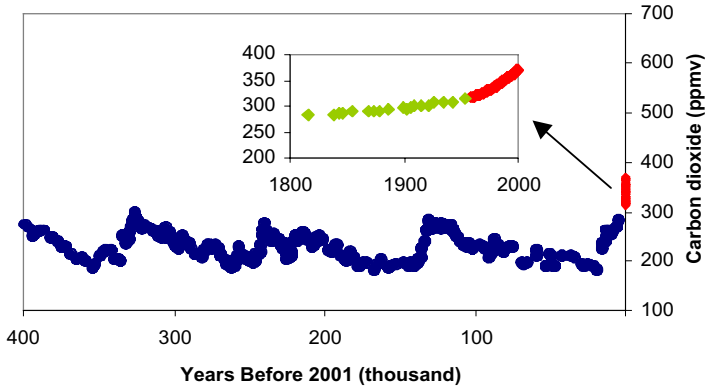
2.1 From Global to Regional Climate Change

There is now a broad scientific consensus that the global climate is changing in ways that are likely to have significant socioeconomic consequences, and that these changes will continue and probably intensify through the twenty-first century. Climate change research findings have been detailed by the authoritative International Panel on Climate Change (IPCC). In its Third Assessment Report (TAR), released in 2001, the IPCC concluded that the increase in the global average surface temperature during the twentieth century "…is likely to have been the largest of any century during the past 1,000 years." Moreover, the modeling studies considered by the IPCC project that this temperature will increase by 1.4 to 5.8°C (2.5 to 10.4°F) over the period 1990 to 2100.

There is also mounting evidence that observed global climate change is due substantially to human activities—specifically the emissions of greenhouse gases (GHGs) such as carbon dioxide, methane, and nitrous oxide. The IPCC Second Assessment Report (SAR), released in 1995, indicated that "The balance of evidence…suggests a discernable human influence on global climate." (IPCC 1995). The TAR contains a much stronger conclusion: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (IPCC 2001). A recent report prepared by the U.S. National Academy of Science at the request of the Bush Administration confirms this finding (National Research Council 2001).

Studies of the paleoclimatic record indicated a link between changes in the atmospheric concentrations of GHGs and changes in climate. Figure 1 shows how ambient concentrations of carbon dioxide (CO_2), the most important GHG, in the atmosphere have changed in the last 400 thousand years. The increase of fossil fuel consumption since the industrial revolution has resulted in a rapid increase of atmospheric concentration of this gas. In fact, twentieth century concentrations are the highest in the last 400 thousand years, as illustrated in the figure.

The results of ongoing scientific research are reinforcing the conclusions of the TAR. For example, scientists from Scripps Institution of Oceanography recently analyzed data that was collected since 1950 on changes in ocean temperatures at depths up to 3,000 meters, to detect and attribute observed climate changes (Barnett, David et al. 2001). The resulting report concludes that "the observed ocean heat-content changes are consistent with those expected from anthropogenic forcing, which broadens the basis for claims that an anthropogenic signal has been detected in the global climate system." (ibid.).



Data Sources: Keeling 2002, Barnola 1999.

Figure 1. Changes in Atmospheric CO_2

Moreover, recent studies of the uncertainty in projected potential changes of average global temperatures during the coming century suggest that the results reported in the TAR may understate the possibility of strong warming (Knutti, Stocker et al. 2002). The new results, obtained making systematic changes to the model parameters (within plausible ranges) while ensuring that the modeling results are still consistent with the recent observed warming, indicate a higher likelihood of warming in the upper end of the range reported by the IPCC, when emissions are as projected in the "B1" SRES scenario (Nakicenovic 2000).[1]

Indeed, research at the frontiers of atmospheric science, on the underlying mechanisms of the climate system, is providing even greater reason for concern regarding the potential character of climate change in the coming decades. Until quite recently, virtually all research on climate change—both scientific and socioeconomic—has focused on scenarios of gradual, smooth shifts, primarily as measured by long-run equilibrium increases in mean global surface temperature. There is, however, growing attention within the scientific community to the possibility that increased concentrations of GHGs may induce abrupt and discontinuous shifts in the climate system on much shorter time scales (National Research Council 2002). Recent scientific evidence shows that widespread major changes in climate have occurred in our planet and that these changes took place with startling speed (i.e., decades or even years). The socio-economic impacts of abrupt climate change would almost certainly be much greater than those of gradual, long-run shifts.

[1] The B1 scenario in the IPCC's *Special Report on Emissions Scenarios* emphasizes "…a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development."

In moving from a global to a regional scale, the possibility of abrupt climate change becomes even more salient. Understanding of global climate trends does not directly translate to the regional scale that is of concern for California, and regional climate modeling and analysis is much less developed than global. Our ability to foresee precisely how global climate change will impact California's climate is accordingly limited. However, the character of climate change in California may be much more in the nature of abrupt shifts, greater variability, and an increased number of "extreme events" such as droughts and floods than the long-run smooth changes in trends that have been the focus of much global-level analysis. Moreover, anthropogenically induced climate change affecting California directly will both be superimposed upon, and interact with, existing natural patterns and variation in the regional climate. For these reasons, anticipating California-specific climate change impacts is more a challenge of assessing risks and uncertainties than of making specific predictions. Nevertheless, enough is understood regarding the regional climate to anticipate *possible* impacts, and in certain cases, relate them to present day trends. These issues are discussed in the following section.

2.2 Pathways of Climate Change in California

As noted above, climate change in the coming century will probably not happen slowly, whether at the global or the regional scale. The observed and reconstructed climate record is replete with examples of how various climate elements have shifted suddenly and strongly. We can expect the climate to undergo a rich variety of changes in the next century, as natural changes add to (and perhaps interact with) changes brought on by anthropogenic climate change. From either source, however, it is important to recognize that California's complex natural and socioeconomic systems are already susceptible to climate variability and change with climatic events such as El Niño (described below), floods, mudslides, coastal erosion, droughts, fires, and heat waves affecting the state's economy and quality of life. This section will discuss some of the factors that affect California's climate and the effect that the climate has on weather patterns in the state. For a more thorough overview of the observed and projected impacts of climate change on California, consult *Confronting Climate Change in California* (Field, Daily et al. 1999), *Climate Change Impacts on the United States* (USGCRP 2001), and *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change: California* (Wilkinson et al. 2002).

California's proximity to the Pacific Ocean, the long axis of the state (which straddles latitudes from just beyond the subtropics northward to the temperate latitudes), and its diverse topography (which produces a variety of drastically different microclimates) combine to produce a unique climate with complex weather patterns.[2] Because of this

[2] For clarification, the term c*limate* pertains to the aggregate distribution of the weather at a given locale, including its statistical properties such as averages and extremes. W*eather* consists of the day-to-day events such as sun, rain, fog, warm, cold, and wind. Although climate can vary from year to year, we expect some state weather trends (i.e., warmth in the summer and rain in winter) to be relatively predictable. However, growing evidence is showing that those expectations may no longer be as valid as they once were.

complexity, large-scale Pacific/North American atmospheric patterns could respond and adjust to global climate change in a variety of ways.

The Effect of Large-scale Oceanic and Atmospheric Circulations on Climate

Two general oscillations of the ocean and atmosphere strongly affect California's climate and weather, and therefore, its habitats and ecosystems: the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Wilkinson et al. 2002).

The El Niño is a weakening of the trade winds and warming of the surface layers of the eastern and central Pacific Ocean. This effect occurs on average about every 2 to 7 years, and typically lasts about 6 to 18 months (Cayan 2002). An El Niño is accompanied by swings in the Southern Oscillation (SO), a seesaw of high and low pressure in the southern Pacific Ocean. During the warm tropical Pacific (El Niño) phase of ENSO, the wintertime Aleutian low system tends to expand, so that north Pacific storms are displaced southward and the southern part of the western United States, including Southern California, has increased likelihood of heavy precipitation, whereas, the Pacific Northwest tends to be drier. Northern California is not reliably wet or dry during most El Niño events, although it seems to be wet during very large El Niños. The West Coast, especially the Pacific Northwest, has a greater likelihood of having a mild to warm winter season during El Niños (Cayan 2002).

The PDO is a longer, decadal phenomenon, which features a recurring pattern of ocean-atmosphere climate variability that is centered in the north Pacific Ocean. It can be described as an El Niño-like pattern with a much longer time between the different phases of the oscillation. The PDO events persist for about 20 to 30 years, rather than ENSO's 6 to 18 months (Mantua 2001). The two most recent reversals of the PDO occurred in 1947 and 1977, and there are some indications that it may have reversed itself to a cold phase in the last few years (Mantua, Hare et al. 1997; Hare and Mantua 2000), as show in Figure 2 below.

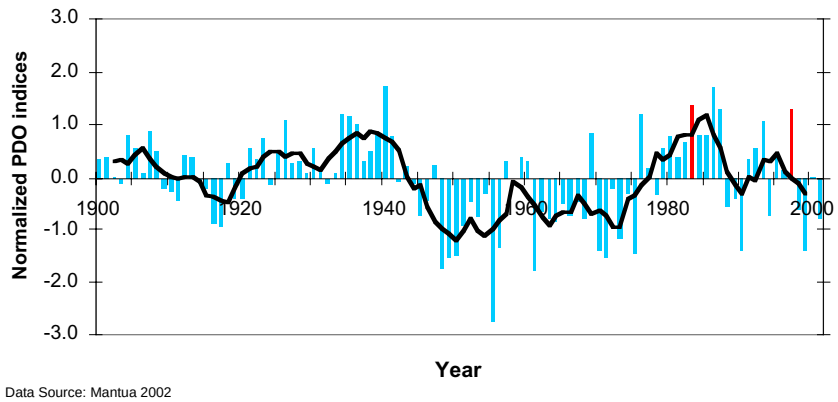


Figure 2. PDO Pattern, 1900–2000

The warm phase of the PDO is characterized by relatively cool sea surface temperatures (SSTs) in the western and central North Pacific, which coincide with unusually warm SSTs close to the west coast of North America (Mantua 2001). Changes of the PDO from one state to another produce widespread ecological changes (Ebbesmeyer 1991), such as the decline in salmon populations in Washington, Oregon, and California that occurred after 1977 (Mantua, Hare et al. 1997) under the warm phase of the PDO. A recent study of tree-ring records in California and Northern Mexico shows a close correlation between these records and the PDO (Biondi, Gershunov et al. 2001). For this reason, the tree-ring records were used as a proxy to estimate changes in the PDO state prior to the historical period—extending the record for a period of about 400 years. The data suggest the conditions in the twentieth century were unusual in comparison with the prior 300 years' data. The differences may be the result of anthropogenic greenhouse warming or just a result of natural variability (ibid.) .

Figure 3 presents the time series of an index (i.e., sea surface temperature at the equator close to the Galapagos Islands) that is used to track the evolution of El Niño events.

It is important to note that in the last 100 years, two of the most intense El Niño events occurred in 1982 and 1997. After 1977, PDO was in its warm phase, which helped amplify these El Niño events (Gershunov and Barnett 1998). Figure 3 also shows that during these two extreme El Niño events the PDO was also in its warm phase, amplifying the severity of these two El Niño events. Some modeling results using global circulation models have

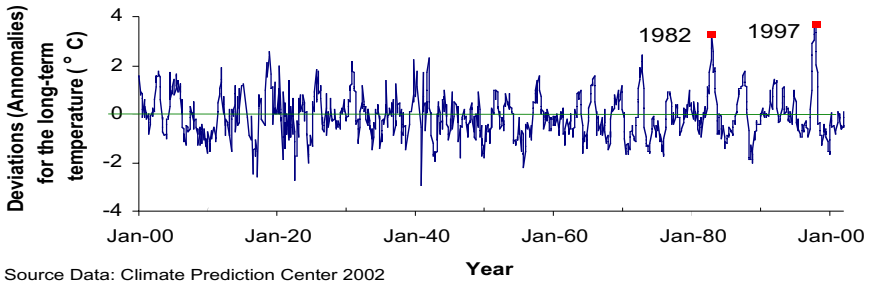


Figure 3. El Niño Anomalies

suggested that climate change will result in more frequent and intense El Niño events (Timmermann 1999, Federov and Philander 2000) but there is still no definitive consensus on this matter (Fedorov and Philander 2000). More frequent and intense El Niño events could have serious implications for California, increasing the number and severity of high-precipitation events with resultant effects on flooding. What is also troublesome is that some scientists believe that global warming may manifest itself in modes of natural climate variability, which may increase the difficulty in detecting the climate change signal (at least at the regional level) (Palmer 1999).

Increased Surface Temperatures

The U.S. National Research Council's (NRC) Committee on the Science of Climate Change confirmed that, "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising."[3]

Much data has shown that global mean surface air temperatures have risen during the twentieth century. The diurnal temperature profiles, however, have not increased uniformly. On a global scale, daily minimum temperatures are increasing at a faster rate than maximum daily temperatures (Easterling, Horton et al. 1997). In California, a similar trend (i.e., more warming at night and during spring) for the period from 1951 to 1997 was observed for the Napa region. This small increase in temperatures resulted in about a 20-day reduction in frost occurrences and a increase of the growing season length. So far, this change has been beneficial to grape growers, and has increased the quality of the wine produced in this region, but further warming may result in an increase of fungal and vector-borne disease outbreaks (Nemani, White et al. 1999).

As California experiences climate change, some extreme events, like the frequency of heat waves and very heavy precipitation, are expected to increase. Widespread, extended

[3] National Research Council. 2001. *Climate Change Science: An Analysis of Some Key Questions,* Committee on the Science of Climate Change, Division on Earth and Life Studies, National Academy Press, Washington, D.C. (http://www.nap.edu).

periods of extremely high temperatures (such as unprecedented high nighttime temperatures) are also expected to become more frequent. Higher temperatures lead to higher rates of evaporation and precipitation, so as the Earth warms, there should be more precipitation. It is likely to fall over shorter intervals of time, thereby increasing the frequency of very heavy and extreme precipitation events (IPCC 1996; Easterling, Meehl et al. 2000; Kim 2003).

Changes in the Timing of the Sierra Nevada Runoff

The last three decades have seen a reduction in the portion of the annual runoff that occurs during spring and early summer in high-elevation streams in California (Roos 1990; Dettinger, Ghil, et al. 1995). Also, the timing of the first major snowmelt–runoff pulses has come earlier (Cayan 2001). This shift seems to be correlated with changes in the warm phase of PDO in the late 1970s, but it may also be associated with a potential long-term warming of the landmass in North America. As discussed above, climate change that occurs as the result of increased GHGs in the atmosphere may also be altering the frequency and amplitude of large-scale ocean-atmospheric oscillations such as the PDO and ENSO. For these reasons, it is unclear how much of the observed changes in the timing of the Sierra Nevada runoff is attributable to natural variability and how much is attributable to a warming planet. Changes due to natural variability should reverse themselves at some point; whereas, changes due to global warming would continue in the foreseeable future.

Some models indicate that, on average, 30% of California's increased precipitation will fall in the spring and autumn, with even larger increases in winter. In addition, a greater proportion of the precipitation will fall as rain, decreasing the snowpack in the mountains. Changes modeled for the summer were not statistically significant. (Kim 2001). Timing of precipitation is important, because water systems in California are based on the concept of storing water during the wet season and in wet years and conveying that water long distance to areas of use. A substantial amount of winter precipitation has historically been stored in the snowpack, which melts as the water in reservoirs is used up, recharging them. Less snowpack means less reservoir water is replaced for use in the summer. More extreme spring storms are also likely to fill available winter flood storage space in the reservoirs. Such effects are demonstrated in a recent regional climate study that modeled the effects of a doubling of CO_2 on California climate and found that temperature increased "…everywhere in the region annually (up to 3.8°C), and in every month, with the greatest monthly surface warming at high elevations. Snow accumulation decreased everywhere, and precipitation increased in northern regions by up to 23%, on a mean annual basis." (Snyder, Bell et al. 2002).

Even though scientists concur that California will get warmer; there is no complete agreement on the level of this warming. With respect to climate change's effect on precipitation in California, the situation is also uncertain. The majority of modeling results suggest that California would experience, in general, higher precipitation levels—but there are also modeling results that suggest slightly lower precipitation levels from

historical levels (Wigley 2000, Miller 2003). For this reason, in an ongoing PIER-funded project on climate change, researchers are using modeling results that represent the widely divergent potential results with respect to precipitation (i.e., dry and wet scenarios) (Miller 2003).

Sea Level Rise

Sea level has risen in California, as shown in Figure 4. These data are in agreement with reported overall increases at the global level IPCC (IPCC 2001). Sea level rises in response to several factors, such as the thermal expansion of the ocean as it warms, glacier melting, changes in the mass of the polar ice sheets, and land motions. This last factor is attributable to post-glacial rebound and tectonic motions and subsidence from the depletion of underground oil/gas fields and removal of groundwater from aquifers. In California, significant changes of ground level from the widespread pumping of groundwater and oil have been reported for the Los Angeles area (Bawden, Thatcher et al. 2001).

El Niños usually produce heightened sea levels (often by several centimeters above tide predictions) along the California coast. Over a longer time frame, sea levels at California tide gages have been rising by about 15–20 cm (6–8 inches) per century, and most experts expect climate change to cause an additional increase (perhaps double the present rate) to this rise. Because El Niños produce higher sea levels and increase the number of vigorous winter storms, the likelihood of coastal flooding, erosion and structural damage is probably greatest during future large El Niño episodes. (Flick 1984; Bromirski et al. 2003; Douglas 2000).

All the factors that contribute to sea level change make it extremely difficult to estimate the contribution of these factors to the observed sea level changes. Modeled sea level rise in the twentieth century is lower than the observations and there is a continuous scientific debate about the reasons for these differences and the implication with regard to this and the next century (Church 2001).

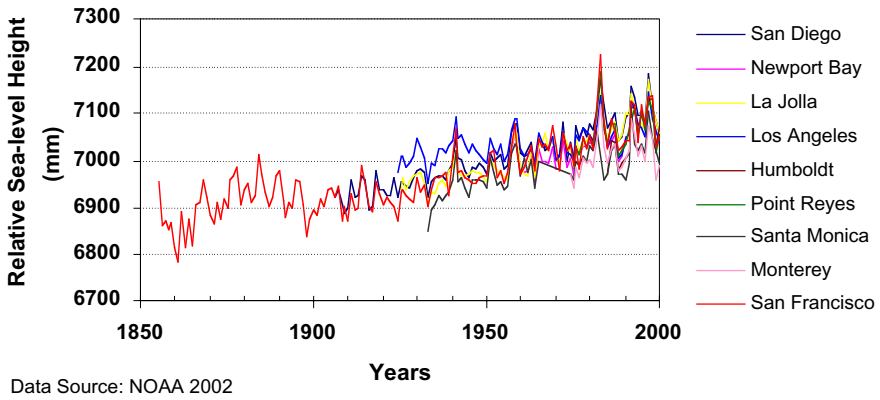
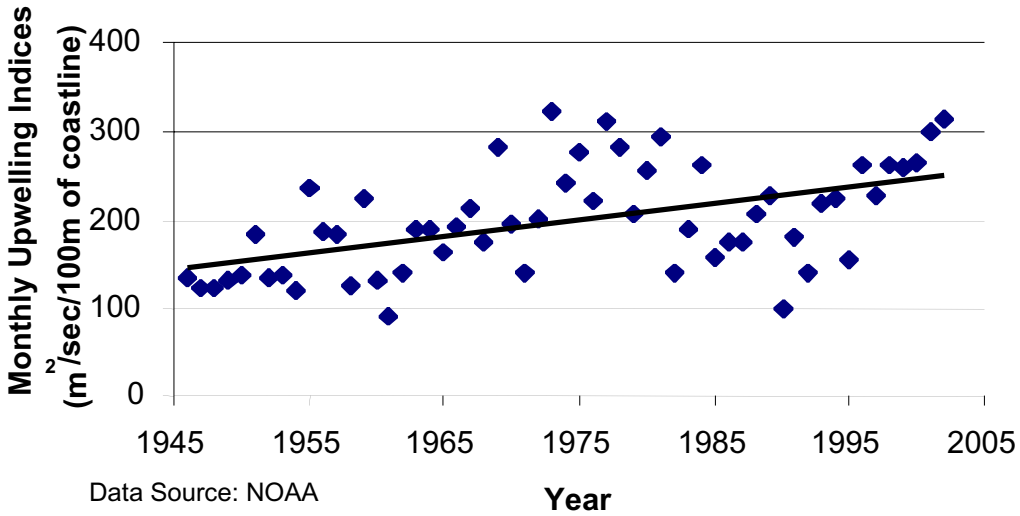


Figure 4. Sea Level Rise on California's Coast

Upwelling

In the summer, winds along the coast of California arrive predominantly from the north. The effect of the wind and the rotation of the Earth result in the movement of surface waters offshore (away from the coast), which in turn results in the vertical transfer (*upwelling*) of relatively deep waters to the surface. Upwelling brings to the surface nutrient-enriched water that supports an abundant ecosystem with valuable commercial value. In 1990, Andrew Bakun postulated that global climate change was intensifying the coastal ocean upwelling in California and in several other locations in the world (Bakun 1990). A more recent analysis for California confirms the increased upwelling along the California coast (Schwing and Mendelssohn 1997). Figure 5 illustrates this upwelling trend. This increase in upwelling, however, has not resulted in a concomitant increase in nutrients, because the region of cold water in the ocean seems to be moving to deeper levels in the ocean. In fact, from 1951 to 1993, surface waters in Southern California warmed by about 1.5°C (2.7°F) (Sanford 2002).

2.3 Potential Impacts of Climate Change in California



timing and levels of precipitation (and the affect of warmer temperatures on the extent and the duration of mountain snowpack) would alter the amount of electricity hydroelectric facilities could generate. It would also affect seasonal availability, with less water available for hydroelectric generation in the spring and summer months, when demand is highest. In addition, there is a high likelihood that dramatically changed precipitation and runoff patterns would lead to changes in broader water policies and end-use priorities, which could further limit hydroelectric production.

Regional climate change is also likely to affect energy demand in California independent of its direct effects on supply, through hydroelectric generation. In projecting these demand-side impacts, account must be taken of patterns of energy use in the state and how they interact with weather conditions. The energy industry uses heating degree-days (HDD) and cooling degree-days (CDD) to estimate energy consumption. Both measure the deviation of the daily average temperatures with respect to a given ideal temperature. In general, scientists assume that energy consumption will increase in direct proportion to the increase of these parameters. For example, a CDD that doubles from one day to another should more or less double the air-conditioning needed for comfort. Figure 6 shows that the long-term 30-year average CDD are increasing in California, at least for the meteorological stations shown in this figure. Peak electricity demand in the state occurs during hot summer days and is associated with increased cooling demand. As demonstrated by California's recent electricity crisis, increases in peak load can dramatically reduce the reliability of the electric power system and result in greatly increased costs to households and businesses. On the other hand, heating degree-days are decreasing, suggesting that less energy may be needed to keep our houses and buildings warm.

An ongoing PIER-sponsored study has estimated tentatively the impacts of higher temperatures on energy expenditures in California, taking account of the effect of higher temperatures in lowering energy consumption for heating houses and buildings. The study has found that this "beneficial" effect does not counterbalance the energy consumption-increasing effects of higher temperatures in the form of higher cooling demand. In addition, and not surprisingly, the difference in impacts would differ

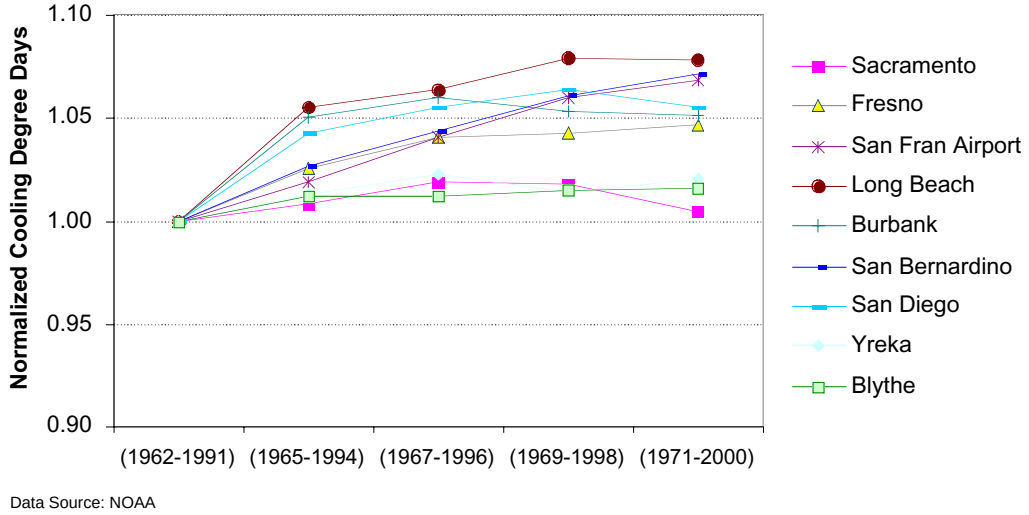


Figure 6. Normalized 30-Year Average Cooling Degree Days

significantly among California's various counties. Energy demand would most likely decrease in the state's northern and mountainous counties; whereas, energy demand in central valley and southern counties would most likely increase. The increased net energy demand (natural gas and electricity) attributable to a warmer climate would be substantial—about 20% over what would be expected under a stable climate (Mendelsohn 2003).

In addition to its role in hydroelectric production, the state's intricate system of reservoirs, canals, aqueducts, and other facilities distributes millions of acre-feet of water around the state annually for use by the residential, commercial, industrial, and agricultural sectors. The performance of this water infrastructure would be directly affected by dramatic changes in temperature and precipitation. California's engineered water systems are already overtaxed, and every major water supply source in California is beyond its physical or legal capacity to be sustained (Wilkinson et al. 2002). Currently, more than half the population depends on water imported from outside their area. Past water management practices and other factors have devastated California's natural aquatic, riparian, and wetland ecosystems, and the challenges posed by climate change and variability will add to the already difficult water problems facing the state. An early 1990s analysis estimated that water-related losses in California due to global climate warming could amount to as much as a billion dollars annually (Vaux 1991).

Threatened Ecosystems

California has a highly diverse landscape that ranges from cool, wet redwood forests in Northern California to hot, dry Mojave and Colorado deserts of Southern California, with many variations in between. As a result, the state hosts more plant and animal species than any other, including 300 natural plant and animal communities, 178 major habitat types (Schoenherr 1992), ten broad biological categories, or "bioregions" based on distinct and consistent climate zones, and 10 floristic provinces that are further divided into 24 sub-provinces (Hickman 1993). There are in the state 5,057 native and nearly 1,000 exotic plant species and 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 (ibid.).

This rich abundance of flora and fauna is already threatened by forces such as land-use changes, invasive species, and air and water quality degradation. Climate change impacts will intensify those threats through increases in temperature, changes in precipitation levels, increased atmospheric CO_2 concentrations, potential increases in extreme events, runoff, and evaporation—as well as from changing ecosystems, changes in snowpack levels, soil moisture, and sea level rise (USGCRP 2001).

Many ecosystem changes illustrate the interrelationship between California's changing ecosystems and its changing climate. The earlier onset of spring, estimated by changes in the blooming of plants (Cayan 2001), temperature increases in the Sierra Nevada since the

1940s (Dettinger et al. 1995; Karl et al. 1993), the observed increased spring salinity in the San Francisco Estuary (Knowles and Cayan 2002), and the increased intensity of larger floods in the last three to four decades in some of the major Sierra Nevada streams are some of these documented changes (Cayan 2003).

As the climate changes, the impact on California's animals, insects, and vegetation will vary, depending on a variety of factors such as their location and the number and intensity of stress factors present. Impacts could include stronger competition with non-native species; decreased biodiversity; reduced habitat as a result of temperature, fire, or drought; and increased exposure to pests and pathogens.

Several studies already report observed responses of individual or groups of California species to California's climatic changes. For example, from 1951 to 1993, there was an 80% reduction of zooplankton volume in California waters (Roemmich and McGowan 1995). Because zooplankton play an important role in the food chain, the continuation of this decline should have deleterious consequences on marine ecosystems. The increased upwelling (but with a reduced contribution of deep nutrient-rich waters) may explain the observed decline of the zooplankton (Sanford 2002). There is some evidence of the potential reversal of this decline, which may be associated with the speculated reversal of the PDO to its cold phase, as discussed above (Greene 2002, Chavez 2003).

As another example, the population of invertebrates in the intertidal zone at Hopkins Marine Station in Pacific Grove has changed dramatically since 1931. Long-term records of sea surface temperatures at this station show a sustained warming. The record shows that almost all southern species increased in abundance; whereas, most northern species decreased, indicating a migration to the north in response to warmer waters (Sagarin 2002).

Reported geographic range shift in some species are in agreement with the observed climate changes in the state. For example, populations of Edith's Checkerspot butterflies moved north and uphill in accordance with increasing temperatures in their habitat. (Parmesan 1996).

Some potential impacts are being modeled, as well. For example, under funding from PIER, researchers are studying potential robust adaptation strategies for the California coastal sage scrub ecosystem under scenarios of changing regional climate. The coastal sage scrub is home to about 100 potentially threatened or endangered species (NCCP 2002) and constitutes an excellent case study of an ecosystem affected by multiple stresses, such as increased urbanization and a changing climate. A state-of-the-science dynamic vegetation model was used to estimate potential changes in vegetation patterns in California under different climate scenarios. Also, the researchers enhanced an urban expansion model to estimate the potential increase of urbanized areas in the state up to the end of this century. The project identified areas that would "survive" both the increase reduction in habitat due to increased urbanization and would have adequate climatic conditions for survival under all the potential climate change scenarios. Two strong

messages arose from this preliminary analysis: (1) urbanization and other stresses should be considered in climate change impacts and adaptation analyses, and (2) improved projections for the regional climate are essential in order to narrow uncertainty and estimate the highest-probability scenarios for climate change in California over the coming decades.

Air Quality

The observed trend towards higher surface temperatures in California may complicate the efforts being undertaken to improve air quality conditions in the state. Preliminary modeling analyses suggest that the Los Angeles region may not be able to comply with the national ozone air quality standards by the end of this decade, because higher temperatures will increase the surface ozone concentrations. The modeling results also suggest, however, that particulate matter concentrations would be lower than expected, because higher temperatures result in less particulated nitrate formation (Kleiman 2002). In the Sacramento region, air quality regulators have also reported a tendency towards more days with meteorological conditions favorable for ozone production (surface temperatures higher than 95˚F and stagnant conditions) (Tollstrup 2002).

Economic Impacts

Understanding and quantifying the potential economic impacts of climate change in California is a major research undertaking, and one of the key elements of the plan presented in Section 3. Nevertheless, it is useful to illustrate potential impacts with examples from the historical record. The economic costs of floods, wildfires and forest fires, and excessive heat or cold are substantial. As shown in Table 1, significant flooding has occurred in recent years in California, resulting in considerable damage to property and crops. Wildfires and forest fires do not occur as frequently as floods, but can result in significant damage—especially to property; the financial loss from crop damage has been relatively less, but is still significant. Excessive heat or cold ("temperature extremes") can result in little property damage, but can lead to significant crop losses and damages—as much as from flooding or wildfires. And extreme temperatures lead to more loss of human life than the other events. As shown in Table 2, fires can be just as costly as the most severe El Niño.

Table 1. Key California Storm Events

Storm Event	Time Period	# Events	Property Damage	Crop Damage	Deaths
Floods	1/1/97–4/30/02	599	$841M	$230M	31
Wild/Forest fire	1/1/90– 4/30/02	264	$845M	$20M	3
Excessive heat or cold	1/1/90–4/30/02	113	$305,000	$846M	46

Source: National Climatic Data Center, Storm Even database: http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms

Table 2. Other Major Events in California

Event	Time Period	Damage in California
Oakland/Berkeley Fire[4]	1991	$2 billion in insured losses (at 1997 prices)
El Niño[5]	1982–1983	$2.2 billion
El Niño[6]	1997–1998	$1.1 billion

Sources: See footnotes.

Even temporary disruptions to infrastructure systems can threaten the health and economic security of individuals, communities, and the state. For example, 1998 El Niño-related storms shut down major rail lines and interstate highways, severed communication and power lines, ruptured gas and oil pipelines, overwhelmed sewage systems, and damaged water supply systems. Economic impacts across the United States were estimated to be on the order of $25 billion, and those in California were estimated to be $1.1 billion (NOAA 2002).

2.4 California Greenhouse Gas Emissions

The previous sections have discussed potential impacts of climate change on California. A complementary topic is California's contributions of GHGs to the global atmosphere, which could be subject to mitigation under future national or state policies. By way of background, carbon dioxide, methane, and nitrous oxide are the three primary GHGs produced by human activity. Carbon emissions, the largest contributor to global climate change, are attributed to four major sectors: transportation, industrial and commercial, electric utilities, and residential. The United States is the world's largest producer of GHGs, both in terms of per capita and total emissions. In 2000, the United States released

[4] Source: Insurance Services Office. 1997. "The Wildland/Urban Fire Hazard." New York, NY.
[5] Source: "The Economic Implications of an El Niño," NOAA Magazine Online (story 24). Web site: www.noaanews.noaa.gov/magazine/stories/mag24.htm
[6] Source: Ibid.

1.56 billion tons of carbon dioxide into the atmosphere. Nationwide, CO_2 emissions are accelerating. The average annual growth rate is 1.5 percent, but in 2000, the CO_2 emissions rate jumped to 2.7 percent (Shogren 2001).

The California Energy Commission maintains an ongoing effort to measure and document California's GHG emissions. The following section briefly summarizes the main findings of a recent inventory prepared by the Commission.

California's Greenhouse Gas Inventory

The Energy Commission's *Inventory of California Greenhouse Gas Emissions and Sinks: 1990–1999,* presents the Commission's preliminary GHG emissions and carbon sink[7] estimates for the 1990s (California Energy Commission 2002). The report examines CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), and focuses on anthropogenic emissions (i.e., those attributable to human activities).

Carbon dioxide emissions represent about 85 percent of the GHG emissions in California, and the vast majority of these emissions are generated from the combustion of fossil fuels. Carbon dioxide emissions from the combustion of fossil fuels have remained close to the maximum levels emitted in the mid-1970s, as shown in Figure 7.

There are several factors that explain this phenomenon. Most significantly, California power plants switched almost completely from residual fuel oil to natural gas in the mid-1970s (because of both cost advantages and regulatory restrictions). Other factors that contributed to these nearly static emissions levels include: California's innovative energy efficiency programs, increased penetration of renewable resources for electricity production, increased use of nuclear energy (from about 10,000 GWh per year in 1975 to about 30,000 GWh per year after 1988), increased fuel economy in the transportation sector, and an increase in the amount of imported electricity (California Energy Commission 2002).

[7] Natural processes can act to store GHGs, thereby reducing the total amount of GHGs emitted into the atmosphere. These processes are called *sinks,* and include land-use and forestry activities that can affect the net amount of CO_2 emissions by absorbing and storing carbon through photosynthesis.

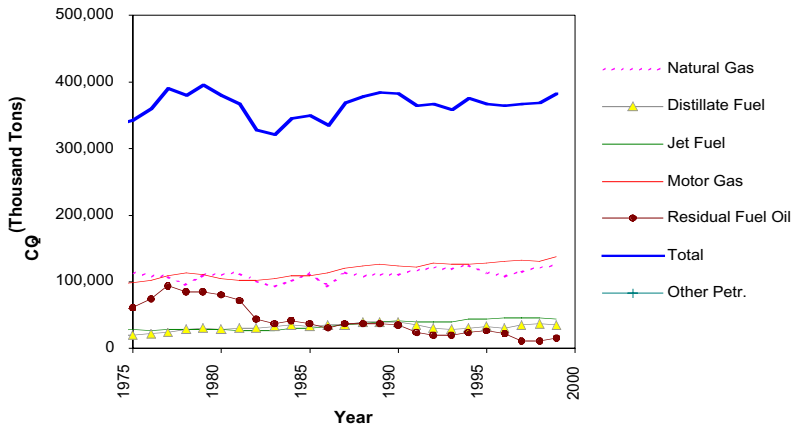


Figure 7. California Carbon Dioxide Emissions, by Fossil Fuel

The effect of energy efficiency programs is clearly shown in Figure 8, which illustrates that California's per capita electricity use has remained practically unchanged, compared to national per capita use, which has increased by approximately 1.5 percent per year.

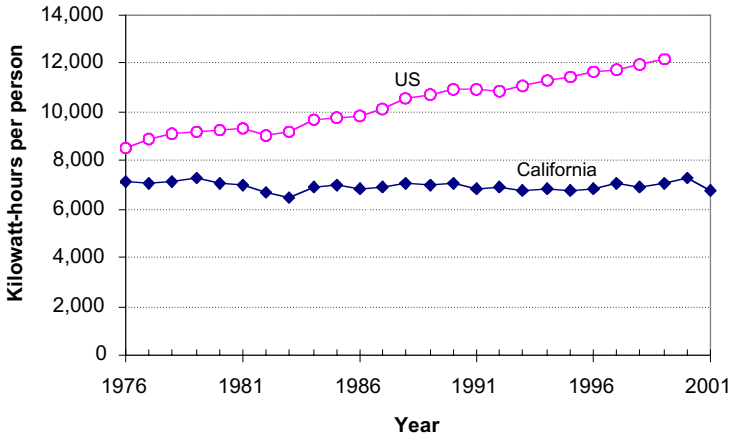


Figure 8. California Per Capita Electricity Use

Figure 9 presents CO_2 emissions from the combustion of fossil fuels per capita and per gross state product (GSP) or gross domestic product (GDP) for California and representative countries. California's emissions per GSP are lower than emissions per GDP for some of the major industrialized countries, but still higher than the emissions

from various others, including France, Sweden, and the Netherlands. On a per capita basis, California emissions are higher than nearly all the countries listed, and lower than emissions in the United States as a whole and in Canada. A similar analysis, comparing California emissions with those from other states in the United States, indicates that California's per capita and per GDP CO_2 emissions are among the lowest in the country A milder climate and a less energy-intensive manufacturing base contributes to these lower emissions, but a more energy-efficient and less carbon-intensive economy also contributes to the California's relatively flat emission levels (California Energy Commission 2002).

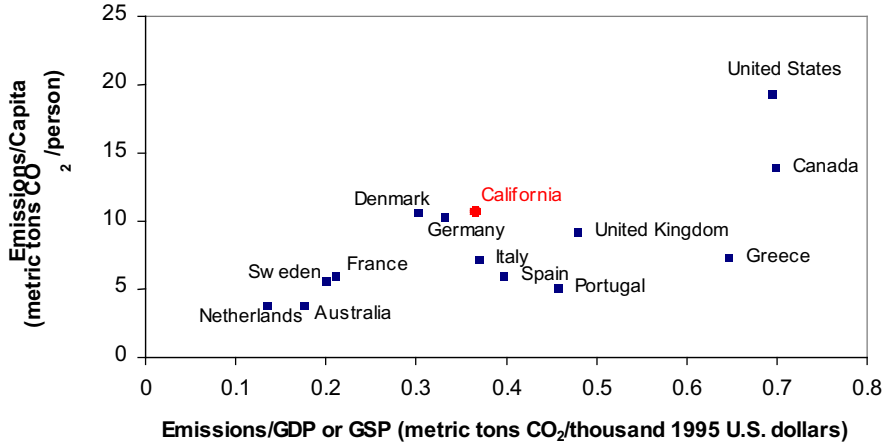


Figure 9. CO_2 Emissions from the Combustion of Fossil Fuels, Per Capita and Per GSP or GDP.

As Figure 10 shows, California's electricity production relies heavily on natural gas, hydroelectric power, and nuclear power. This is in sharp contrast with the United States as whole, which relies heavily on coal to generate electricity.

Power Plants: Major Contributors to GHG Emissions in California

In-state electricity generation contributes about 16% of the annual carbon dioxide (CO_2) emissions (about 55 tons per year) from all the sources located in the state. California's electricity consumption, however, is responsible for much higher emissions, because the state imports a substantial amount of electricity from other states—some of which is generated by coal-burning power plants. Burning coal generates about twice the amount of CO_2 per unit of energy released during combustion than natural gas, the fuel of choice in California. Even though California only imports about 30% of the electricity consumed in the state, out-of-state power plants emit more CO_2 than in-state power plants (California Energy Commission 2002).

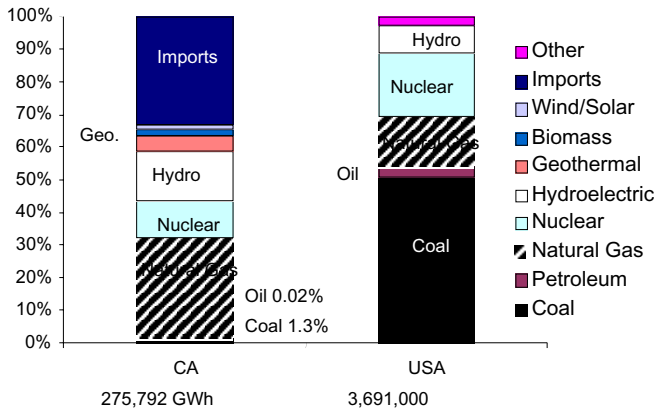


Figure 10. California's Electricity Generation Mix: 1999

2.5 Summary

The climate is changing, both globally and on a regional scale that will directly affect California. The exact details of climate change in California over the coming decades cannot be predicted, but there is a likelihood that current trends will continue or be exacerbated, and that both variability and sudden shifts or "extreme events" may increase. There is a high likelihood of not just further increases in temperature but also alternations in patterns of precipitation, including storms and the timing of rain and snowfall in the Sierras, as well as sea level rises. These various changes will affect energy production and demand, the state's extensive water infrastructure, ecosystems, and air quality.

3. PIEREA Research Agenda and Benefits

The following subsections summarize the PIER climate change research agenda. As discussed in Section 1, this agenda is based on research roadmaps commissioned by PIER, but constitutes a selection of topics in each research area that have been identified as priorities for support with the limited resources available to PIER. These priority topics were chosen according to the following criteria:

- relevance to PIER objectives,
- potential to generate useful results in a four- to five-year time frame,
- potential to inform policy decisions,
- the magnitude of potential impact on the science / art of regional impacts and adaptation analysis,
- ability to generate co-benefits (i.e., a "no regrets" strategy) , and
- potential for securing co-funding.

This research plan is intended to provide a structured California climate change program that can be enhanced and extended with collaboration and funding from other state, federal, and private entities. Potential sources of co-funding include: the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the National Center for Atmospheric Research (NCAR), the University of California Kearney Foundation of Soil Science, EPRI, the Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGS), and the Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE).

Each subsection begins with background information, lists policy-relevant questions, and describes the PIER projects or project areas selected for support. Each subsection also identifies the benefits of the selected research.

Two research areas—*Climate Change Sensing and Modeling* and *The Economics of Climate Change Mitigation and Adaptation in California*—represent this research plan's main core of activities. Improved understanding, and projections, of potential climate changes in California will be primary inputs to all other research activities. Similarly, economic analysis will integrate the PIER- and available non-PIER-funded studies into a common analysis framework, using a language and method of evaluating benefits that can inform policy initiatives.

Within the research agenda of each topic is a critical research path that connects projects that are essential for the development of tools and methods needed to answer the policy relevant scientific questions. Projects will receive either high, medium, or low levels of support from the PIER program. The medium level will consist of PIER funding combined with outside co-funding, and low levels of funding will apply to projects funded mostly with outside funding. In the latter case, PIER would provide mostly seed money to undertake these projects, but vigorously persuade other funding agencies of their

importance. In all cases, PIER will try to leverage its resources, to contain costs and maximize benefits to the state.

3.1 Climate Change Sensing and Modeling

Researchers have performed climate change impact analyses for California for more than a decade. How have they projected future climate conditions for California? Are their efforts adequate for impact and adaptation analyses? The following paragraphs will address these questions and suggest why additional work in this area is needed.

The primary tools for projecting the evolution of global climate—including potential anthropogenic changes—are general circulation models (GCMs), which are numerical representations of the basic physical processes of the entire global atmosphere. For studying regional-scale climatic phenomena, however, GCMs have a fundamental limitation: their degree of spatial resolution (i.e., the average size of the grid cells used to represent the Earth's surface) is on the order of 300 Km. Thus, to take an example from California, GCMs cannot resolve important topographic features such as the Sierra Nevada and the Coastal Ranges, as shown in Figure 11.

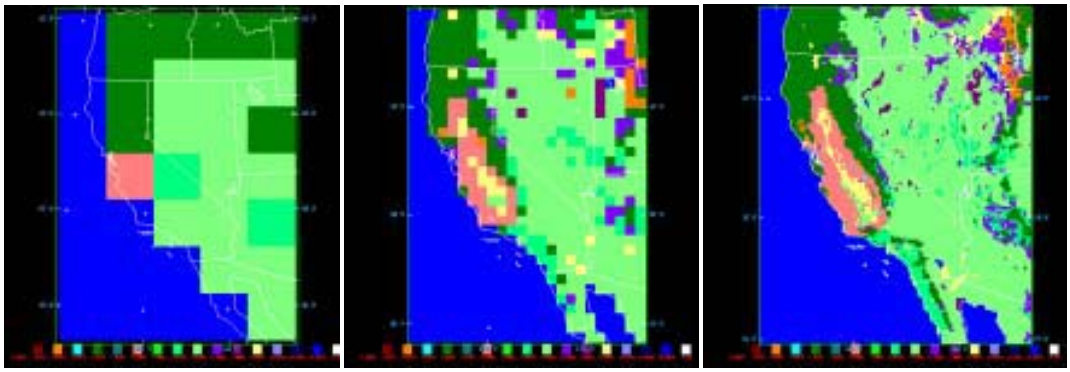


Figure 11. Differences in Resolution Among GCMs. (This graphic illustrates the mountains of California as resolved by various grid-box sizes. The resolution of most GCMs (~300 km) gives no detail of California's mountain ranges. At the 50-km resolution, common to many regional models, the central Valley and Sierra begin to be discernible; whereas, a grid size of 20 km reveals their regional structures, as well as that of the Coast Ranges.)
Source: W. L. Gates. *Modeling Regional Climate Change in California.* 2002.

Impact and adaptation analyses require climatic data at a much higher geographical and temporal resolution than that available from GCMs. Researchers have used several approaches to develop these data. For example, historical California climate data (e.g., the instrumental record of the last 100 years) have been adjusted using factors obtained from GCM outputs to estimate future climatic conditions (Miller 2003). This technique, however, remains subject to the deficiencies of the GCM modeling results at the regional

level, because the GCMs do not resolve mountainous features that are important determinants of climate in California. Dynamic or numeric regional climate models (RCMs) suggest that temperatures would increase at a more rapid rate at higher elevations (IPCC 2001, Kim 2001) so this omission is crucial. In addition, it is not clear that the adjustment of historical data by factors developed using GCM modeling outputs result in physically plausible scenarios.

Some researchers have instead used uniform climatic scenarios, which are arbitrarily prescribed constant temperature and precipitation shifts of the historical time series (Mendelsohn 2003, Miller 2003). This approach shares the same drawbacks as the previous method and, in addition, ignores the fact that most of the impacts from climate change may be attributable to increased variability (i.e., changes in weather conditions). Moreover, with this technique there is again a high likelihood that the results will not accurately portray actual physical events.

Climate information at high spatial resolution can also be obtained using dynamic numerical models and/or statistical techniques. The dynamic numerical models (mesoscale models) or regional climate models (RCMs) are similar to the global models, but they are applied to specific regions with grid cells on the order of 10 to 50 Km. The GCMs provide the lateral boundary conditions required by the regional models. Two notable recent examples of this type of work were conducted by Lawrence Berkeley National Laboratory (LBNL) (Miller 2003, Kim 2001) and the University of California at Santa Cruz (Snyder et al. 2002). Their work, however, provides only two or three estimations of potential changes in California climate from a multitude of potential outcomes. Their outputs are heavily dependent on the GCM run used to drive the RCMs. As discussed previously, there are several potential GCM modeling runs that could be used to generate RCM outputs and, in addition, the regional models could be exercised with different initial conditions (ibid.) or with a different range of options and parameters in the RCMs—potentially producing numerous plausible alternative scenarios.

These existing studies also model California's climate under two atmospheric CO_2 concentrations, which represent existing atmospheric CO_2 levels (about 340 parts per million (ppm)) and a doubling of CO_2 concentrations from pre-industrial levels (about 540 ppm). Although this information is very useful, it is now also clear that there is a need to estimate the trajectory of the changing climate with time (transient response), because the response of economic and ecological systems are dependent on how the climate changes with time (Neilson 2002, Schneider 2002).

An alternative to regional modeling is to statistically relate the output of GCM simulations to the climate (or climate-related processes) at specific locations. Such *statistical downscaling* correlates the variability of selected model variables with those observed on a smaller scale, and assumes that this relationship will apply to future climates as well (von Storch 2000). Statistical downscaling has the advantage of being relatively inexpensive to apply.

The users and developers of dynamic models argue that because numerical models mimic the physical processes involved in oceanic and atmospheric phenomena, their use ensures physical consistency among the downscaled variables, as well as between the output from the global models and the downscaled data (Kim 2001). On the other hand, some users of statistical downscaling techniques suggest that dynamic numerical models amplify the known GCM errors and that statistical techniques are preferred because they use the large-scale features that are relatively well-represented by GCM models (von Storch 2000). However, statistical techniques assume that the statistical relationships that are valid under present conditions continue to be valid in the future. This could not be the case for climate change, mainly because the future is highly likely to produce new conditions outside the range for which these relationships were developed (von Storch 2000, Leung 2003). Some scientists consider this caveat so important that they urge "…scientists to use extreme caution before adopting such empirical techniques for global change applications." (Schneider 2002). Statistical techniques may also result in physically implausible scenarios (Kim 2001).

At this time, the best approach to estimate future climate conditions at the regional level is unknown. What is irrefutable is the need for physically plausible scenarios with high temporal and geographical resolution.

Questions That PIER-funded Activities Should Try to Address

Development of climate change scenarios for California, using the best scientific tools, should be a priority for California and for the PIER program in particular. All future impact and mitigation analyses depend on the accuracy of these scenarios. PIER-sponsored research on regional climate should be designed to answer the following questions:

- How is the climate in California changing in relation to the historical and pre-historical conditions? Is this change unique?
- What are the expected signals of a changing climate in the state, and how they should be monitored?
- What are the potential changes of California climatic conditions, based on the increased concentration of GHGs in the atmosphere?
- What is the estimated likelihood of the different climatic scenarios?
- How would the frequency and severity of extreme events change in the future?
- What are the potential impacts from abrupt climate changes in the state and what would the resulting climate look like?

A focused long-term research program is necessary to develop the tools and data needed to answer these questions. The very limited PIER funds will not be able to adequately address all of these questions, but through coordination and involvement with ongoing and new efforts at the national and international levels, we hope to advance the scientific understanding needed to provide meaningful answers to these questions. For example, basic research on abrupt climate change and the development of new GCMs are areas of research that should be in the purview of national and international research institutions. At the same time, however, PIER will encourage the agencies working under the United States Global Climate Research Program (USGCRP) and Climate Change Science Program (USCCSP) to carry out much more high- resolution global circulation modeling, in order to provide more useful input for regional modeling efforts, such as the one to be undertaken in California and to better understand the possibility of more frequent and severe El Niño events, which is one of the potential abrupt changes in climate identified by the National Research Council (NRC 2002).

The research projects described below focus on California. In this subsection, the term r*egional modeling* refers to modeling that encompasses California as a region, but the modeling could include areas of the Western United States, as needed, to produce the information necessary for the California impact/adaptation analyses or necessary to ensure the quality of the modeling for the California region.

PIER Short-term Research Projects

This subsection identifies the project areas to be supported by PIER in the next three to four years. Please note that some efforts—such as the data collection activities—should be permanent and receive PIER support as long as needed.

3.1.1. Compilation and Analysis of Historical Climate and Measurement of Key Variables

A better understanding of a changing climate in California needs a strong observational component and a climate diagnostic effort to make sense of the data and to uncover associations and cause-and-effect relationships between different climatic phenomena. PIEREA will contribute to the development of a long-term climate database for California, using existing data sources and adding key measurement sites as needed. The database will be used to understand how climate has changed and is changing in the state, and for evaluation of regional models.

There are multiple data collections on California meteorological data that have not been included in a comprehensive climatic database for the state. This data includes, for example, fire and agricultural weather observations and data collected during special monitoring programs. PIER will sponsor the development of this comprehensive California-focused climate database. The quality of some of the data will need to be ensured before it is incorporated into the comprehensive climate database. Some of the older data may also need to be digitized.

In some cases, additional monitoring sites should be added. For example, there is a lack of meteorological and hydrological observations in certain remote areas of the state. This data gap is hampering our understanding of some of the important physical processes that have valuable ecological and economic importance, such as the processes involved with high elevation snow accumulation and snowmelt.[8] Numeric hydrological models used to estimate changes in runoff under different climate scenarios have been developed with very limited data from high elevations, and, for this reason, some of processes simulated by these models are ill-known and can only be inferred from indirect measurements. PIER would fund long-term measurements in key locations of parameters such as snow levels, form of precipitation (snow or rain), wind velocity, and temperature designed to gather information that will allow researchers to better understand some of these important physical processes.

For a long time, the absence of measurements in remote ecological sensitive areas has been an issue of concern. The relatively high costs associated with these collecting these measurements (because of their remote locations and the restrictions placed on measurement stations in sensitive wilderness areas) have resulted in very sparse measurement sites in high elevations and other areas. PIER will support the development of new, non-intrusive and less expensive remote monitoring systems to increase substantially the number of monitoring sites and monitoring parameters measured in key regions of the state.

PIER recently initiated a project with Scripps Institution of Oceanography to develop low-cost remote sensing environmental monitors and to install these monitors in Yosemite National Park. Scripps will make the data available to researchers on a near-real-time

[8] http://meteora.ucsd.edu/cap/snow_monitor.html

basis through the Internet. The California Department of Water Resources (DWR) will provide technical support for this project.

In addition, the National Center for Atmospheric Research (NCAR) is planning a reanalysis of climate data that would directly benefit California and could be used to determine which additional monitoring stations should be established to reduce the uncertainties related to estimating changes in climate with a finite number of stations.

The NOAA and the National Science Foundation (NSF) are currently partially funding the development of low-cost remote sensing systems, but more funding is needed to field-test these systems and to install and operate them in key sites in the state. Collaboration with other state agencies is essential for the success of this project.

Benefits: This effort would facilitate better snow-level forecasting and detection of subtle climatic changes, help develop improved models based on higher-quality and more comprehensive data, enhance the state's ability to determine to what extent the observed increase (or decrease) in cooling degree-days (or heating degree-days) is attributable to increased urbanization, and improve understanding of energy consumption patterns and climate.

The development of better climatic databases for the state would result in immediate benefits to the state. For example, the data could be used to develop statistical relationships between snow levels in given years with major climatic indices, such as those used to estimate the strength of PDO and the ENSO events, potentially allowing better forecasting of snow levels, with adequate lead time for planning.

The data could also be used to detect subtle changes in climatic conditions that are not evident when assessing the data from the existing measurement site network. The new data will allow more stringent evaluations of numerical hydrological models, which should result in more advanced and accurate models. Because these models are used for the management of water resources, including hydropower, their improvement should benefit the state even without factoring in climate change benefits.

3.1.2. Intercomparison of Regional Climate Models

Although many regional models have been used to simulate the climate over selected regions of the United States and elsewhere (Houghton et al. 2001), there has been little attempt to evaluate and intercompare the models (i.e., compare the models against each other and against observational data) at the needed resolution. The lack of standardized experimental conditions makes it difficult to identify characteristic model errors. Researchers need to identify a common nested model domain[9] and develop a regional modeling protocol. There is also a need to compare statistical methods against RCMs and historical data not used in the development of the statistical methods.

[9] A model's *domain* is the area being modeled.

Under this project, PIER will fund the development of a modeling protocol to validate and intercompare RCMs and statistical models and other promising modeling approaches. The protocol should provide different alternatives for its implementation and should indicate the levels of funding needed for the options discussed. After the modeling protocol has been developed, the PIER program will decide what option to implement and, if appropriate, proceed directly to the development of climate scenarios based on the results of models already being implemented in California. PIER reserves this option, because even though a modeling intercomparison study would be extremely useful, the high level of resources needed to undertake this effort may preclude this exercise without substantial outside sources of funding.

The intercomparison implementation should use GCMs that have demonstrated modeling results that adequately represent features of interest for California. For example, to the extent feasible, the GCMs should be able to represent the historical variability of ENSO and PDO cycles reasonably well (Collins et al. 2001). Also, researchers should develop or adapt a method from other studies to minimize the influence of poorly performing GCMs when creating ensemble simulations (Giorgi and Mearns 2002).

Benefits: Standardization of modeling protocols would enable the state to evaluate models and compare data, and identify the most appropriate RCM(s) for California applications.

3.1.3. Development of Climate Scenarios for California

The goal of this activity is to help California develop a comprehensive understanding of likely regional climate changes that will affect the State's hydrology and agriculture and natural ecosystems.

If the model intercomparison takes place, the best performing models (both GCMs and RCMs) will be used to develop future climate scenarios for California. If this activity does not take place, selected regional modeling approaches will be evaluated against historical and perhaps paleoclimatic data to ensure an adequate performance of these models and to understand the errors associated with the use of these models. In either case, the models will be used to develop ensembles of regional climate change projections, which will allow researchers to assign probability to the different climate scenarios.

The climate scenario work will be coordinated with the projects on impact and adaptation analyses to ensure that the climate modeling results provide adequate geographical and temporal resolutions for the parameters needed for impact and adaptation analyses.

Recent work by the Pielke Research Group at Colorado State University has shown the importance of considering the effect of anthropogenic land cover changes (e.g., urbanization) and changes in vegetation patterns on global and regional climate (Lu, Pielke Sr. et al. 2001); (Pielke Sr. 2002). Of course, there is a two-way linkage between vegetation patterns and climate (i.e., they each affect the other), which makes these types

of studies extremely computationally intensive, but they seem to be essential for producing realistic climate change scenarios. Some researchers are already using GCMs linked to vegetation models. The recent linkage between the Community Climate Model and the Integrated Biosphere Simulator is an example of this work (Delire 2002). At a minimum, the PIER program should explore this issue for the scenario development work.

Benefits: California would gain the ability to develop a comprehensive understanding of likely regional climate changes that will affect its hydrology, agriculture, and natural ecosystems.

3.2 Impacts of Climate Change on California Water Resources

The research roadmap on water resources (Roos 2002) identifies the following priority research items for California:

1. Monitor hydrologically important variables
2. Test operation of the Central Valley Project and State Water Project system with modified runoff
3. Model future precipitation
4. Update depth-duration-frequency rainfall data
5. Evaluate Golden Gate tide datum
6. Catalog sea level trends along the coast, in San Francisco Bay and the Delta
7. Check for recent changes in evapotranspiration
8. Estimate future changes in evapotranspiration and crop use
9. Evaluate effect on major multipurpose flood control reservoirs
10. Model water temperature in major reservoir / river systems
11. Estimate the effect of climate change on regions adjoining California

This is a daunting list of areas of research that cannot be fully supported by the PIER program, because of the limited funds available for climate change research.

The PIER program is currently funding a research project with the University of California at Davis to investigate the impact of climate change on hydropower generation. Hydropower should not be viewed in isolation from the rest of the state water system; therefore, the analysis entails the simultaneous consideration of the effects on agriculture, urban demand, and ecological resources. The researchers, headed by Profs. Lund and Howitt, are using an enhanced version of the CALVIN model for this study. Very preliminary and partial results from this study suggest that groundwater aquifers could ameliorate adverse impacts by acting as new water reservoirs (Zhu et al. 2003).

PIER, together with NOAA and CALFED, is also funding a demonstration project designed to show the benefits of modern hydrological forecasting decision analysis tools. A preliminary study for the Folsom Lake reservoir demonstrated that operational changes at this reservoir could increase hydropower production and free more water for

consumption and the environment (Yao and Georgakakos 2001). The same integrated forecast-decision system for Folsom was used to estimate the response of the system under future climate scenarios (ibid.). The study demonstrated that the system could be very effective for coping with the increased variability produced by climate change. The climate scenario analyzed is a relatively wet scenario, and therefore it is unknown if the system would also be able to handle more demanding dry scenarios. However, at least in principle, the new forecasting-decision system should be a significant improvement over the use of existing operational rules. The demonstration area covered by INFORM—a research development, technology transfer, and demonstration program for users of climate information for water resources management—includes the Folsom, Oroville, Shasta, and Trinity reservoirs. This project represents a "no-regrets" strategy that, if successful, will result in better operation of the existing reservoirs in the near future and a more flexible system that would be able to alleviate some of the potentially adverse climate change impacts.

Finally, PIER just started a project with Scripps Institution of Oceanography to develop and install a number of remote sensing devices to measure snow levels and other meteorological and hydrological parameters in Yosemite National Park. The data will be collected in a near-real-time basis, allowing detailed studies of snow-streamflow dynamics that will be extremely useful for future hydrological modeling development and validation work. The long-term operation of these stations may also serve to detect the sign of changing climatic conditions in the state.

Questions That PIER-funded Activities Should Try to Address

Hydroelectric generation is an important resource in California, representing about 20% of the electricity generation in the state. California also imports a significant amount of hydropower from the Pacific Northwest.

- How may climate change and population growth affect California's future water resources, including hydropower production and ecological systems?
- How should the operation of hydropower facilities be improved, so that the state will be able to cope (or benefit, if feasible) under the expected significant changes in precipitation levels and the timing of snowmelt in the Sierra Nevada?
- What hydrological variables should be monitored to improve our understanding of the natural and managed water systems in the state?

PIER Short-term Research Projects

The following is a list of projects designed to address the questions listed above.

3.2.1. Monitoring of Hydrologically Important Variables

Regular, consistent and sustained measurements of hydrologically important variables are essential to track hydrologically important variables and to verify model predictions. Measurements of variables such as precipitation, and other climate data

such as snowpack and streamflow should be continued. Measurement should focus on locations where significant change is expected—for example the mountain snow zone. The measurement program should also consider locations where additional measurements could allow the analysis of important processes.

The work on climate sensing and modeling will be used to identify the best locations in the state for these hydrological measurements, with the dual goal of improving our understanding of important processes and being able to detect the climate change signal as soon as possible. The latter goal will require a long-term monitoring program that should be supported by PIER as long as possible, but conclusive results should not be expected during this plan's implementation period (i.e., the next four to five years).

The NOAA and the NSF are currently partially funding the development of low-cost remote sensing systems, but more funding is needed to field-test these systems and to install and operate them in key sites in the state. Collaboration with other state agencies is essential for the success of this project.

Benefits: This work would result in an improved understanding of important hydrological processes and enable researchers to detect and interpret climate change signals as early as possible. (The latter goal would require a long-term monitoring program that should be supported by PIEREA, but conclusive results should not be expected during the implementation period of this plan.)

3.2.2. Testing the Operation of the State Water System under Different Plausible Climate Scenarios

This work will entail a study of the state water system, with an emphasis on the operation of the Central Valley Project and the State Water Project. These two major water projects furnish about 30% of California net water demand for agricultural and urban uses. The major reservoirs of these two projects are located on watersheds likely to see large shifts in runoff patterns as a result of rising snow levels (i.e., the Trinity, Sacramento, Feather, and American). At least 50 years of monthly hydrology are suggested as a minimum duration for comparisons. Currently, many studies are conducted based on data from the 1922–1994 historical period of 72 years. This longer period includes simulation during the two major six-year historical droughts (1928–1934 and 1987–1992). This work could involve enhancing the CALSIM and CALVIN models. CALSIM is the model developed by the California Department of Water Resources and used for planning purposes in the state. CALVIN is an economic-engineering optimization model of California's water supply system that identifies optimum operation conditions. It is a new model, developed under NSF. As indicated previously, PIER is funding the modification of this model for climate change studies. However, to estimate the likelihood of the idealized optimization results provided by CALVIN, a simulation model like CALSIM may be needed. These models would be used to study the impact of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes.

At this time, the INFORM project does not include the testing of the integrated forecast-decision system under different climate scenarios that will be developed under the work outlined in Section 3.1. The current phase of the INFORM project will most likely end in 2006. The PIER program should support the testing of the system developed by the INFORM project to investigate the advantages of using this reservoir operation management tool under different climate scenarios.

Benefits: The state would have the ability to study the impact of climate change on the availability of water for agricultural, urban, industrial, recreational, and environmental purposes; and conduct scenario studies of a large portion of its water system.

3.3 Impacts of Climate Change on Ecological Resources

The roadmap of research on climate change impacts on ecological resources identified the following important project areas for California:

1. Ecological assessment and monitoring using ecological indicators specific for climate change studies
2. Development of climate scenarios at adequate resolution for ecological studies
3. Enhancement and development of modeling tools to estimate future changes in vegetation patterns and ecosystems in general
4. Compilation and analyses of paleontological data to better understand past ecological responses to climate change and to test models
5. Development of an experimental and modeling research program to understand the impact of multiple stresses such as impacts form non-native species, air pollution, urbanization, and climate change
6. Evaluation of methods for incorporating climate change concerns in land use and conservation planning.

PIER is currently funding a research program designed to estimate potential changes in vegetation patterns in the state attributable to a changing climate. This study is being conducted with a state-of-the-science dynamic vegetation model (i.e., a model that estimates changes in vegetation patterns as a function of time) called MC1, which combines the MAPPS and CENTURY models (Neilson 2002). In addition, under PIER funding, a group of researchers from the University of California at Berkeley are developing plausible scenarios of urban development in the state. Both studies are being used to estimate the joint impact of climate change and urban development on a particular ecosystem (coastal sage scrub). This study represents a significant improvement from previous studies but, as discussed below, it still did not address some important issues.

Questions That PIER-funded Activities Should Try to Address

As indicated in previous sections, it is now clear that land use changes and vegetation patterns in particular may have a strong effect on regional climate and the hydrological cycle both at the global and regional levels. Of course, climate also affects vegetation patterns; therefore, they form a complex interacting system. Changes in vegetation patterns and hydrology will, in turn,

impact energy demand and the availability of hydropower. For these reasons, PIER-supported projects should be designed to address the following questions:

- What are the potential changes in vegetation patterns in California, and how would they affect and be affected by the state's climate and the hydrological cycle?
- How would urban development and climate change affect vegetation patterns in California? Would urban areas impede the migration of species, and therefore be a dominant feature determining vegetation patterns?

PIER Short-term Research Projects

The following is a list of the projects selected to address the above questions. As with all the roadmaps, the selected projects represent a small universe of the potential projects that should be funded to fully address the potential impacts of climate change in the state.

3.3.1. Enhancement and Application of Dynamic Vegetation Models (DVMs) for California

It will not be possible to assess the full extent of ecosystem responses to global climate change through experimentation alone (Aber et al. 2001). To explore ecosystem responses to multiple global changes, researchers will also need to use ecosystem models that utilize critical information from field experiments.

The PIER-funded project briefly described above greatly enhanced our understanding of potential changes in vegetation patterns in California (Lenihan et al. 2003). For example, the DVM that was used (the *MC1*) simulated 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. Although these model simulations should not 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 DVMs. Four of these drivers deserve immediate attention:

1. **Land use.** The existing 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. The role of migration corridors should also be investigated.
2. **Age structure of vegetation.** In the current DVMs, 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 DVMs. 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 DVMs 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 above 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.

Dynamic Vegetation Models should also be enhanced to consider the impact of other stressors such as air pollution. These DVMs or reduced form models (i.e., simple models that mimic the behavior of more complex models) should be used with regional climate models to investigate the interaction between climate and vegetation.

This work should be heavily coordinated with field studies to incorporate new findings in the formulation of dynamic vegetation models. The PIER program may also consider providing some seed funds for field studies with a high potential of delivering key insights for DVM improvement .

Benefits: DVMs that model interactions between a greater number of critical ecosystem factors would improve understanding of the impacts of each factor and of the interrelated systems. These models could also enable researchers to identify and interpret ecological trends more readily.

3.4 Carbon Sequestration in Terrestrial Ecosystems and Geological Formations

Terrestrial ecosystems offer significant potential to capture and store carbon at modest costs, providing net social benefits. Recognizing the importance of carbon sequestration in combating global climate change, the Kyoto Protocol to the United Nations Framework

Convention on Climate Change (UNFCCC) established the principle that carbon sequestration can be used by participating nations to meet their respective net emission reduction targets for CO_2 and other GHGs (UNFCCC 1997). In September 2002, California's governor signed into law Senate Bill 812, which requires the California Climate Action Registry to allow the registration of carbon reductions produced by the sequestration of carbon in forested lands or by reforestation.

About 31% of California is covered by forest ecosystems (Horwath et al. 2001), with much of this forestland in federal, state, and urban parklands. Most California forests can provide excellent long-term carbon storage in long-growing, woody species (i.e., for thousands of years, barring natural disasters). Changes in management of existing forested lands can increase the amount of carbon per unit of area, and restoration of trees in riparian areas offer another good opportunity. However, forest loss appears to be growing exponentially in California, where more forest land was lost between 1982 and 1997 than during the previous thirty years (Best and Wayburn 2001). In fact, the U.S. Forest Service expects the greatest loss in the next 50 years to come from the Pacific Region: Close to 20% (12 million acres) of non-industrial forest land is expected to be lost to development in California during this time (ibid.).

The agricultural sector in the state also provides excellent opportunities for carbon sequestration. This sector represents over 11% of California's land base. Plant biomass can be returned to the soil in the form of residue, different crops or varieties of crops can be selected to enhance residue production, cover crops can be grown specifically to produce organic material for the soil, and buffer strips surrounding agricultural fields can be managed for carbon sequestration.

Because the large majority of California cropland has been in production for several decades, the large initial release of carbon has already occurred and current releases are now very low (estimates range between 2.7 and 15 million metric tons of carbon annually) (Gephart et al. 1994; Lal et al. 1998). Thus, simply reducing practices that lead to carbon losses would increase carbon storage in soils. California's agricultural soils show additional promise for sequestration, because many are managed year round, which increases their value and the efficacy of using them as a carbon sequestration tool.

Bioenergy—energy derived from biomass—may be produced from purpose-grown crops or forests, from urban carbon-based residuals, or as a byproduct of forestry, sawmilling, and agriculture. Sustainable bioenergy generation results in substantial net reduction of GHGs because the carbon released during combustion is reabsorbed during the next growing season. Biomass can be utilized directly for heat energy or converted into gas or electricity for energy production (especially, small modular biomass systems, sized from 5 kW to 5 MW).[10] California's biomass resource is much larger than what is currently being used. Total biomass in wastes and residues exceed 56 million bone dry tons (BDT) per

[10] Biomass can also be used for fuels (ethanol and renewable diesel) for transportation purposes and in the manufacture of chemicals.

year—ten times the current use to date (Springsteen 2000). Of this, 16 million BDT can be considered available, with a much larger fraction available if forest fuels reduction programs and energy crops production were to be developed in California (ibid.). Bioenergy may be also one of the best options available to comply with a state law passed in September 2002 requiring that 20% of the electricity sold by electric utilities be from renewable sources of energy by 2017. [11]

Geologic sequestration is a form of direct sequestration, where CO_2 is captured from large point sources of anthropogenic emissions, transported, and injected into underground formations. Some of these underground formations have structure, seals, porosity, and other geologic properties that make them ideal for long-term storage of CO_2. Geologic formations are likely to be the first large-scale option to be considered for CO_2 storage, since developers of geologic storage technologies can draw on the experience gained from oil, gas, coal, and water-resource management (USDOE 2002a). For example, the petroleum industry is currently injecting 30 million tons of CO_2 per year into geologic formations for improving oil recovery (USDOE 2002b).

A study of geologic sequestration options for California suggests that oil reservoirs, gas fields (in the near term), and brine formations (in the long term) present the most promising geologic reservoirs for carbon in the state (Benson 2000). The sequestration of carbon in California oil fields may be an especially attractive option if it is implemented with enhanced oil recovery.

The roadmap of research on carbon sequestration identified the following priority research areas:

1. Improve the understanding of processes and mechanisms involved in carbon sequestration in terrestrial ecosystems and geologic formations in California
2. Identify and assess the technical feasibility and carbon impacts of carbon sequestration practices in California
3. Evaluate the economics of implementing carbon sequestration strategies in California
4. Evaluate the environmental and social impacts of implementing carbon sequestration strategies in California

In addition, the roadmap identified the need to develop guidelines for the design, implementation, monitoring, evaluation, reporting, verification, and certification of carbon sequestration projects in the state and the desirability to coordinate research projects with the creation of the California Carbon Sequestration Network.

The PIER program and CDF are already funding a research project designed to identify, in relatively broad terms, the opportunities for carbon sequestration in existing forested areas or by reforestation in marginal lands at the state level. The researchers are making use of the extensive databases developed by CDF regarding the characteristics and extent of

[11] This law does not include large hydroelectric facilities in its definition of "renewable" sources of energy.

forests and other land types in the state. This project also includes a measurement component for two types of sequestration opportunities (i.e., forestation in marginal agricultural lands and lengthening rotation in existing commercial forests) to be selected by PIER and CDF. That part of the project will test and demonstrate the use of remote sensing instrumentation for verification of carbon sequestration projects. The researchers will also develop monitoring protocols for the two types of sequestration opportunities selected by PIER and CDF.

Traditionally, the electricity-generating sector has been one of the first targeted for mandated emission reductions. The U.S. Congress has already considered a requirement to limit CO_2 emissions from this sector. These proposals also seem to suggest that any emission reduction requirements would allow for a flexible compliance mechanism, as was done for the Acid Rain Program (that is, power plants would be able to reduce emissions from other sources in lieu of more expensive reductions at their own facilities). Therefore, it seems prudent to start cataloging any potentially low-cost options that California electricity ratepayers may use to ameliorate or negate potential adverse economic impacts from potential requirements to reduce CO_2 emissions from in- and out-of-state power plants serving California.

Questions That PIER-funded Activities Should Try to Address

The selection of specific projects for support from the PIER program should be designed to address the following questions listed below:

- What would be the costs associated with carbon sequestration projects in the state? How much carbon would they be able to sequester? What areas are the best sites for these projects?
- What are the potential social, economical, and environmental impacts associated with the most promising carbon sequestration options in the state?
- What would be the role of bioenergy in any efforts designed to reduce GHG emissions from in-state sources?

PIER Short-term Research Projects

PIER has decided not to fund basic research projects on terrestrial carbon sequestration, because these projects are being funded by other agencies and because the limited PIER funds would not be able to make a difference. Instead, PIER will fund applied research projects to generate the information that is needed to inform policy implementation or formulation. With respect to carbon sequestration in geological formations, PIER is willing to provide seed funds to execute the project described in section 3.4.3, but most of the funds must come from other sources, due to the high costs that would be associated with this project.

3.4.1. Development of Carbon Supply Curves for Forestry and Agricultural Soil Strategies in California

Supply curves are graphs or tables showing the cost and amount associated with different sequestration options. The development of supply curves must include analyses of the potential secondary benefits and drawbacks. For example, trees placed in a riparian area between an agricultural area and a stream could help reduce the amount of pollutants from runoff that enter the stream—an added benefit. Conversely, some research has suggested that increasing carbon in soil can also increase the levels of nitrous oxide—a disbenefit.

The development of supply curves for forestry strategies in California would enhance the ongoing PIER/CDF project discussed above by adding more field measurement studies and performing a detailed analysis for one or two California counties. The studies at the county level will allow a more refined analysis, generating more precise cost estimates and more realistic carbon sequestration potential estimates.

In addition, PIER believes that there is a significant potential to sequester large amounts of carbon in agricultural soils at reasonable costs and with great social benefits. Significant field and analytical studies are being conducted outside California with support from the federal government. It is surprising that these large federally funded studies are not supporting research in California, given the importance of California's agriculture. The research on agricultural soil carbon sequestration will involve the following steps:

1. A broad scale study of the opportunities of carbon sequestration in agricultural soils in the state
2. The selection of one or two counties for detailed study
3. Detailed field studies of different promising management practices, as needed
4. An evaluation of existing models of carbon and nitrogen budgets and carbon sequestration (such as the CENTURY model) using the field data collected in the previous phase of the project and model improvement work if the model does not perform satisfactorily
5. An estimation of the costs and carbon sequestration opportunities for the selected county(ies) based on a validated model

Benefits: An economic assessment of forestry and agricultural soil carbon sequestration strategies would help decision makers prioritize those strategies, and also help agricultural and forestry specialists who are involved in allocating resources among competing alternatives. This research would also provide an economic assessment of promising forestry and agricultural soil carbon sequestration strategies. Even without considering climate change benefits, this assessment should be helpful for agricultural and forestry specialists involved in allocating resources among competing alternatives.

3.4.2. Economic Studies of Bioenergy Strategies in California

The PIER program and others are funding research designed to develop or improve technologies that use renewable sources of energy. Under this research plan, PIEREA would complement this work with analytical studies designed to identify obstacles in the deployment of these technologies and proposing solutions. The main goal is to develop an adequate understanding of the private and social costs associated with the use of bioenergy projects as a tool to reduce GHG emissions in California.

Some of the activities that may be undertaken include: (1) collect and analyze costs to farmers and foresters on energy crop cultivation in California (including collection, processing, and distribution costs that will be necessary for large-scale biomass utilization); (2) conduct life-cycle assessment of bioenergy strategies in California;[12] (3) study the economics of biorefineries, to reduce the costs of biomass collection and transport in California; (4) conduct a study of the economic feasibility of using urban carbon-based residuals for bioenergy production; (5) develop models of broad-scale biobased products and bioenergy market development, identifying the impacts of different economic scenarios and the most effective drivers and incentives within each scenario; and (6) develop models of rural development to support production, processing, and utilization of biomass.

Benefits: This project will help develop a more comprehensive understanding of the feasibility and economic factors involved in bioenergy use in California, as well as potential solutions for overcoming barriers to the use of bioenergy in the state.

3.4.3. Carbon Sequestration in Geological Formations

PIEREA proposes to support research designed to address the major technical issues associated with geologic storage in California. Research topics include:

1. Monitoring and verification
2. Risk assessment, human health and environmental impact
3. Tectonic stability
4. Economic analysis / viability of technologies
5. Leakage assessment, petroleum reservoir analogues
6. Performance assessment
7. Evaluation of novel technologies

PIEREA will not fund carbon separation technologies (separation of carbon or carbon dioxide from other combustion gases prior to injection) because other entities, including the programmatic PIER areas, are funding those technologies.

PIEREA also proposes to support the development and demonstration of storage technologies through field demonstrations. These will be collaborative efforts between research groups and industrial partners. Candidate technology demonstrations include:

[12] This work will be coordinated with other lifecycle analyses identified in the PIER Environmental Area Research Plan. Lifecycle assessments for other carbon sequestration strategies might be conducted.

1) Enhanced oil recovery, either miscible or immiscible, optimized for CO_2 storage; 2) Enhanced gas recovery, optimized for CO_2 storage: 3) Disposal in deep saline formations; and 4) Disposal accompanying subsidence mitigation.

Prior to, and parallel to, these technology demonstrations will be a site-selection study to rank potential storage sites in California.

A second parallel activity will address CO_2 sources and storage infrastructures. Present and potential future CO_2 sources need to be characterized. Compression, pipeline, and injection well infrastructure needs to be assessed.

Benefits: The identification and quantification of the feasibility, economics, and potential of various strategies for sequestering carbon in geological formations would help decision makers prioritize options. Implementation of this carbon sequestration option could result in enhanced recovery of oil and gas from California oil / gas fields.

3.5 Inventory Methods and Supply Curves

Inventory Methods

The uncertainties in GHG emissions inventories are relatively high, and that uncertainty may make it impossible to track emissions trends accurately (Rypdal and Winiwarter 2001). Carbon dioxide emissions from the combustion of fossil fuels can be estimated with sufficient accuracy and precision if the energy flows for the inventory region are known. However, this is not the case for non-CO_2 gases. There are significant uncertainties associated with most of the emission estimates for non-CO_2 gases; primarily because the complex factors affecting non-CO_2 emissions are not taken into account by the relatively simple methods adopted by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Environmental Protection Agency (USEPA). Research needs to identify the limitations of these inventory methods and develop methods that account for the complex factors that affect non-CO_2 emissions.

Supply Curves

Supply curves have been used in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. These early conservation supply curves were intended to graphically illustrate the amount of energy *savings* that could be achieved through widespread implementation of energy conservation measures, as well as the *costs* of achieving those savings. In this way, conservation supply curves were designed to allow direct comparison of the costs of saving a unit of energy with the costs of producing it. Generally, the vertical axis of the curve represents the cost of each conservation measure (usually in dollars per unit of energy saved), and the horizontal axis represents the total amount of energy savings available. Measures are ordered on a marginal, least-cost basis as shown in Figure 12 below.

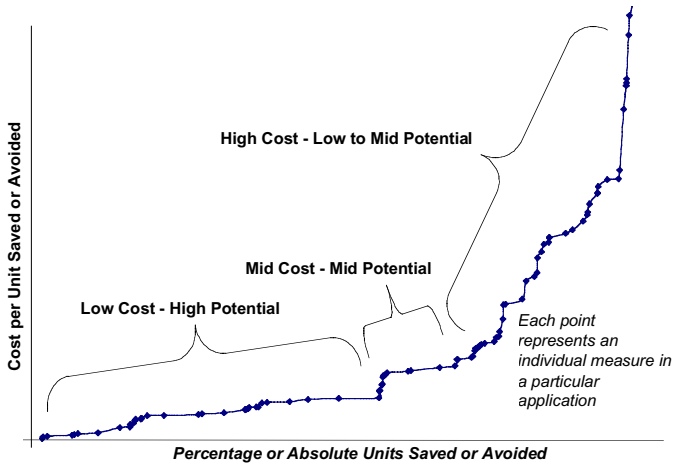


Figure 12. Example Conservation Supply Curve

Over the last ten years, the energy conservation supply curve framework was adapted and applied to the cost and benefit characterization of various GHG mitigation strategies. In these GHG mitigation supply curves, costs are generally expressed in dollars per ton-of-carbon-equivalent reduction and plotted against the total amount of carbon-equivalent reduction that can be achieved by implementing the mitigation measures.

The accuracy of estimated GHG emissions is obviously one of the most important factors in determining the technical integrity of the supply curves. For example, if methane emissions from landfills are overestimated, the estimated cost of controls (expressed in dollars per ton) may give a false impression that the control of those emissions may produce significant environmental benefits at a relatively low cost, or at a net benefit. The development of sound GHG-reduction policies are linked to high-quality emissions data.

If the Kyoto Protocol goes into effect, a formal international carbon market will be developed in the near future. It is unclear, however, how emission reductions in California could be part of this formal international market without the ratification of the Kyoto Protocol by the U.S. government. A national market could be developed as part of the voluntary programs being implemented by various states (including California) and by the U.S. government. These programs allow companies to voluntarily register their GHG emissions reductions, so that they may be considered for potential mandatory emission reduction requirements in the future. The goal is to protect companies that are reducing emissions now by acknowledging their current level of emissions reductions and taking them into account, should a cap and trade (or similar) program be instituted in the future.

An international or national market for GHGs has the potential drawback of funneling significant resources out of California to pay for emission reductions occurring outside the state. Several studies suggest that it may be more economical to reduce emissions in the

former Soviet Union or in developing countries instead of implementing "costly" local emission reductions in developed countries. These studies, however, may be misleading, because they do not consider the potential co-benefits of reducing local or national emissions. Although potentially it could be less expensive for an individual company to reduce emissions outside of the United States, such an action does not account for the indirect costs and benefits that make up the net social cost for California and its citizens. For example, reducing GHG emissions in California may also reduce conventional air pollutant emissions and result in substantial air quality benefits.

As discussed in subsection 3.4, power plants in California may at one point be required to offset their GHG emissions. To reduce the cost impact of implementing these potential requirements on electricity ratepayers, it is necessary to catalog the state's available GHG reduction opportunities, to identify the most feasible, cost-effective options.

Questions that PIER-funded Activities Should Try to Address

- What are the costs associated with reducing emission in other sectors of the economy, in comparison to those of reducing emissions from the electricity sector?
- What emission estimation methods should be improved to better characterize emissions and emission reduction opportunities?
- What methodological features should be enhanced to improve the usefulness of supply curves for policy analyses and for their consideration in macroeconomic analyses?

PIER Short-term Research Projects

The following is a list of projects designed to address the questions listed above.

3.5.1. Energy Balances for California

Carbon dioxide emissions from the combustion of fossil fuels are one of the best-quantified emissions. State and federal agencies track the consumption of major fuels such as natural gas, motor gasoline, and diesel fuel relatively well, and emissions can be estimated from that data. However, only federal agencies estimate the consumption of minor fuel such as kerosene, petroleum coke, residual fuel oil, distillate fuel oil, propane, still gas, and other fuels. These "minor" fuels have been shown to be extremely important in the determination of the CO_2 emission trends in California (California Energy Commission 2002).

Every year, the Energy Information Administration (EIA) publishes the *State Energy Data Report*, which contains energy consumption data for every state in the Union. All state-level inventories of GHG emissions are mostly based on this publication. The EIA

data is extremely well documented and available in electronic form. The EIA is the repository of fuel sales data, which is provided by organizations engaged in the trade and sale of fuels in compliance with federal law. The EIA also maintains an excellent database of fuel production, storage, and transactions for Petroleum Administration for Defense districts (PADD) in the United States. California is in PADD 5, along with Alaska, Arizona, Hawaii, Nevada, Oregon, and Washington. The EIA uses the fuel sales and PADD data to estimate fuel consumption at the state level, ensuring that all the energy flows are accounted for and add up to the reported energy balance totals for each PADD. The end results are balanced energy flows for every PADD in the nation. An energy flow balance at the PADD level, however, does not guarantee an energy balance at the state level, and it could result in incorrect fuel consumption level data at the state level.

Estimations of California emissions from crude oil refinement could be inaccurate, as well. The amount of crude oil processed in California's refineries decreased since 1990, as shown in Figure 13. Crude oil delivered to the refineries in 1999 was about 636,198 thousand barrels, which represents a 8.6% reduction from the 696,410 thousand barrels processed by state refineries in 1990. The amount of carbon dioxide associated with this reduction is about 26 million metric tons. This amount is very significant, representing about 7% of the CO_2 emissions from fuel combustion in 1990. Although California refineries have increased their productivity since 1990 (Berman and Bui 2001), it is unlikely that this productivity increase could fully explain the significant decrease in the amount of crude oil processed by state refineries, particularly while they are satisfying an increased demand for motor gasoline and other products. Some increase in the amount of imported refined products must have taken place. A significant amount of energy and CO_2 emissions are associated with crude oil refining and, therefore, the import of refined products may have also contributed to the estimated trend of emissions for in-state sources. Only a carefully designed energy balance study for California can determine the role of imports into the estimate emission trends since 1990.

Annual energy consumption and CO_2 emissions from the combustion of fossil fuels in California respond to multiple factors, such as: weather conditions, availability of hydropower, state of the economy, structural changes of the state economy, changes in

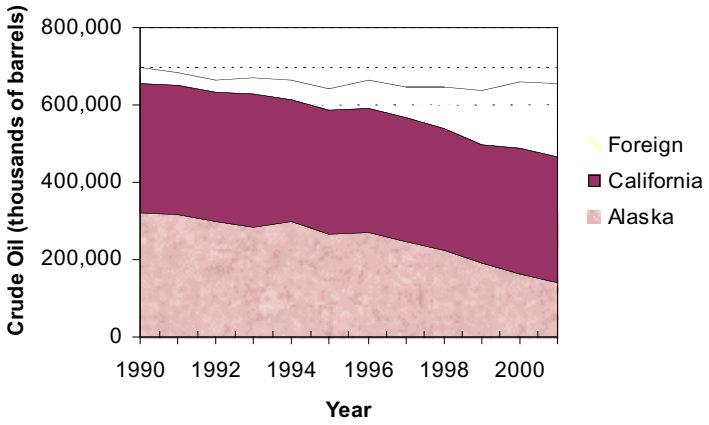


Figure 13. Crude Oil Processed in California Refineries, 1990–2001

energy standards, and regulatory requirements. It has proven very difficult to disentangle the reasons for observed changes in emissions, because there is a lack of readily available disaggregated data that would allow the factors contributing to the observed trends to be analyzed. The pioneering work that sought to understand observed energy consumption trends in California was hampered by the lack of adequate state energy balances (Schipper and McMahon 1995).

Since the restructuring of the electricity system in California, the distinction between electric utilities and non-utilities no longer makes sense. However, the energy consumption data from non-utilities is not readily available and has not been completely subjected to the same quality control procedures that utilities face, which makes data comparisons difficult. The energy balance for California will review the existing fuel consumption data for power plants in the state, regardless of their prior classification as utility or non-utility generators.

In summary, under this research area, PIEREA will fund the development of energy balances for California at the highest possible level of spatial and temporal disaggregation. This work will help researchers improve energy consumption data for California, associated CO_2 emissions data, and the analyses of energy and emission trends. The data will be also used in the economic analyses described in subsection 3.6.

Benefits: Accurate data would be available in a form that researchers can use to improve estimates of energy consumption and CO_2 emissions from the combustion of fossil fuels in California, and more data would be available for economic analyses.

3.5.2. Research on New, Improved Methods to Estimate Non-CO_2 Emissions

Some researchers have attempted to determine the level of uncertainty in the existing inventories by assigning probability to the range of potential parameters affecting emissions. In theory, this approach should work, assuming that the subjective probability distributions are close to reality. The main problem with this approach is that in some cases, the basic equations or methods used to estimate emissions do not incorporate all the parameters of importance to estimate emissions (i.e., the equations are essentially incorrect). For example, the standard method used to estimate nitrous oxide emissions from fertilizer applications assumes that emissions are directly proportional to the amount of fertilizer applied to the land. It would follow, then, that one could estimate reductions in nitrous oxide by measuring the reduction in the amount of fertilizer applied to the soil. However, studies have shown that significant reductions in nitrous oxide emissions can be accomplished by simply changing the *timing* of the fertilizer application, producing more pronounced results than those that would expected by just looking at the reduction in the amount of fertilizer applied to the soil. In this case, the standard method would significantly underestimate emission reductions.

Work on this area of research would start by: (1) studying the level of uncertainties associated with the different emissions sources, (2) identifying potential new sources not being considered in existing inventories, and (3) prioritizing which methods to study in detail with field studies and/or model development work. An example of a potential new source of emissions not being considered in the existing inventory is composting. The current assumption is that composting is an aerobic process that does not result in nitrous oxide and methane emissions. In practice, however, composting may generate substantial amounts of GHG emissions, because anaerobic pockets inside the composting pile create ideal conditions for methane and nitrous oxide generation. This distinction is important because composting is an important state strategy being used to reduce the volume of the waste prior to its burial in landfills.

Benefits: Standardized methods to estimate non-CO_2 emissions could be developed, based on more comprehensive, California-focused data. Accurate estimates are necessary for the development of sound emission reduction options.

3.5.3. Development of Supply Curves for California

Research in this area will be heavily coordinated with the inventory methods development work described above. In addition, a number of methodological and macroeconomic integration issues will be studied and implemented.

The roadmap on supply curves commissioned by PIEREA (Rufo 2002) identified a number of ongoing and planned studies developing supply curves for California for the electricity sector. These supply curves mostly consider existing technology and have a time horizon of about 20 years. PIEREA will take these studies and advance the science/art of supply curves by developing methods to extrapolate these relatively short-term supply curves to much longer time horizons that take into account potential technology changes. This project will also advance the science/art by developing curves that identify the adoption barriers of the different options included in the supply curves and their effect on the actual performance of the different options. This process will include the consideration of non-energy costs and benefits that are traditionally not quantified in the development of these curves. It is often difficult enough within the scope of many studies to quantify direct costs and benefits of measures, much less indirect ones. Nonetheless, identification and quantification of indirect costs and benefits is critical to improved modeling of adoption and would increase the credibility of many studies.

The PIER program will also develop the information needed to include the options identified in the supply curves studies in macroeconomic analyses. The addition of this information will allow for the simultaneous consideration of multiple factors that cannot be considered in the preparation of supply curves. For example, changes in energy prices will change the attractiveness of the different options included in the supply curves, but they can only be considered in a dynamic fashion through the use of computable general equilibrium models, or at least partial equilibrium models. These

models simulate the entire economy or the part of the economy that is affected by the action considered, and therefore can capture the interaction of the different options or measures with the rest of the economy.

Benefits: This work would develop dynamic supply curves that researchers can use to estimate the long-term costs and benefits of GHG-mitigation measures, over a larger portion of the economy, to make direct comparisons between competing options.

3.6 The Economics of Climate Change Mitigation and Adaptation in California

The previous sections have described how PIER research will improve our knowledge of regional climate change, potential climate impacts on California's ecosystems and water resources, and the possibilities for biological and terrestrial carbon sequestration in California. Integrating and applying the results of this work to policy-making is a primary goal of PIER-sponsored economic research. Economic methods are the primary tools for evaluating the socioeconomic implications of climate change and the costs and benefits of policy responses. Economics is also the primary disciplinary source of theoretical and computational tools for integrating climate science and policy.

Several decades of research on the economics of climate change at the national and international levels—as well as recent PIER-supported work specific to California—provide a foundation for new PIER-sponsored research on the economics of climate change in California. This section summarizes the specific topic areas, and reflects the need for PIER research to address two broad categories of questions:

1. How can the state's policy-makers better understand the complex and uncertain nature of potential climate change impacts on the state's economy, how should we address the economic risks they entail, and how should policy actions be coordinated across different sectors of the economy and different regulatory areas?
2. How can California design and implement cost-effective policies for GHG abatement, how will these policies affect that state's energy system, and how can we ensure that reducing GHGs in California does not impede the state's continued economic growth and vitality?

More precisely, PIER research will address the following questions:

Questions That PIER-funded Activities Should Try to Address

- How will the impacts of climate change and measures to abate GHGs affect the California economy in the coming decades?
- What are the key economic risks for California from climate change, and what are the particular risks from abrupt and/or extreme climate change?
- How will climate change affect the state's integrated water/agricultural system, and what will be the costs and benefits of policies to address potential impacts on this system?
- What are the costs and benefits of both price and non-price-based policies designed to increase energy efficiency in the California economy?
- How will energy-saving technological change affect the costs of carbon-abatement policies in California?

- How should California design regional markets for emissions trading?
- How should GHG-abatement and air quality policies be integrated?
- What are the costs of abating non-CO_2 GHGs?

PIER Short-term Research Projects

PIER's roadmapping process has identified a series of priority topics that would build upon and extend both previous economic research and PIER's current economic research (which is summarized in this section). It must be emphasized that these topics do not constitute an exhaustive list of needed research on the economics of climate change in California. Instead, they have been singled out because they have a strong potential for providing innovative advances that will be particularly relevant to the state's climate policy planning.

The specific research topics reflect three broad themes:

1. **Risk and Uncertainty.** There is a need to view climate change in California as a problem in the economics of risk and uncertainty, directly confronting the fact that we cannot precisely predict climate change, the future evolution of the state's economy, or the exact details of climate/economy interactions.
2. **Economics of Energy.** There is a need to improve our knowledge of the economics of energy, particularly in regard to the costs and benefits of policies that increase energy efficiency.
3. **Integrated Policy Making.** There is a need to carefully integrate climate-related policies with other economic and environmental policies, particularly those involving fiscal and air quality issues.

3.6.1 Integrated Modeling and Impact Analysis

The dominant tools in economics-based climate policy analysis are numerical models of an entire (usually national or world) economy. These computable general equilibrium (CGE) models represent the detailed interactions of supply and demand and the decisions of households and firms, typically over long time scales. In energy and climate applications, they are used to estimate the costs of price-based policies (carbon or energy taxes, or tradable emissions permit systems) to reduce GHG emissions, as well as the costs of climate change impacts.

A first step in PIER research will be to adapt an existing CGE model of California to estimate the potential impacts of climate change and GHG mitigation policies on the overall state economy. This effort will provide a benchmark for further work and a first assessment of the possible aggregate economic impacts of climate change and GHG policy on California. This modeling will be based, in part, on the new California energy balances described in Section 3.5, which will ensure that energy demand flows in the state are modeled accurately. In addition, the state CGE modeling effort will provide an initial integrating framework that will incorporate results of the PIER research on water and agriculture, energy demand, technological change, and other key areas. For example, this

CGE modeling will be able to apply the results of the PIER research on costs of forest and soil carbon sequestration from Section 3.4 to the study of the costs and benefits of carbon abatement policies in California. The CGE work will also analyze the potential for California to implement "revenue recycling"—that is, to use proceeds from measures such as auctioned tradable GHG emissions permits to reduce taxes on consumption or capital investment, or otherwise improve the state's fiscal balances.

The PIER plan for computational modeling reflects a well-known limitation of the standard CGE approach. This type of model is typically deterministic, which means that it assumes that all future events—whether purely economic or involving climate change impacts—are perfectly known. Although such an evaluation can provide a useful first approximation in many instances, this assumption is clearly problematic for application to climate policy, for a variety of reasons. First, on the time scales involved (decades or more) perfect foresight becomes implausible, even in the absence of climate change. Second, exact prediction of regional climate change is beyond scientific capability and likely to remain so; instead, regional climate science can provide as an input ranges of possibilities of how global climate change may impact California. Third, it is well-established that estimating the economic costs of GHG abatement depends on assumptions regarding future technological progress, particularly relating to energy efficiency, which is in turn is difficult or impossible to predict.

For these reasons, PIER will support the development of a new modeling framework to analyze the economics of climate change in California that will take account of risk and uncertainty. The appropriate design of this framework will be the first focus of research, for this effort will take place at the current frontiers of modeling. A primary aim of this work will be to determine how to achieve a reasonable level of model detail while maintaining computational tractability. From a policy perspective, the goal of this work will be to enable policy-makers to determine robust strategies in response to uncertain climate, economic, and technological change: these are dynamic policies that have a high —but not certain—likelihood of success across a wide range of possible futures.

This decision-analysis framework will be particularly important for applying the results of PIER work on regional climate change to policy analysis and implementation. This work will provide a large range of plausible scenarios for the future evolution of the regional climate, rather than one or a small number of "best guesses." A risk-and-uncertainty-based integrated modeling approach is essential for policy-makers to analyze the economic implications of different scenarios and to identify the most effective ways to manage the risks they entail.

Both the CGE modeling and new decision-analysis framework will be used to integrate and apply findings from new PIER research on the sector-specific impacts of climate change in California. Previous work on climate impacts has documented the potential vulnerabilities of both natural and economic systems on international, national, and regional levels extensively. Current PIER-funded work on California-specific impacts is assessing potential impacts and costs associated with specific sectors and systems, as well

as identifying possible adaptation or mitigation measures to address these impacts; the focus of this work includes agriculture, water, ecosystems, and timber. To extend this research, PIER will focus on better understanding key risks and uncertainties, and develop models that will enable policy-makers to address them effectively, emphasizing the following topics.

First, almost all work to date on climate impacts—including PIER's current work on California—has been based on the assumption of gradual, smooth climate change. There is increasing recognition and concern among atmospheric scientists, however, that climate change in the coming century may entail abrupt and/or extreme shifts, whether at the global or regional level. From the standpoint of economic analysis, this difference is critical: low-cost adaptation is likely to be difficult or impossible in the case of abrupt or extreme changes; therefore, the economic impacts will be larger. Accordingly, PIER will emphasize this type of potential climate change in its economic research.

Second, standard economic models typically assume optimal behavior on the part of households and firms, and do not represent institutional factors such as policy or regulatory constraints on economic decisions. Like the "perfect foresight" assumption discussed in the previous section, these assumptions provide a useful benchmark in many applications, and dramatically simplify certain technical aspects of modeling. However, they are problematic in analyzing critical economic aspects of climate change. California sectors and systems that may be most vulnerable to climate change—such as the integrated water, energy, and agricultural system—operate under substantial institutional constraints. These existing "real-world" factors will play a major role in the state's formulation of policies to address climate change. Similarly, the decision rules actually used by economic agents may deviate considerably from the ideal posited in the standard economic treatment.

PIER will focus research that addresses these issues (i.e., non-smooth climate change, institutional factors, and realistic decision rules) on California's water and water-related sectors. In California and neighboring states, a major pathway by which increased climate variability and change will affect the region's society and economy is through the impact on streamflow within the region and on the region's developed water supply. Any change in the developed water supply will have important consequences for the allocation of water between agricultural water users, urban water users, hydropower generation, and in-stream uses of water for water-based recreation and ecosystem services. Each of these stakeholder groups may face increased costs and/or reduced benefits as the result of a reduction in the reliability of water availability.

The goal of this research is to assess the impacts on each sector from a change in water supply reliability. Researchers will develop a set of quantitative and explicitly probabilistic measures of water supply reliability for the various agricultural and urban users of water at different locations around the state, using existing climate conditions, and based on the actual experience of the operation of the California water system over the past 20–30 years (since the early days of the State Water Project). Researchers will then use these measures

to develop sets of marginal benefit functions, showing the incremental benefit or losses associated with changes in the reliability of water supply for agricultural users, urban users, and hydropower generation at various California locations. This analysis will utilize the empirical measures of supply reliability under existing conditions for agricultural and urban users in different parts of the state, which will be derived from the hydrologic analysis described above. A third research component will develop projections and analyses of water use and electricity demand, taking account of location and housing density. PIER research will estimate both the monetary and non-monetary magnitudes of these impacts, incorporating several methodological innovations that will reflect the research priorities described above: explicit treatment of the surface water supply system, inclusion of regulatory and legal constraints on the existing process for water allocation, and representation of the actual decision rules employed in California's water system.

Benefits: This effort would provide a benchmark for further work and a first assessment of the possible aggregate economic impacts of climate change and GHG policy on California. The state CGE modeling effort would provide an initial integrating framework that would incorporate results of the PIEREA research on water and agriculture, energy demand, technological change, and other key areas. In addition, this research would provide improved theoretical and empirical tools for understanding the potential impacts of climate change on California's integrated water/energy/economic system, as well as the costs and benefits of potential adaptation and mitigation measures associated with this system. Ultimately, this work would enable policy-makers to develop robust strategies in response to uncertain climate, economic, and technological change.

3.6.2 Energy Efficiency and Technological Change

California's energy system will be a major focus of carbon mitigation policies, whether undertaken directly by the state or implemented as part of broader national or international efforts. Thus, estimating the costs of carbon abatement from a number of policies directed at altering energy demand patterns—including tradable carbon emissions permits, vehicle emissions limits, and end-use energy-efficiency standards—will be a central challenge for California's policy-makers. Although the potential magnitude of these costs has been the central focus of the economic aspects of climate change, that discussion remains extremely contentious.

PIER will therefore sponsor research to improve policy-relevant methodologies and help researchers better understand how economic decision-making and the character of existing markets determine the costs of increasing energy efficiency and/or abating carbon emissions. These advances will in turn provide California's policy-makers with improved tools for implementing carbon mitigation policies. This research will be integrated with that on supply curves (described in Section 3.5.3), to improve the theoretical and empirical basis for the supply curve methodology.

The first area of research focuses on the degree to which energy-efficient technology is optimally allocated by markets in the absence of policy intervention. The focus of this

debate has been the so-called "energy efficiency gap": the putative under-adoption of such technology without government policies to encourage (or compel) it. (This is also commonly referred to as the "top-down/bottom-up" debate.) Technologists have consistently argued that the gap is both real and substantial; whereas, economists have strongly questioned this claim on both theoretical and empirical grounds.

The persistence of this controversy has significant policy implications. California has a substantial investment in—and indeed has been a leader in deploying—policies based on the "bottom-up" perspective, such as appliance energy efficiency standards and utility demand-side management. Looking ahead, such policies will almost certainly form a major component of California's carbon mitigation efforts. According to standard economic models, the benefits of these policies cannot exceed their costs. This is a quandary demanding careful attention from economists and technology researchers.

PIER research will aim to understand the sources of this dispute both empirically and theoretically and to develop improved empirically based economic models of energy-efficiency decision-making. The first phase will examine carefully the literature on the "gap," to determine the robustness of findings in this literature to sources and quality of data, the soundness of the theoretical models employed, and the role of assumptions regarding market structure. The second phase will develop new models of consumers' and firms' efficiency-related choices, building on the insights and methods of behavioral economics—a rapidly developing field that integrates theoretical economic methods with the insights of cognitive psychology and other social sciences, and grounds theoretical models firmly on detailed empirical observation.

The second research area is the measurement and modeling of energy-related technological change. It is well-established in energy modeling literature that assumptions regarding technological change have a substantial impact on modeled estimates of the costs of reducing energy demand or carbon emissions. Traditionally, energy-economic simulation models (such as the CGE models discussed in Section 3.6.1) have represented technological change as "autonomous" or "exogenous," that is, influenced neither by the workings of the market system nor by policy actions on the part of government.

In recent years, however, economists have made significant progress in understanding the processes of technological innovation and change in a modern economy, and in developing theoretical and empirical models that represent these processes. A central theme in this research is that technological innovation and invention are *economic* activities that respond to incentives and market forces —that is, that they are endogenous to the economy. A related phenomenon is known as "learning-by-doing," the decline in the cost of producing a technology that results from manufacturing experience.

Both endogenous technological change and learning-by-doing phenomena have recently begun to receive the attention of the modeling community, and preliminary results strongly indicate that including either phenomenon in a CGE or other simulation model has significant effects on modeled estimates of the costs of reducing energy consumption

or carbon emissions. They are therefore important potential components of the economic modeling of California's economy and its response to GHG-reduction policies. The PIER program will support research on endogenous technological change and learning-by-doing in order to better understand the significance of these phenomena in California industries, and their implications for climate policy, and to better model the overall state economy in the context of GHG abatement studies. Researchers will first develop case studies on selected state industries to model and measure learning-by-doing and its relation to other key parts of the industrial innovation process, such as the adoption and diffusion of new technology. Second, they will study ways of incorporating both endogenous technological change and learning-by-doing in the program's CGE modeling (see Section 3.6.1) and in the new computational modeling framework that will be developed. The work will focus both on technical issues involving the numerical solutions of models with these elements, and on applied policy studies.

An important area of research related both to the energy-efficiency gap and to technological change is the rapidly increasing role of information technology (IT) in the California economy. There is an emerging consensus that IT may be shifting the American economy to a higher level of aggregate productivity. At the micro level, IT is dramatically changing the nature of many business practices, with potentially significant firm-level productivity effects. The implications of the IT "revolution" for energy trends, however, remain to be explored for the most part. The relationship between IT and energy could have significant implications, both for the design of policies to mitigate GHG emissions and for the response of the larger economy to these policies. This is true not just for the national economy, but also for California in particular, where IT plays a substantial and increasing economic role. Current levels of funding do not allow for a specific PIER research project on IT and energy. Because of the potential importance of this area, however, PIER will actively seek co-funding to study how IT may affect California's energy system and its response to carbon abatement policies. This work would examine the relations among economic growth, IT diffusion, and energy consumption in the overall state economy, as well as the detailed economic characteristics of IT-based energy management and control technologies in households and firms. The results of this work would be incorporated in the CGE and further aggregate modeling sponsored by PIER.

Benefits: This project would help improve understanding of the role of energy efficiency in reducing GHG emissions by quantifying benefits and costs from these measures and exploring the optimal implementation and use of energy efficiency technologies for this purpose.

3.6.3 Non-CO_2 GHGs and Markets for Emissions Trading

Economic modelers have recently called attention to the importance of integrating CO_2 with other GHGs in devising mitigation strategies. Their findings include substantial cost reductions resulting from a multi-gas (as opposed to a CO_2-only) approach to reaching GHG concentration targets, with little difference in climate or ecosystem effects between the two. At the same time, it is known that a number of policies to control CO_2 emissions

would also reduce emissions of other pollutants, with important implications for regional air quality. Moreover, these reductions would yield health and other benefits on a much shorter timescale than that applying to climate-change-mitigation effects of CO_2 reductions. As a consequence, the costs of CO_2 mitigation actions are likely to be reduced once analyses account for these "co-benefits" or "ancillary benefits."

Such results demonstrate the importance of integrating carbon and non-carbon mitigation measures both analytically and in the formulation of California policy. Given the State's strong commitment to maintaining air quality, as well as the likelihood of broad climate-related mitigation efforts in the coming decades, PIER will support research on developing a multi-GHG approach that fully exploits potential synergies and reaps ancillary benefits. Simultaneously, PIER will fund research to improve the methodology for constructing marginal cost or supply curves for non-CO_2 greenhouse gases. The aim here will be to develop a theoretical model that allows for empirically verifiable negative cost abatement as well as cost-reducing technological change. This work will be integrated with that described in Section 3.5.2.

Emissions trading has emerged in recent years as a favored instrument for reducing GHG emissions, specifically as an alternative to direct government regulation of emissions through "command and control" measures. An emissions trading system imposes a cap on the total emissions of a pollutant while providing incentives for abatement to be undertaken by whichever emitters can do so at the lowest cost, thereby minimizing the aggregate cost of meeting the overall emissions cap. Emissions trading gained considerable currency as a result of its successful implementation in 1990 to reduce SO_2 emissions from electric power generators. Looking ahead, there is a very high likelihood that some form of emissions trading system—national, international, or both—will eventually be put into place to achieve GHG mitigation targets.

In the meantime, however, smaller-scale trading regimes are being studied and in some cases implemented. The PIER program will sponsor a feasibility study for a California intrastate trading market. This study will identify and examine the appropriate geographical and sectoral scope, which GHGs would be included, the required institutional mechanisms, and related elements. It will also address implementation issues in the context of emerging (or by-then established) national and international policies. The goal will be to determine the appropriate elements of a regional trading market, whether implemented as a stand-alone state response to climate change or in response to national or international agreements.

Benefits: Multi-GHG reduction strategies would expand and speed air quality benefits, at a lower overall cost. Development of a regional GHG trading market could also speed GHG-emissions reduction.

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Attachment I

Modeling Regional Climate Change in California

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Executive Summary

This roadmap addresses the issue of regional climate modeling, with the purpose of identifying those research issues that need to be addressed if California is to respond in an adequate and timely manner to future climate change. Climate changes in California, especially in the winter precipitation, may have serious impacts on the state's water and energy supply, while changes in coastal and regional climates may affect the state's economy and resources in significant ways.

There is presently considerable uncertainty surrounding the possible future climate changes in California, and research needs to focus on the quantification and reduction of these uncertainties. It is expected that improved high-resolution regional models will be able to portray the magnitude and distribution of future climate changes in California with significantly more certainty than now available, including (but not limited to) the expected changes in temperature and precipitation. To this end, PIER should support a balanced research program in which projects focus on the evaluation and intercomparison of regional climate models for California, the development of improved statistical downscaling techniques for hydrologic applications, and the assembly of a regional California climate databank.

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

Objective	**Projected Cost ($000 per year)**
Design a model intercomparison protocol	800* (for both)
Perform control simulations and analyze results	
Evaluate downscaling methods	400* (for both)
Analyze errors of hydrologic applications	
Develop a California climate database	600* (for both)
Develop a data access system	
Total Short-term Cost per Year	**1,800**

Note: An asterisk (*) indicates a high probability that approximately equal funding will be available for each project from other sources. The figure given is the California Energy Commission's projected per-year expenditure over the short-term period.

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 an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

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 in the area of modeling regional 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 done to address issues of modeling regional climate change.

Acronyms

ACACIA	A Consortium for the Application of Climate Impact Assessments
ACPI	Accelerated Climate Prediction Initiative
ARB	California Air Resources Board
CDEC	California Data Exchange Center
CCPP	Climate Change Prediction Program
DOE	U.S. Department of Energy
DRI	Western Regional Climate Center at the Desert Research Institute (University of Nevada)
ENSO	El Niño–Southern Oscillation
EPRI	Electric Power Research Institute
GCM	global general circulation model
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
PNNL	Pacific Northwest National Laboratory
PIRCS	Program to Intercompare Regional Climate Simulations
RCM	Regional climate model
SIO	Scripps Institution of Oceanography
USGS	U.S. Geological Survey
USGCRP	U.S. Global Change Research Program

1. Issue Statement

It is necessary to develop more accurate regional climate models that will provide physically realistic estimates of potential changes in key variables as part of California's climate change impact assessment process. It is also necessary to design and implement a coordinated regional climate modeling program for the State.

2. Public Interest Vision

Regional climate modeling attempts to provide a more detailed spatial depiction of possible future climate changes than that provided by the conventional global models. From the information provided by regional models, other models (either dynamical or statistical) may in turn address local or site-specific variables such as snow accumulation or river runoff as part of the climate change impact assessment process. Regional models thus bridge the gap between the large scale and the local scale on which most impacts of climate change actually occur. The need for such information is especially strong in California, where complex mountain ranges and an extended coastline support a variety of regional and local climates. There is also need for improved information on the occurrence of extreme events, such as floods, persistent El Niño conditions, and extended hot spells. The consequences of climate change may be particularly serious in California, in view of the threats to the state's water supply and power infrastructure (Gleick 1987). The design and implementation of a coordinated regional climate modeling program for California is therefore an important challenge.

Implementation of this roadmap will reduce the uncertainties in the projection of future regional climate changes in California, and will thereby provide guidelines for the more effective management of the state's water and energy resources in the face of the expected increases in population and development. Completion of the recommended research program will significantly advance our knowledge of the expected regional climate changes throughout California, and will serve as a model for similar studies in other states and regions.

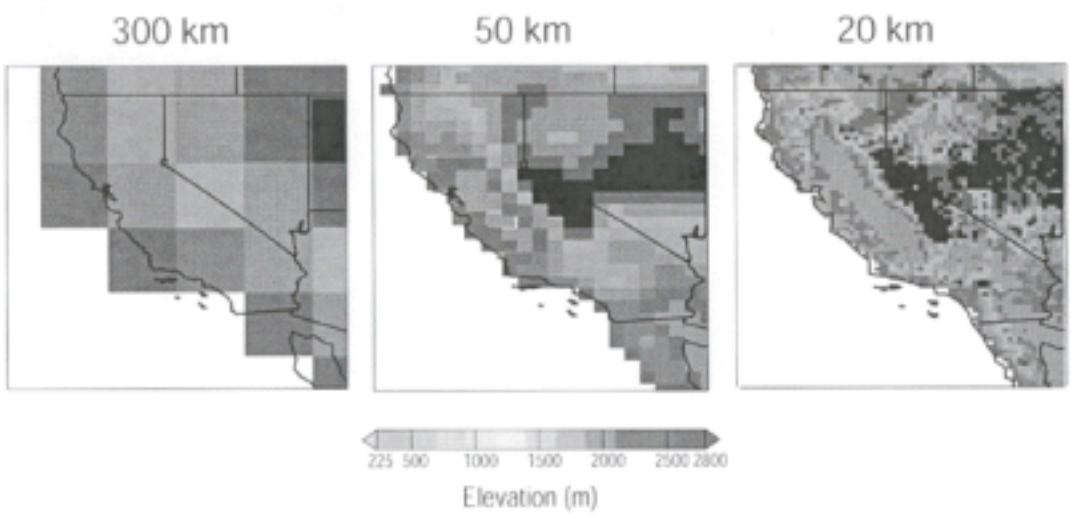
3. Background

3.1 State of the Science

Regional climate modeling—defined as the application of dynamical models over a region of the Earth (of the order of 1000 km) with horizontal resolutions of the order of 10–100 km—was first performed about ten years ago (Giorgi 1990; Dickinson et al. 1989). The technique used was to imbed a regional climate model (RCM) within a global general circulation model (GCM), with the latter providing the lateral boundary conditions required by the regional model. During the ensuing years, this approach has been used in many simulations of regional climate and climate change with a variety of RCMs and GCMs, as recently summarized by Giorgi and Mearns (1999), the Intergovernmental Panel on Climate Change (IPCC) (Giorgi and Hewitson 2001), and Pan et al. (2001). Although there are a number of outstanding technical issues with regional climate models (such as

the their lateral boundary conditions, their resolution and location, and their compatibility with the driving GCM), it is generally recognized that RCMs are able to provide a useful portrayal of climate and climate change on scales smaller than those seen in a GCM, especially in regions of varied topography such as California.

The importance of resolving regional topography is illustrated in Figure 1. The higher-resolution results from the limited number of RCMs that have been applied to California in climate change simulations generally show higher temperatures and precipitation in the Sierra than do the direct results from GCMs (Snyder et al. 2001; National Research Council 2001; and Tom Wigley, personal comm.), and offer the opportunity for further improvement by statistical downscaling to specific sites.



The orography of California as resolved by various grid-box sizes. The resolution of most GCMs (~300km) gives no detail of California's orography. At the 50km resolution common to many regional models, the Central Valley and Sierra begin to be discernible , while a grid size of 20 km reveals their regional structure as well as that of the Coast Ranges.

Figure 1. Orographic[1] Representation of California from Models at Different Resolutions

In spite of this increase in precision, regional climate models continue to be subject to the shortcomings of the driving GCM. These GCM errors (which vary considerably from model to model) often take the form of a cold bias in the higher latitudes, the underestimation of variability, and the deficient portrayal of the effects of clouds and surface processes. Recent efforts to improve RCMs have focused on reduction of the errors

[1] Orography is the branch of physical geography associated with mountains.

introduced by the imposed lateral boundary conditions[2] (Noguer et al. 1998; Qian et al. 1999) and improvement of the RCMs' parameterizations[3] (Giorgi and Shields 1999). Advances in the development of GCM that are expected over the next several years include the use of higher resolution, and the incorporation of: a coupled carbon cycle (for both terrestrial and oceanic components), interactive vegetation, and improved aerosol/cloud physics. Regional climate model development should keep pace with these advances to the extent possible.

The need for climate information at high spatial resolution may also be pursued by statistically relating the output of GCM simulations to the climate (or climate-related processes) at specific locations. Such *statistical downscaling* attempts to correct the biases of the GCM by correlating the variability of selected model variables with those observed on a smaller scale, and assumes that this relation will apply to future climate as well. This technique has been widely applied in recent years, and Wilby and Wigley (1997) have recently summarized the methods used. Depending upon the application, such statistical downscaling can achieve a level of skill comparable to that provided by regional climate models (Mearns et al. 1999; Leung 2002). Although it has the advantages of simplicity and economy, statistical downscaling is generally unable to provide insight into the physical relationships characterizing regional climate, and offers only an empirical basis for improvement. Nevertheless, statistically downscaled data from GCMs have proven useful in conjunction with local hydrological models for the estimation of streamflow and water resources in mountainous regions (Hostetler and Giorgi 1993; Leavesley 1994; Xu 1999; Gershunov et al. 2000; Miller 2001), and could be used with the results from high-resolution RCMs.

3.2 The PIER Focus

Impacts from climate change will affect California's ecosystems, infrastructure, and economy. Modeling these changes helps State decision makers and planners envision and implement the activities that will b e necessary to protect these systems effectively. However, California's unique palette of microclimates, ecosystems, and land uses requires regional modeling that challenges existing modeling technologies. To be able to model regional climate in California with a better degree of certainty, researchers must identify and improve upon regional models and modeling techniques, and develop a more comprehensive data set for the State.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Research to develop regional climate modeling that focuses on California applications is one such effort. The results of this research would also extend to other state agencies (e.g., California Air Resources Board), which could use these tools and data for their own public benefit projects. PIEREA aims to address this topic through its

[2] The variations of the variables such as temperature, pressure, wind, and moisture around the edges of a selected region.
[3] Prescribed relationships between the large-scale structure and behavior, as portrayed in a model, and that on smaller, unresolved scales.

own targeted research and to attract collaborators that will share data and work with PIEREA.

Other PIEREA roadmap chapters address other aspects of the effect of climate change on California resources and systems. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

In spite of the high level of current activity in regional climate modeling, there are a number of issues of particular relevance to California that have not been adequately examined. These mainly concern the intercomparison of models, the application of statistical downscaling, and the observational database. The research areas in need of attention in modeling regional climate change for California are therefore identified as:

1. Regional Model Intercomparison
2. Statistical Downscaling for Hydrologic Applications
3. Observational Database Development

It is important to note that researchers intercomparing regional models must have access to extensive computing resources if they are to adequately model California's regional climates.

The following discussion outlines the status of current work in these areas and identifies the needed research in more detail.

4.1 Regional Model Intercomparison

Although many regional models have been used to simulate the climate over selected regions of the United States and elsewhere (as recently summarized by Leung 2002), there has been little attempt to evaluate and intercompare the models at the needed resolution. Each investigation has used different model formulations at horizontal resolutions of about 50–100km in different regions over different time periods. As pointed out earlier, this resolution is insufficient to adequately resolve important features of California's topography, and the lack of standardized experimental conditions makes it difficult to identify characteristic model errors. A common nested model domain[4] needs to be identified and a regional modeling protocol developed.

The Program to Intercompare Regional Climate Simulations (PIRCS) at Iowa State University has examined the performance of a variety of RCMs in the simulation of selected drought and flood events in the central United States (Takle et al. 1999), but has not undertaken an intercomparison of interest to California. In Europe, regional model

[4] A selected area in a global or large-scale model within which a higher-resolution model is imbedded.

intercomparison has been carried out for selected areas (Jacob 2001), and a comprehensive intercomparison for all of Europe has recently been launched under European Union sponsorship. This project (PRUDENCE) will include several European RCMs at high resolution run under several forcing scenarios for the European area (D. Jacob, personal comm.).

Recent research at the Lawrence Livermore National Laboratory (LLNL) has focused on the simulation of climate and climate change at the highest resolution (50 km) yet achieved with a global model. This research (supported by both the U.S. Department of Energy (DOE) and LLNL) provides an unprecedented opportunity to validate conventional RCMs at comparable resolution, while serving as the basis for regional modeling at even higher resolutions. The LLNL Program for Climate Model Diagnosis and Intercomparison (PCMDI) has extensive experience in the comparative evaluation of GCM performance, and has developed versatile software for data retrieval, diagnosis, and display.

Research Needs

There is an urgent need for the systematic comparative testing, analysis, intercomparison and validation of RCMs for California at resolutions of about 20 km. The RCM intercomparison should include several driving GCMs and several RCMs at the highest possible resolution. Comparisons should result in an ensemble of regional climate change projections that would permit researchers to determine definitively the models' characteristic errors and to prepare robust estimates of the statistical confidence with which regional California climate changes can be simulated.

4.2 Statistical Downscaling for Hydrologic Applications

The statistical downscaling of GCM results needs to keep pace with resolution increases in regional models, with which they should be systematically compared. The economy and flexibility of statistical downscaling need to be exploited in the development of improved local hydrologic models (Wilby et al. 2000; Hay et al. 2000; Wilby et al. 1998).

At the Scripps Institution of Oceanography (SIO), research supported by the National Oceanic and Atmospheric Administration (NOAA), DOE and the U.S. Geological Survey (USGS) is focused on the sensitivity of the Sierra snowpack and streamflow to climate change, using statistical techniques to downscale the output from GCMs (Wilby and Dettinger 2000). Related research addresses the effects of climate change on selected watersheds and the Sacramento-San Joaquin Delta (Knowles and Cayan 2001) and of the El Niño–Southern Oscillation (ENSO) on the statistics of temperature and precipitation extremes (Gershunov et al. 2000). Other Scripps studies supported by NOAA are using RCMs to generate high-resolution seasonal forecasts over California, from which researchers can derive climatological statistics useful in water management (J. Roads, personal comm.).

At the National Center for Atmospheric Research (NCAR), Tom Wigley is continuing research on the statistical regression of large-scale variables onto regional or local scales

(Hakkarinen and Smith 2001), while others at NCAR are preparing guidelines for the use of downscaled climate information in impact studies, including hydrology (Mearns and Wilby 2002). At the Lawrence Berkeley National Laboratory (LBNL), researchers have developed statistical downscaling regression models to estimate the regional hydrologic impacts of precipitation (Kyrakidis et al. 2000).

Research Needs

Important research gaps in the statistical downscaling of regional climate for hydrologic applications include: (1) the need for an evaluation of the statistical methods in comparison to regional climate modeling using as nearly the same boundary conditions as possible, (2) the need for further research on the effects of the possible variation of the statistical relationships over time, and (3) more adequate treatment of the water and energy budgets in regions with non-uniform surface characteristics.

4.3 Observational Database

Availability of observational data is fundamental to the success of regional climate models, not only so that they can deliver meaningful results, but also so that researchers can evaluate their performance confidently. Although selected California data are available at a number of institutions, a comprehensive and easily accessible regional California climate database has not been constructed.

Both the National Center for Atmospheric Research (NCAR) and the Western Regional Climate Center at the Desert Research Institute (University of Nevada) routinely collect climatological data for California, and the latter institution in particular has extensive supplemental data from local California sources. The National Center for Atmospheric Research is developing, with partial support from the Electric Power Research Institute (EPRI), a data access system for selected GCM data; it has not, however, been applied to regional data and is less flexible than the data access software developed at LLNL. Although not explicitly concerned with regional climate data, the California Air Resources Board (ARB) has collected regional meteorological and air pollution data during a number of test periods. These data may be useful additions to the proposed regional climate database, as might the data holdings of other state and private organizations, including the California Data Exchange Center (CDEC). A new regional reanalysis for the entire United States is being planned by NOAA's National Centers for Environmental Prediction (Mesinger et al. 2002), and that project should be a valuable guide for a similar effort addressing California.

Research Needs

All available regional California climate data need to be assembled into a comprehensive quality-controlled database, and a software system with flexible and robust input-output software needs to be developed for efficient documentation, access, and display of these data. Particularly needed for model validation are data on regional atmospheric, hydrologic, and land-surface processes at high resolution; information on the occurrence

of extreme and unusual events; and new measurements of precipitation, snowpack, and soil moisture in the higher elevations of the Sierra. Such observations would be of value to water management practices in the state even in the absence of climate change. Although progress is being made in the assembly of regional data for RCM validation elsewhere (Widmann and Bretherton 2000; New et al. 2000), no such effort has been initiated for California.

5. Goals

The importance of reducing the uncertainty surrounding possible climate changes in California stems from the vulnerability of the State's water supply and almost all aspects of its economy. Faced with such a challenge, it is necessary to focus on the modeling issues that are the most relevant to California. This can best be done by creating a coordinated program with a clearly articulated goal, strategy, and implementation plan.

The goal of the Regional Climate Modeling portion of the PIER Climate Change Research Plan is to help California develop a comprehensive understanding of likely regional climate changes that will affect the State's hydrologic and agricultural infrastructure and natural ecosystems.

To reach this goal, efforts must support research that is most likely to improve regional climate modeling for California, as distinct from that which may be most useful in a general or global sense. The relevant projects are thus identified as: (1) high-resolution model intercomparison, (2) statistical downscaling for hydrologic applications, and (3) observational database development.

Section 5.1 outlines the anticipated objectives or milestones over the short-, mid-, and long-term[5] for the recommended research projects, together with the factors that are likely to be critical to the projects' success. All projects are seen as continuing over the short, mid and long terms.

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

[5] 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.

5.1 Short-term Objectives

5.1.1 Regional Model Intercomparison

A. Design a model intercomparison protocol.

Activities needed: (1) Define a common domain for California RCMs. (2) Select atmospheric GCMs. (3) Determine a simulation length and resolution. (4) Identify and document participating RCMs.

B. Perform control simulations and analyze results.

Activities needed: (1) Run the selected GCMs. (2) Determine systematic errors of GCMs. (3) Repeat with selected imbedded RCMs at high resolutions per protocol. (4) Analyze systematic errors of RCMs driven by GCM control and reanalysis runs, including the mean and variability of selected critical variables over diurnal, seasonal, interannual, and decadal timescales, including extreme precipitation events.

Critical Factors for Success:

- Availability of computer time.
- Liaison with modeling community.
- Interface with impacts community.

5.1.2 Statistical Downscaling for Hydrologic Applications

A. Evaluate downscaling methods.

Activities needed: (1) Determine relative accuracy of alternative downscaling techniques. (2) Compare performance with comparable regional models.

B. Analyze errors of hydrologic applications.

Activities needed: (1) Evaluate sensitivity of selected hydrologic variables to downscaling errors. (2) Determine hydrologic variables' sensitivity to resolution.

Critical Factor for Success:

- Availability of observational data.

5.1.3 Observational Database

A. Develop a California climate database.

Activities needed: (1) Collect all available local and regional data. (2) Document data and place into the database.

B. Develop a data access system.

Activities needed: (1) Develop software for data storage, access, diagnosis, and display. (2) Distribute data to the research and impacts communities.

Critical Factor for Success:

- Cooperation of public and private data holders.

Table 1. Short-term Budget

Project Objective	**Projected Cost ($000 per year)***
5.1.1.A Design a model intercomparison protocol	800 total for A & B
5.1.1.B Perform control simulations and analyze results	
5.1.2.A Evaluate downscaling methods	400 total for A & B
5.1.2.B Analyze errors of hydrologic applications	
5.1.3.A Develop a California climate database	600 total for A & B
5.1.3.B Develop a data access system	
Total Short-term Cost per Year	**1,800**

* There is a high probability that approximately equal funding will be available for each project from other sources. The figure given is the California Energy Commission's projected expenditure over the short-term period.

5.2 Mid-term Objectives

5.2.1 Regional Model Intercomparison

A. **Perform climate change simulations.**

Activities needed: (1) Run ensemble of high-resolution (50-km) GCM greenhouse scenarios. (2) Make parallel runs with selected imbedded RCMs at high resolutions (50 km and 20 km) per protocol.

B. **Analyze model results.**

Activities needed: (1) Determine ensemble characteristics of RCMs' simulated climate changes and changes in variability for wide range of variables, processes, and timescales, including coastal climate and extreme precipitation events. (2) Estimate statistical confidence of results. (3) Prepare probabilistic estimates of climate changes (including upper and lower bounds).

C. **Include new/improved models in intercomparison.**

Activities needed: (1) Perform simulations per protocol. (2) Analyze model results. (3) Compare with statistically downscaled results.

Critical factors for success:
- Availability of computer time.
- Liaison with modeling community.

5.2.2 Statistical Downscaling for Hydrologic Applications

A. **Develop improved downscaling techniques.**

Activities needed: (1) Incorporate physical considerations into downscaling. (2) Incorporate supplemental local data. (3) Examine statistical stability over longer time periods.

B. **Improve coupled hydrologic models.**

Activities needed: (1) Evaluate needed regional detail in parameterization. (2) Determine response sensitivity as a function of scale. (3) Improve models' energy and water budgets.

Critical factor for success:
- Availability of observational data.

5.2.3 Observational Database

A. **Incorporate new data.**

Activities needed: (1) Identify and support acquisition of new hydrologic observations in higher elevations of the Sierra. (2) Identify and support new surface observations in other regions of state. (3) Recover undigitized and remotely sensed data. (4) Distribute downscaled data to impact assessment groups.

B. **Perform reanalysis for California.**

Activities needed: (1) Use the selected RCM to perform high-resolution long-term reanalysis with all available data. (2) Add reanalysis data to database.

Critical factors for success:
- Support of other public agencies for new observations.
- Availability of computer time.

5.3 Long-term Objectives

5.3.1 Regional Model Intercomparison

A. **Expand intercomparison.**

Activities needed: *(1) Incorporate new/improved models, including those with coupled chemical, hydrologic, and biological processes. (2) Perform expanded ensemble of control and climate change runs per protocol. (3) Refine simulations' error statistics. (4) Refine probabilistic estimates of climate changes.*

B. **Develop innovative solution methods.**

Activities needed: *(1) Design and incorporate interactive regional resolution. (2) Develop and apply non-hydrostatic models to resolve changes on scales in the 1–10 km range.*

Critical factors for success:

- Availability of computer time.
- Liaison with modeling community.

5.3.2 Statistical Downscaling for Hydrologic Applications

A. **Develop hybrid downscaling approach.**

Activities needed: (1) Combine modeling and statistical downscaling approaches. (2) Determine the model's systematic errors.

B. **Systematic model use in hydrologic applications.**

Activities needed: (1) Examine the stability of parameter representation. (2) Document model applicability in different regions.

Critical factor for success:

- Availability of observational data.

5.3.3 Observational Database

A. **Continue database development.**

Activities needed: (1) Continue support of new data acquisition. (2) Add selected satellite, marine, and ecological data. (3) Improve data software system.

B. **Promote database use.**

Activities needed: (1) Use as data-of-choice for model validation. (2) Publicize database to public and private sectors.

Critical factor for success:
- Cooperation and support of other agencies.

5.4 Implementation

The key to the success of the proposed California climate change modeling initiative is to implement it as a *program,* with defined targets and priorities, and in which each element has a clear relationship to the others. Such a program would require the California Energy Commission to hire a research manager whose duties should include scientific overview of the program's projects, preparation of program reports for the Commission and others, coordination with appropriate national and international efforts, and the maintenance of effective outreach and public relations. Ideally, this manager should be experienced in climate modeling and research so that he/she can ensure that the results are used effectively.

Coordination among the various research projects requires that each project be aware of the work of the other projects being supported, especially in those cases where the success of one project is dependent on the results of another. A participation protocol should be developed under which each project would agree to share its findings (prior to their publication in the scientific literature), to contribute its results and/or data to a common database, and to employ common standards and procedures whenever possible. Coordination would also be increased by regular meetings of the program's investigators, at which the projects' results would be reported and future programmatic plans discussed.

Rather than supporting a large number of separate research tasks (in the manner, say, of the National Science Foundation, or NSF), it is recommended that the program instead be organized around a small number of basic collaborative projects that focus on issues of critical importance to California and to which unique local capabilities can be brought to bear. In this way, the desired level of cooperation among the groups participating in each project can be built into the program from the beginning. Among the three recommended projects, regional model intercomparison is seen as the core of the program, although it is recommended that an overall program balance be maintained. Support of research in statistical downscaling for hydrologic applications is of particular importance for California, and the assembly of a comprehensive observational database is of value across the program.

In view of the unique and widely recognized experience of the potential California participants, it is recommended that competitive bidding be used to select the groups best

qualified to carry out the recommended research. The availability of co-funding from other sources should be an important consideration.

6. Leveraging R&D Investments

In order to use the funds available for the research recommended in this roadmap most effectively, it is important that they be leveraged whenever possible and appropriate against the support that is (or may be) available from other sources. In particular, leveraged support should be sought with relevant ongoing projects at the University of California campuses and laboratories, supported by the DOE, NSF, the National Aeronautics and Space Administration (NASA), and NOAA.

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.

6.2 Opportunities

Co-sponsorship opportunities are likely under the following scenarios:

- The DOE currently supports research on statistical downscaling for the western United States at the Scripps Institution of Oceanography under the pilot Accelerated Climate Prediction Initiative (ACPI) project, and supports limited research on regional modeling at Pacific Northwest National Laboratory (PNNL) and at the Universities of Maryland and Quebec under the Climate Change Prediction Program (CCPP). The ACPI proposed the establishment of several centers for regional climate prediction and application, but the initiative was unfortunately not implemented. In the spirit of ACPI, efforts should be made to secure support from DOE's Office of Biological and Environmental Research for the PIER regional climate modeling program, in which California could serve as a useful test bed for the development of a subsequent national effort.

- The DOE and LLNL currently support research on high-resolution climate modeling in the Laboratory's Energy and Environment Directorate. Plans are being developed for the extension of this work.

- The NOAA currently supports research at Scripps on the use of regional models for seasonal forecasting in California, and supports research on their use for regional climate simulation at LBNL (in cooperation with NASA). The NSF supports considerable research that is relevant to regional climate modeling at universities and at NCAR.

- The U.S. Global Change Research Program (USGCRP) coordinates a wide range of relevant climate modeling research supported by the NSF, NOAA, DOE and NASA, and endorsement of the proposed program by the USGCRP would be useful.

7. Areas Not Addressed by This Roadmap

There are several areas that are relevant to the modeling of regional California climate and climate change that are not recommended for PIER support at this time. These are:

- The development of new global or regional models. There is a sufficient number of both kinds of models now available, and their improvement is an important ongoing objective principally supported by the NSF and other federal agencies. As improved models are developed, however, it is important that PIER follow their status so that their suitability for inclusion in the PIER model intercomparison can be evaluated.
- The development or use of impact assessment models. Models of the impact of climate change on specific activities, such as crop production or tourism, should be funded primarily by the appropriate state agencies or by the private sector.
- The use of regional models for weather forecasting. Regional models are commonly used in numerical weather prediction and are increasingly being applied in seasonal forecasting. This work is amply supported by NOAA.
- The use of regional models for the simulation of paleoclimate. Although the reconstruction of past climates provides a unique view of climate changes, the data are sparse, and not necessarily representative of future changes in California climate.

It is recommended, however, that the program maintain an awareness of developments in these areas as a source of supplementary information and possible future cooperative projects.

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Appendix A
Current Status of Programs

This section outlines those efforts in California, the United States, and abroad that most closely address the regional modeling of climate change.

Current Status: California

California Air Resources Board (ARB)

- Although not explicitly concerned with regional climate modeling, ARB has supported the development of the MM5 regional model for use with high-resolution photochemical models for the short-term prediction of air quality, and has collected meteorological and air pollution data during a number of regional test periods. This experience and these data may be useful in the proposed regional climate modeling program.

Lawrence Berkeley National Laboratory (LBNL)

- Use of regional climate models to drive high-resolution hydrologic models for selected Sierra watersheds (Norm Miller). This research is supported by NOAA and NASA. The regional model is itself forced by the control and increased CO_2 scenarios from GCMs, as well as by global reanalyses (Miller and Kim 2000; Kim[6] 2001).

Lawrence Livermore National Laboratory (LLNL)

- Research supported by the Laboratory in its Energy and Environment Directorate has enabled the commencement of a multi-year integration of the NCAR GCM with a global horizontal resolution comparable to that currently used in many RCMs (i.e., ~50 km). This work will permit direct examination of the accuracy of an imbedded RCM at this resolution (P. Duffy, personal comm.). Other relevant research at LLNL focuses on the analysis and intercomparison of the systematic errors of GCMs and the development of diagnostic software in the Program for Climate Model Diagnosis and Intercomparison.

Scripps Institution of Oceanography (SIO), University of California at San Diego

- Use of statistical downscaling techniques to apply GCM-simulated climate changes to hydrologic models for the western United States, including snowfall and streamflow in the Sierra (Dan Cayan). This research is part of the DOE ACPI pilot project, with related support from NOAA and USGS. Scripps is also conducting research with an RCM to study the effects of El Niño on California streamflow.

National Centers for Environmental Prediction, NOAA, Washington, D.C.

[6] Jinwon Kim recently moved to UCLA, where he will use a regional climate system model to study the impact of climate change on hydrology and agriculture (J. Kim, personal comm.).

- Planning for a U.S.-wide, regional-scale reanalysis, using the operational ETA model (Fedor Mesinger).

University of California at Davis (UCD), Department of Land, Air, and Water Resources

- Use of regional climate models for study of vegetative surface fluxes over the western United States (Bryan Weare).

University of California at Los Angeles (UCLA), Department of Atmospheric Sciences

- Use of regional climate models to simulate climate change in California, with emphasis on Sierra precipitation (Jinwon Kim).

University of California at Santa Cruz (UCSC), Department of Earth Sciences

- Use of a regional climate model for simulation of climate change in California, in collaboration with LLNL (Lisa Sloan).

Current Status: Regional and National

Desert Research Institute (DRI) of the University of Nevada, Reno, Nevada

- Reconstruction of past precipitation fluctuations in Central Valley from blue oak tree-ring widths, and maintenance of regional climatological records (Kelly Redmond).

Electric Power Research Institute (EPRI), Palo Alto, California

- Cooperation with ACACIA project at NCAR and with PIRCS project at Iowa State University (Chuck Hakkarinen).

Iowa State University (ISU), Department of Atmospheric Sciences, Ames, Iowa

- ISU is evaluating the performance of a variety of regional climate model simulations as part of the Project to Intercompare Regional Climate Simulations (PIRCS), with emphasis on hydrology (Bill Gutowski, Gene Takle, Ray Arritt). Examinations are focusing on selected drought and flood events in the central United States (Takle et al. 1999), and on the uncertainties in regional downscaling (Pan et al. 2001). This work has support from both EPRI and NOAA.

National Center for Atmospheric Research (NCAR), Environmental and Societal Impacts Group, Boulder, Colorado

- The National Center for Atmospheric Research is continuing research on the statistical regression of large-scale variables onto regional or local scales, and is developing a data access system with partial support from EPRI (Hakkarinen and Smith 2001). Linda Mearns and Tom Wigley of NCAR are preparing guidelines for the use of downscaled climate information (Mearns and Wilby 2002), and participating in an NCAR impact assessment initiative (L. Mearns, personal comm.).

Pacific Northwest National Laboratory (PNNL), Richland, Washington

- Use of regional climate models for the Pacific Northwest, including downscaling to hydrologic variables (Ruby Leung), as part of the ACPI pilot project supported by DOE in cooperation with Scripps.

Current Status: International

European Union (EU)

- The European Union is continuing to sponsor the development, application, and intercomparison of regional climate models over selected regions in Europe (Giorgi and Francisco 2000 a, b; Jacob et al. 2001; Hagemann et al. 2001; Christensen et al. 2001). The EU has also recently launched a new project (PRUDENCE) in which the performance of several RCMs driven by the Hadley Centre GCM will be intercompared for a 30-year period over Western Europe.

Hadley Centre for Climate Prediction and Research, United Kingdom Meteorological Office (UKMO), Bracknell, UK

- High-resolution models are being used to examine the effects of the RCM's domain on the quality of the simulated regional climate, driven by the centre's operational GCM (R. Jones, personal comm.)

Max-Planck Institute for Meteorology (MPI), Hamburg, Germany

- Research is under way on the sensitivity of simulated regional climate to the parameterization of surface process with resolutions of 1/2 and 1/6 degree (D. Jacob, personal comm.).

University of Quebec, Montreal, Canada

- At the University of Quebec in Montreal, research is under way on the effects of an RCM's resolution and lateral boundary conditions in an experiment similar to that underway at LLNL (Denis et al. 2002a, b), although focused on eastern North America. A new Canadian Regional Climate Modelling Network has recently been established to pursue a broad range of relevant research over the next several years (R. Laprise, personal comm.).

Attachment II

The Effects of Global Climate Change on California Water Resources

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Executive Summary

Climate change has the potential of affecting a wide variety of water resource elements. These elements include water supply, hydroelectric power, sea level rise, more intense precipitation events, water use, and a number of miscellaneous items that include water temperature changes. Some 35 items for possible research are reviewed and discussed in this chapter. After discussing these issues with other water experts, the author identified a dozen as priority items for investigation in the short-term.

In the short-term (1–3 years) this roadmap recommends addressing the objectives summarized in the table on the following page.

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.

Objective	Projected Cost ($000)
Support the regular, consistent, and sustained measurement of hydrologically important variables	1,500*
Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data	500
Conduct a simple test of the impact on water supply of the CVP-SWP system of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing.	600
Conduct detailed tests of the impact on CVP-SWP system water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume, including likely upstream reservoir operational changes	1,400
Support the development of global climate models that can better project future precipitation in California	1,000
Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage	100*
Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast	200
Measure current evapotranspiration (ET) to compare current data with earlier data	500
Assess likely changes in ET in a year 2050 or 2100 scenario with warmer average temperatures and higher carbon dioxide content of the atmosphere.	300
Conduct a systematic review and evaluation of flood protection adequacy in major multipurpose flood control reservoirs under projected climate scenarios.	600*
Model water temperatures in both regulated rivers and natural streams	400*
Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.	200*
Total Short-term Cost	**7,300**

Note: An asterisk (*) indicates a high probability that the work can be leveraged with other ongoing efforts. The figure given is the California Energy Commission's total projected expenditure to complete each objective (over a three-year period).

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

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 pertains to the impact of climate change on water resources in California. *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

ARB	California Air Resources Board
CAP	California Applications Program
CALFED	Cooperative State-federal program addressing water issues in California
Cal-(IT2)	California Institute for Telecommunications and Information Technology
CALSIM	A model for simulating California water resource systems
CALVIN	An economic-engineering model for water allocation
CO2	carbon dioxide
CVP-SWP	Central Valley Project - State Water Project
DOE	U.S. Department of Energy
DRI	Desert Research Institute of Nevada
DWR	California Department of Water Resources
ENSO	El Niño–Southern Oscillation
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ET	evapotranspiration
GCM	general circulation model
GHG	greenhouse gas
GPS	Global Positioning Systems
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame
LBNL	Lawrence Berkeley National Laboratory
mafy	million acre-feet per year
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NSF	National Science Foundation
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
PDO	Pacific Decadal Oscillation
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
PMF	probable maximum flood
PRMS	Precipitation-Runoff Modeling System
TMDL	total maximum daily load
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey

1. Issue Statement

Global climate change can affect the timing, amount, and form of precipitation that California receives, as well as the level of the Pacific Ocean. Moreover, changes in weather patterns caused by climate change can affect water use and consumption. To ensure that the State's natural systems and infrastructure can accommodate hydrological changes brought about by climate change, research needs to improve detection of changes in the State's water systems and investigate the potential impacts of, and responses to, such changes.

2. Public Interest Vision

This report on suggested research on the effects of global climate change on California water resources is part of a larger effort by the California Energy Commission to analyze potential impacts on California of future global warming. The Intergovernmental Panel on Climate Change (IPCC) was jointly established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to study climate change. The IPCC has issued several reports since 1990 outlining possible global warming and the effects as a result of increased amounts of carbon dioxide, methane, and other trace gases including nitrous oxide and the halocarbon gases (such as freon, which is covered under the Montreal Protocol, and the replacement hydrofluorocarbons) originating from human activities. The amount and timing of such an increase is subject to uncertainty.

The National Water Assessment Group for the U. S. Global Change Research Program (Gleick and Adams 2000) provides a good assessment of the state of research on the potential consequences of climate change on water resources in the United States, including what is known and what is not known.

The most recent IPCC Working Group I Summary Report (IPCC 2001) projects a 1990 to 2100 average global surface temperature increase of around 3°C, with a range of 1.4° to 5.8°C. The different scenarios cover a wide range of assumptions about the rate of future increases in greenhouse gases and the amount of radiative forcing in the climate system. The estimated increase in global surface temperature during the twentieth century was estimated to be about 0.6°C, much of which occurred by 1940, before the increase in man-made gases was significant (Folland and Karl 2001), and a recent significant increase after 1980 which is believed to be primarily of human origin. California inland rural temperatures do not seem to have followed the world trend and have risen only slightly since 1940 (Goodridge 2001). California coastal temperatures, even in rural locations, do show warming in the 1980s and 1990s corresponding to warmer ocean temperatures. Because of warmer temperatures, some increase in global evaporation and precipitation are projected during the twenty-first century, more likely at higher latitudes. For hydrology and water resources, precipitation is the most important variable.

Sea level is projected to rise around 0.5 meter by 2100 with a range of 0.1 to 0.9 meters (IPCC 2001). The rise during the twentieth century appears to have been around 0.2

meters, with a range of 0.1 to 0.25 meters (IPCC 1995). This estimate is consistent with the historical trend reported at the Golden Gate tide station, although it is possible that tectonic movement, or settlement, has influenced the measured stages there.

There is a general expectation that a warmer climate will lead to more intense precipitation events, thereby causing somewhat higher runoff and floods and more intense convective storms (thunderstorms), thereby affecting the rainfall statistics used for storm drainage design.

The increase in carbon dioxide, from the current 370 parts per million (ppm) to perhaps 600 to 700 ppm by the year 2100 is expected to be beneficial to plant growth, unless temperatures get too warm. To some extent, higher carbon dioxide concentrations could partly offset the higher water use (evapotranspiration) resulting from higher temperatures.

All of these projected changes, as well as some not yet identified, are likely to affect the hydrologic cycle and the water resources of California.

3. Background

3.1 Water Resources in California

Northern and central California precipitation is quite seasonal, typical of a Mediterranean climate, with cool wet winters and warm dry summers. On average, half the annual precipitation occurs in the three months of December, January, and February. Three-fourths occurs in the five-month November through March period (see Figure 1). The only significant departures are in the dry southeastern desert areas, which have a summer monsoon peak as well as a winter season maximum.

In California, the wetter regions contributing most of the State's runoff are in the north. Most of the demand for water is in the central and southern portion of the State. Three-fourths of the State's 87 cubic kilometers (71 million acre-feet) of average natural runoff originates north of Sacramento, the State capital; about 80% of the demand for urban and agricultural water is south of Sacramento. Approximately 3.6 million hectares (9 million acres) of farmland are irrigated, producing about 13% of the agricultural value for the entire United States (DF&A 2000). Irrigated acreage is expected to decline slightly, perhaps 5%, by year 2020 as population increases from 34 million in 2000, to a projected 48 million. In recent decades, environmental needs are receiving increasing attention. Demands for more fresh water for fisheries and wetlands are rising, partly at the expense of agriculture. Water conservation and other water management measures can help stretch supplies (on the order of 3 to 5%) but these tools cannot solve major shortfalls.

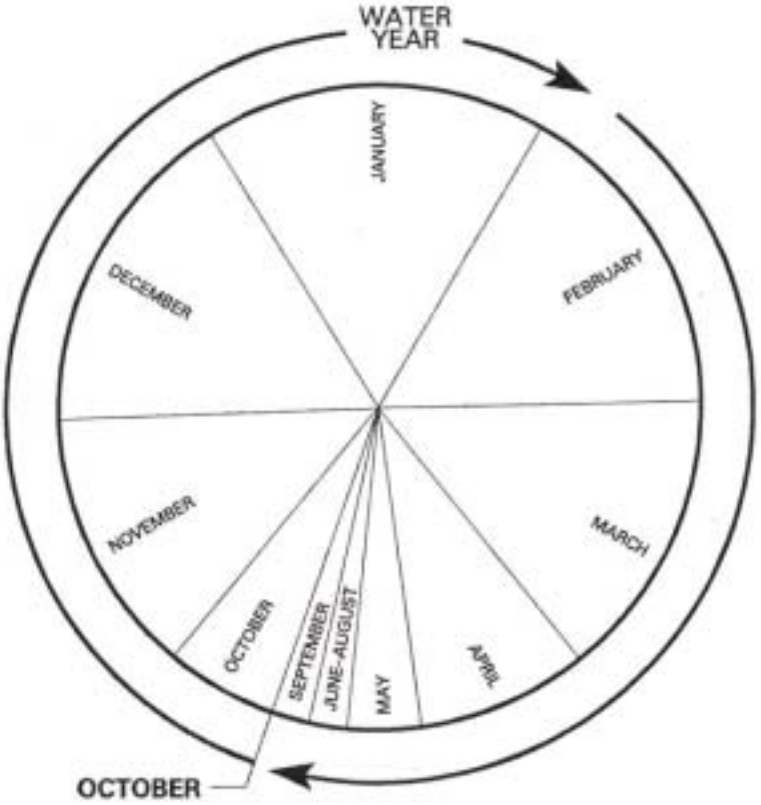

Figure 1. Monthly Precipitation Distribution in the Sierra Nevada
Source: 1947–1986 precipitation records for Sierra stations as compiled by DWR and Scripps Institution of Oceanography.

Water development in California is based on the concept of storing water during the wet season and in wet years with long-distance conveyance to areas of need. Major water transfer projects have been built to convey water from areas of plenty to the drier central and southern portions of the state. The tidewater region of the Sacramento-San Joaquin Delta is the hub of major water transfer; water quality there can be affected by salinity intrusion from the ocean via San Francisco Bay.

Large reservoirs in the north provide water storage and flood control. Water is then released downstream to be exported by large pumps in the southwestern corner of the Delta. During low-flow months, additional water is released to repel ocean salinity incursion in the western Delta as a hydraulic barrier to preserve suitable fresh water quality within the estuary and for export. Total export pumping averages around 7.5 cubic kilometers per year (6 million acre-feet). These exports supply approximately one-fourth of all the current water use in central and southern California including the San Francisco

Bay area. The rest of the use is supplied from local surface and groundwater sources and from the Colorado River.

The large reservoirs are multi-purpose projects built to provide flood control during the winter wet season. Figure 2 shows an example of flood control operations for Lake Oroville, based on California Department of Water Resources (DWR) operations records. The upper and lower lines are flood space requirements, less when the watershed is relatively dry and more when wet (lower line), and show how the permissible storage changes during a season. The large storm in mid-January caused a rapid change in basin wetness and allowable storage. Excess runoff was temporarily stored during the winter storm (note the sharp rise in reservoir storage in mid-January), then released after the storm. A substantial amount of winter precipitation has historically been stored in the snowpack. During the spring (late March, April, and May), flood control requirements are eased and, if all goes well, the reservoirs fill from spring snowmelt (see Figure 2). In this example, reservoir storage peaked in early June, but did not quite fill before the higher summer water demands started the seasonal draw down cycle. Potential loss of a large fraction of snowmelt runoff would make it more difficult to fill the large reservoirs in most years, with corresponding reductions in water supply yield, some losses for recreation and hydroelectric power, and possible temperature problems for downstream fisheries.

Based upon Department of Water Resources Bulletin 160-98 (DWR 1998), estimated applied water use and supply are shown in Table 1, in million acre-feet per year (mafy), at the 1995 level of development. Current uses in 2001 are believed to be about the same as those in the table. The urban category includes water for commercial, industrial, residential, and government uses, including many city parks.

Table 1. California 1995 Water Budget with Existing Facilities and Programs (mafy)

	Average Year	Drought Year
Water Use		
Urban	8.8	9.0
Agricultural	33.8	34.5
Environmental	36.9	21.2
Total	**79.5**	**64.7**
Supplies		
Surface Water	65.1	43.5
Groundwater	12.5	15.8
Recycled and Desalted	.3	.3
Total	**77.9**	**59.6**
Shortage	**1.6**	**5.1**

Source: DWR Bulletin 160-98.

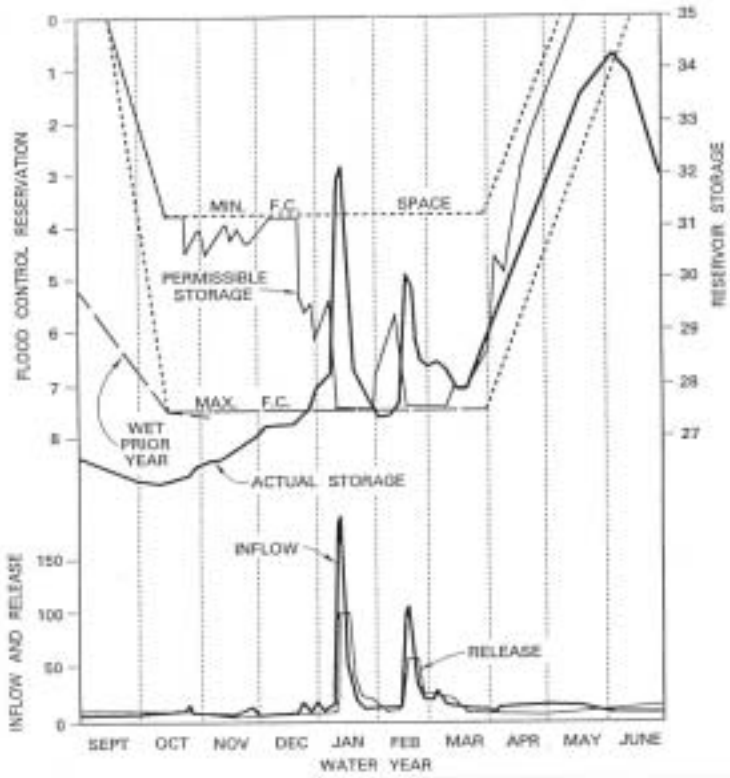

Figure 2. Typical Example, Reservoir Flood Control Operation
Source: DWR Lake Oroville operating records for Water Year 1980.

The shortage includes groundwater overdraft of about 1.5 mafy, mostly in the San Joaquin Valley. Instream wild and scenic river flows account for 23.6 and 10.6 million acre-feet (maf), respectively, of the estimated environmental use in average and drought years. (The primary reason for the drop-off of environmental usage in a drought year is that this category includes the North Coast wild and scenic river runoff, which is much lower in a dry year.) Of the total out-of-stream usage for urban and agricultural purposes, nearly 80% was used by agriculture. Updated figures will be available in about a year in DWR's Bulletin 160-2003, but the ones above are believed quite representative of today's conditions.

Climate change could affect both water supply and water demand. Unless water supply becomes deficient, which will cause yield losses, water use will probably only show a small increase in evapotranspiration. A rise in cool season temperatures may enable more double cropping of annual or seasonal crops. Currently irrigated land in the State totals

about 9.1 million acres, with about 0.4 million acres of multiple crop, for a total crop area of 9.5 million acres (DWR 1998). For some perennial crops, such as alfalfa, a longer growing season could generate more cuttings, hence higher production per acre, but with a proportional increase in water use per acre. A rise of 3°C could trigger crop shifts from the more southern valleys to the north.

The more substantive changes to be expected are in the water supply sector. Higher snow levels during winter storms mean more direct runoff from rain, less snowpack, and less spring snowmelt runoff. The shift in runoff patterns from spring snowmelt into winter runoff as a result of temperature increases would cause major changes in usable water (water available at the time of need) from major California rivers and reservoirs, especially in the lower elevation northern Sierra Nevada. The following chart from data in DWR files and operation studies, may help illustrate this point.

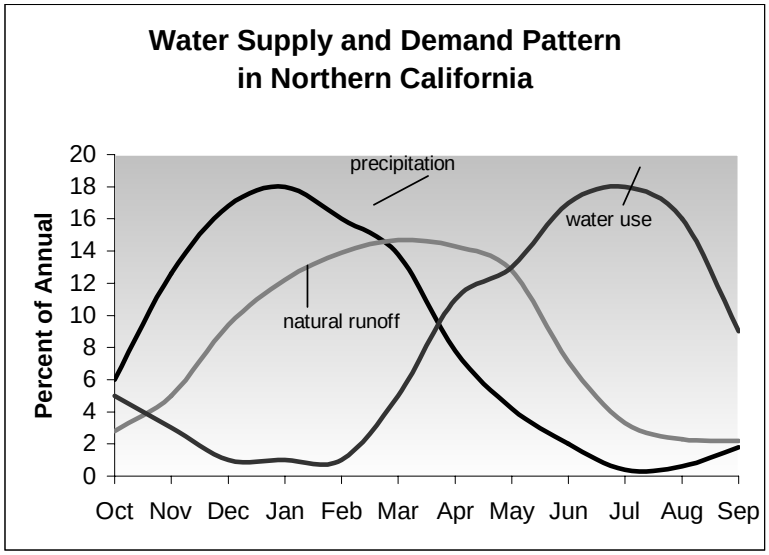

Figure 3. Water Supply and Demand Patterns in Northern California
Source: DWR.

The first curve (precipitation) shows the average monthly pattern of precipitation in the northern Sierra. The peak precipitation month is January; December and February are not far behind. These three months account for half the annual precipitation. (The water year in Figure 3 begins in October and ends in September to correspond to the normal runoff season.) Rainfall patterns are quite similar in all of northern and central California. The second line (middle curve) shows runoff in the Sacramento River basin. The primary reason for the lag is the natural storage of a portion of the winter precipitation as snowpack and its gradual release during the spring melting season. The summer peaking line is a typical demand for water use in northern and central California. Snowmelt runoff provides a substantial share of early demand directly; as demand rises and natural runoff

decreases, stored water must be used to make up the difference. As a general rule, less spring runoff means a greater need for winter storage to provide the same annual demand. For California's major foothill reservoirs, added winter runoff often is not storable because of the need to maintain flood control space at that time.

In addition to seasonal patterns, variability in annual runoff is an important element in California water supply. Dry years are interspersed with wet years. The records of precipitation and runoff show that extremely dry periods often last several years. Figure 4 shows the history of Sacramento River system unimpaired runoff (sometimes called the Four River Index). The bars are coded in the five categories, from wet to critical, used in determining Delta water quality criteria (the 40-30-30 Index). The driest single water year was 1977 at about 28% of average and the wettest was only six years later in 1983, at 207% of average. The driest two-year period was 1976 and 1977, at about 36%. Two six-year sequences of drought stand out: 1929–1934 and 1987–1992. Many reservoirs were built to maintain a certain level of planned deliveries or reliability, should there be a repeat of the 1929–1934 drought.

One of the concerns in a changed global climate is whether droughts would be either longer or more severe. Some additional data on the range of variations in historical climate, and presumably some insight on likely future variations, can be gleaned from paleoclimate reconstructions, including tree ring studies.

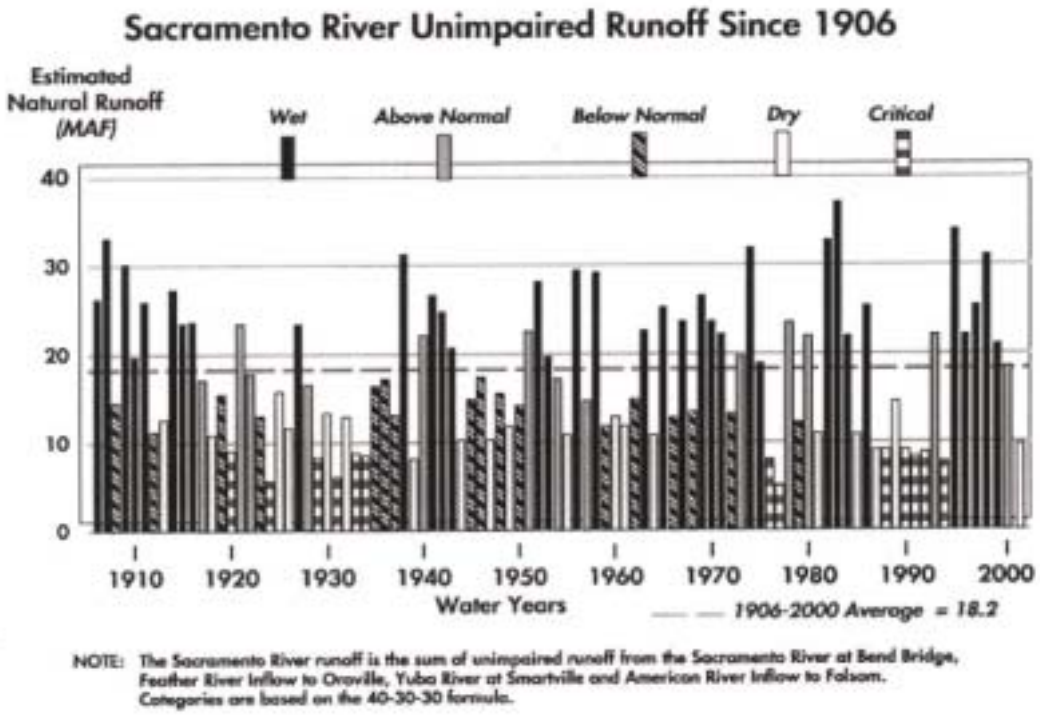

Figure 4. Sacramento River Unimpaired Runoff Since 1906
Source: DWR Snow Surveys Program records.

Assuming no significant change in average precipitation, less spring snowmelt runoff would make it more difficult to refill reservoir flood control space during the late spring and early summer of many years, thus reducing the amount deliverable. Lower early summer reservoir levels also would adversely affect recreation and hydroelectric power. If precipitation increases sufficiently, it is possible for snowmelt runoff to increase in the higher elevation southern Sierra watersheds (Dettinger 2000). Each of these issues is worthy of further analysis and research.

Warmer temperatures are likely to lead to more extreme storm events. If anything, this would require that all currently available winter flood storage space in the reservoirs be kept open, or would require more space.

Sea level rise could especially affect the Sacramento San Joaquin River Delta, the hub of California's water transfer system. Higher tide levels would pose additional problems to the precarious Delta levee systems, with a risk of more island inundations and the corresponding threat to export water quality.

3.2 The PIER Focus

Although the specific effects of climate change on California's water resources are still uncertain, research to date indicates that shifts in precipitation and sea level rise will be issues that must be addressed in the near-term future. To ensure the reliable delivery of water, the protection of the State's infrastructure, and the safety of its citizens and their property, California must have the tools and methods in place to be able to collect and analyze hydrology data throughout the State. 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 water resources 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 on water resources in 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

There are several areas of potentially fruitful research on the impacts of climate change on California's water resources. These can be grouped into items affecting water supply, hydroelectric power, sea level rise, water use—especially in agriculture, flood risk and storm drainage design, and other categories such as river temperature and water quality (primarily mineral content and dissolved oxygen). One needs to have a good understanding of potential physical changes in order to focus research priorities. Because it is uncertain which physical changes to expect, this is no easy task. Monitoring, both to detect changes and to calibrate atmospheric and hydrologic models, is basic to successful research.

The following discussions outline the status of current work in these areas and identify areas affecting water resources where new or additional research is needed. Table 2 attempts to give a roadmap overview of research suggestions.

Table 2. Roadmap on Water Resources Research Suggestions

Major Task	Subtasks
Monitoring	• Weather changes • Hydrologic changes
Water Supply	• Modeling future precipitation • Snow level and runoff changes • Test operation of CVP-SWP system • Impact on reservoir recreation • Winter flood control space • Groundwater recharge • Offstream storage • Changes in radiation • Climate change in adjacent regions • More understanding of hydrologic variability
Loss of Hydro at Foothill Reservoirs	• Average conditions • Long base period studies
Sea Level Rise	• Catalog trends along coast • Evaluate Golden Gate tide datum • Effect on Delta levee stability • Salinity intrusion • Silt in the Delta • Vulnerability of coastal Marshes • Coastal aquifer salinity intrusion • Grade line of sewers and storm drains • Coastal erosion
More Intense Precipitation	• Risk of bigger floods and rain events • Revise depth-duration-frequency data • Bigger probable maximum floods • Erosion potential
Water Use	• Changes in ET and crop water use • Recent changes in ET • Change in growing season • Effect of changed ET on aquifer recharge • Increased smog effect
Other Items	• Water temperature • Transition zone erosion • Water weeds • Wild fires • Increased salinity • Drinking water treatment

4.1 Monitoring

Regular, consistent, and sustained measurement of hydrologically important variables are essential to track what is happening and to verify model predictions. This means continuing measurements of variables such as precipitation and other climate data, streamflow, snowpack, and ocean and Delta tide levels.

The National Weather Service, in its newly reorganized Climate Services Division, is developing a climate reference network of 250 weather stations as a national benchmark of long-term climate monitoring stations. These would be stations with a long history (50 years or more) which are expected to have a stable local environment, not subject to urbanization or other changes, during the next 50 years (Robert Livezey 2001, personal comm.). About five stations will probably be located in California. They are likely to be lowland stations, because good mountain stations are difficult to sustain, especially where snow is part of the precipitation mix. Consideration should be given to establishing and maintaining station networks along gradients such as east to west, north to south, and across climate zones. In view of the outlook for substantial changes in snowpack, the measurements in the high Sierra snow zone should be increased, including some discrete new sites in wilderness areas. Leaving out the wilderness leaves large holes in data coverage in an area likely to change. High elevation climate trends and variations are not as well understood as those at lower elevations, yet do affect vital elements of the State's economic structure.

A useful start on high-elevation monitoring has begun in Yosemite National Park. As part of the University of California's California Applications Program (CAP), the Climate Research Division of Scripps Institution of Oceanography installed a number of snow measurement and meteorological instruments in the park. Their purpose is to monitor meteorological, snowpack and hydrologic conditions in more detail and with greater consistency than in the past. This project is supported by the National Park Service (NPS), National Oceanic and Atmospheric Administration (NOAA), California DWR, Desert Research Institute of Nevada, as well as the Cal-(IT^2) program and the National Science Foundation (NSF). Besides its use in monitoring climate change, better information in the snow zone may help improve water supply runoff forecasts and flood forecasts.

Research Needs

Basic data programs are relatively expensive and, like maintenance, are subject to budget cuts in tough financial times. Recognition of their foundational value is something to be stressed when dealing with funding agencies. Continuing assessment of changes in runoff patterns, sea level, precipitation events, and water use are important elements.

4.2 Water Supply

Providing an adequate supply of developed water for all California uses is already a problem, especially during dry years. The key variable is the amount of precipitation in the form of rain and snow on watersheds and the resulting runoff. Projections of regional precipitation, however, are not reliably available from global climate models and it is doubtful that definitive projections will be forthcoming soon. Dry years and dry periods are of most interest to water supply planners, although flood events are also a concern.

The problem of reliably projecting precipitation will be the subject of continuing investigations by PIER-sponsored work on regional modeling, by climate researchers at Scripps, at Livermore and Berkeley National Labs, and by general circulation model

(GCM) modelers themselves. The national assessment on water (Gleick and Adams 2000) and the hydrology study by Miller et al. (2001) that is part of the current Energy Commission/EPRI project on Climate Change Impacts on California have looked at some of the model extreme precipitation and flooding cases to see what they reveal. Both the Hadley and the Canadian GCM, and the National Center for Atmospheric Research PCM model, suggest more frequent and more severe flooding in California (Gleick and Adams 2000, Miller et al. 2001).

Higher temperatures could have a large impact on natural runoff, especially in the lower elevation northern Sierra. Assuming that other factors (such as precipitation) will be the same, higher snow levels during winter storms mean more direct rain runoff, less snowpack, and less spring snowmelt runoff.

In the semi-arid climate of California, effects of climate change on water supply are paramount. As noted before, the hydrologic parameter of most importance is precipitation in enough detail to analyze individual river basins. So far, results of GCMs have not been consistent, either as a 100-year preview snapshot with higher greenhouse gases or as a progressive 100 future years of varying seasons.

The best approach for initial work on hydrologic changes would be to assume about the same precipitation and precipitation patterns as now, but with warmer temperatures. However, it would also be a good idea to look at some of the extreme model precipitation cases in the National Assessment and, as is being done, in the current Energy Commission/EPRI project on Climate Change Impacts on California.

4.2.1 Modeling Future Precipitation

Future precipitation is probably the most important variable influencing water resources and water supply. It is also most difficult to predict at the regional and watershed levels. It should be no surprise that research should continue into modeling likely future precipitation in enough detail in time and space to feed into individual watershed runoff models. Good work has been done in the University of California system, including Scripps and the Lawrence Berkeley National Laboratory, on using GCM models developed by other institutions and downscaling data into regional climate models. Continued, but slow, improvement in such models is expected.

Lawrence Livermore and Lawrence Berkeley National Laboratories—in collaboration with the National Center for Atmospheric Research (NCAR) in Boulder and other groups—are working on a Community Climate System Model. This model's planned scale, at an approximately 100-kilometer spacing grid, should improve GCM projections considerably in the next five years. Finer grid spacing will be needed, however, to better simulate mountain area precipitation.

Research Needs

Climate modelers should continue to verify and improve the large GCMs and their handling of precipitation. Newer, more powerful computers will help, and continued improvement is expected, but it is doubtful precipitation on the scale needed by the hydrologist can be modeled well in the near future. There are so many variables in modeling the atmosphere that it may not be practical to expect reliable precipitation simulation to be provided at the watershed scale in the next decade. However, atmospheric modeling should be a continuing effort and the uncertainty of future precipitation and precipitation patterns is in itself a topic of future research. There is some consistency in modeling results thus far to show a tendency for the southern part of California to be drier and the north to be wetter (Larry Gates 2001, personal comm.).

It is essential that knowledgeable university groups continue to monitor progress of the various GCM model centers around the world. This would include NCAR, the British Hadley Centre, the Canadian Centre, and the Geophysical Fluid Dynamics Laboratory at Princeton. Special attention should be given to the Community Climate System Model work previously mentioned. For now, since there is more confidence in temperature projections, the more robust temperature results can be used in watershed models, assuming the current patterns and amounts of precipitation continue in California. At the same time it would be a good idea to look at some of the more extreme cases, wet or dry, to see what the effect would be.

4.2.2 Snow Level Changes and Resulting Runoff Changes

Existing models are capable of modeling snow level and runoff changes. The U.S. Geological Survey-developed detailed hydrographic unit model, Precipitation-Runoff Modeling System (PRMS) (Leavesley et al. 1983), has been used to model a number of California basins. The National Weather Service flood forecasting model (National Weather Service River Forecast System, or NWSRFS) (Page 1996) may be useful as an alternative for evaluating some scenarios. This system was the major tool used by Lettenmaier and Gan in their seminal study of the sensitivity of the Sacramento-San Joaquin River basin to global warming (Lettenmaier and Gan 1990).

Some guidance can be expected in the near future by downscaling GCM precipitation and temperature and inputting that into hydrologic models for each watershed, as is being done by Dr. Norman Miller and his associates at LBNL. Their hydrologic model, which is really the NWSRFS model, may also have potential in deriving unimpaired runoff of major rivers for ultimate climate scenarios as input to reservoir operation studies by DWR and others.

Research Needs

Projected changes in natural runoff from California's major water production rivers should be evaluated, initially assuming precipitation patterns like the present but with higher snowpack elevations. These rivers would predominately be the major ones draining the southern Cascade and Sierra Nevada region. Ideally it would be nice to have

a watershed model and input simulating the entire watershed, including its vegetation, in all future climate regimes, but that is for the longer-range future. Practically, running a basin simulation with historical precipitation with seasonal temperature changes from the GCM work seems like a reasonable approach, using the PRMS and/or NWSRFS watershed models. Modified runoff by month, which could be obtained from the preceding watershed models, could then be routed through the reservoir systems downstream to estimate the change in the usable water supply yield.

4.2.3 Test Operation of CVP-SWP System

The combined Central Valley Project and State Water Project (CVP-SWP) system furnishes about 30% of the State's net demand for urban and agricultural water. The reservoirs of these two projects are, in large measure, located on watersheds (Trinity, Sacramento, Feather, and American) likely to see large shifts in runoff patterns as a result of rising snow levels. At least 50 years of hydrology are suggested as a minimum length for comparisons. Currently, many studies are made for the 1922–1994 historical period of 72 years and the model hydrology is now being extended through water year 1998 for a 77-year period. The longer period includes simulated operation during the two major 6-year historical droughts, 1929–1934 and 1987–1992.

Research Needs

Existing monthly reservoir operation models, like DWR's CALSIM II model, should be used to run some simple (and later, more detailed) two-step tests of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume. The CALSIM monthly simulation model, or something like it, is the best model to show potential impacts on water supply. CALSIM II simulates operation of the State Water Project and Central Valley Project system facilities, including the Sacramento and San Joaquin River system, Delta operations, and SWP and CVP deliveries to northern, central, and southern California.

These test evaluations should logically proceed in two stages, (1) a simplified run involving approximate adjustments to major project reservoir monthly inflow and (2) more detailed studies involving all major facilities, including local reservoirs and upstream power reservoirs.

Initial studies (in the two-year time frame) should focus on the assumption of precipitation similar to the historical amounts, except with higher temperatures. The initial crude estimate, which may also be confirmed with the CALVIN model developed at U.C. Davis, should provide guidance to ongoing DWR Bulletin 160 water planning and the CALFED process. The simple test, which could be done in a year by DWR, would enable some initial planning responses; better and more detailed operation studies with all major facilities in the Central Valley watershed could follow. Adjusting the operation of other locally operated reservoirs (including upstream power reservoirs) could require studies on how to approximate such an effect for initial runs. A compatible estimate of changes in

salinity repulsion requirements in the Delta, during those months when water quality standards control Delta operations, would be part of the CALSIM runs. Outputs would compare combined water project export supply, foothill reservoir hydroelectric power production, and flood control releases.

In the three- to five-year time frame, several runs could be made with varying wet and dry GCM scenarios, hopefully with year-by-year results over a long hydrologic base period, to fully evaluate the hydrologic impact of potential climate change. These later studies might include some alternative reservoir operation strategies.

Watershed input (unimpaired or natural flow of major streams) for the more detailed CALSIM model runs could be obtained from further development of the PRMS models being worked on by Scripps Institution of Oceanography. Basic input to the PRMS models would be from several GCM runs. An alternative may be the wetlands and watershed models used in the current EPRI/Energy Commission study being conducted by LBNL's California Water Resources Research and Applications Center, headed by Dr. Norman Miller. The PRMS models seem to be able to handle the snow zone changes. The NWSRFS model used by LBNL is probably better at assessing flood changes, and may be improved when Dr. Miller's group completes subdividing the incorporated Anderson snow model into finer zones or levels.

4.2.4 Impact on Reservoir Recreation

Lower summer water levels in foothill reservoirs have a strong economic impact on reservoir recreation. Lake fishing and boating are prime pursuits of recreationists; reduced volume and area has a negative influence on the fishery, too. Many of the nearby foothill communities depend on reservoir recreation and visitor spending as a substantial component on the local economy. For example, low reservoir levels at Lake Oroville during the summer of dry year 2001 noticeably hurt the local economy, according to local newspaper accounts. According to figures from the Department of Parks and Recreation, visitation at the Lime Saddle recreation area on Lake Oroville during May through August decreased about 35% in the low water years of 2000 and 2001.

Warmer summer weather may drive some visitors to higher elevation lakes, but it may also lengthen the recreation season because of presumably warmer spring and fall temperatures. Reservoir recreation is one of the many economic impacts likely as a result of global warming in California.

Research Needs

The CVP-SWP system water yield analysis, which can include monthly reservoir storage, would be a base upon which to evaluate recreational impacts, at least initially. Because a 3°C rise by year 2100 is likely to be a long-range assumption, smaller rises could be estimated by proportioning results downward for nearer futures or for smaller

temperature-increase assumptions. It would be nice to get some sense of effects for a range of temperature increases from 1 to 5°C.

4.2.5 Winter Flood Control Space

Some increase in the size of large winter floods is likely, according to the IPCC (Working Group I Summary Report 2001) and the National Assessment (Gleick and Adams 2000). Most flood control reservoirs are multipurpose, with a certain amount of dedicated flood space in the wet season, originally designed to protect downstream areas from a very large flood. That space may not be adequate if future floods are larger, but an increase in reservoir flood space would reduce all other functions of the reservoir, primarily affecting water supply and power. The alternative of increasing downstream channel capacity in developed areas will be difficult and costly. However, there may be some areas where levee setbacks are feasible. There may also be some situations where increasing the flood plain for moderate floods could add to groundwater recharge

Konstantine and Aris Georgakakos and their associates (Carpenter and Georgakakos 2001, Yao and Georgakakos 2001) have been looking into methods of improving reservoir flood control and power operations at Folsom reservoir with probabilistic forecasting. Their method is to make ensemble forecasts[1] of inflow and develop operational strategies to try to optimize benefits. The U.S. Bureau of Reclamation in Sacramento is testing use of probability inflow ensembles now, with guidelines on reservoir flood operation for Folsom from a model developed by Dr. David Bowles of Utah State University in Logan.

Another modeling option for Central Valley flood runoff and foothill reservoir operation is the hydrology and hydraulics models being developed for the Corps of Engineers Comprehensive Study of the Sacramento and San Joaquin River basins. These models can simulate flows throughout the river systems that flow into the Delta (the models do not extend into the Delta waterway system). The model work is nearing completion; with some adjustments, these models should be able to handle watershed meteorological data generated by GCMs. The models are in use for flood studies in the Sacramento District office of the Corps.[2] The upstream watershed hydrology portion is being developed by the Hydrologic Engineering Center in Davis.

Currently, the months of greatest risk of a large flood occurring are December, January, and February, and this is reflected in the seasonal shape of the flood reservation envelope (See Figure 2.) However, it is unclear whether the late winter and spring risk is increased or decreased in a warmer world. If some encroachment in midwinter reservoir flood space could start earlier in the spring, this could reduce some of the loss in water supply and hydroelectric power resulting from snow level and runoff pattern changes.

[1] An ensemble forecast is a series of equally likely future inflows (for example 10 runoff scenarios) for given conditions, reflecting the uncertainty of weather forecasts.
[2] For more information, contact the comprehensive study staff.

Research Needs

Researchers should conduct a systematic analysis of the likely increased need for flood control due to climate change. It is important to evaluate whether or not California's reservoir space is adequate if future floods are larger, and examine how an increase in reservoir flood space would affect all other functions of the reservoir (primarily water supply and power). In addition, research should explore the feasibility and cost-effectiveness of levee setbacks, new compensated flood plain storage, and alternatives for increasing downstream channel capacity in developed areas.

A small but useful project would be for PIER or the Energy Commission to sponsor a two-day seminar in Sacramento, at which the operations research specialists would explain in detail their research and suggested operational changes. The target audience would be those who operate, regulate, or plan flood control operations for major Central Valley foothill reservoirs.

Currently, the U.S. Corps of Engineers and the State Reclamation Board are engaged in a comprehensive study to improve flood management in the Sacramento and San Joaquin Valleys. Information on possible changes in flood runoff—both rain floods and, for the southern Sierra, snowmelt floods—would be valuable to them as they seek to develop alternatives for an admittedly inadequate flood system.

Research in this area also needs to target the change in risk of a large flood during each month of the rainy season—particularly whether the late winter and spring risk is increased or decreased in a warmer world. A careful examination by knowledgeable scientists of historical intense rainfall patterns and those projected by the GCMs could provide some new information. There may be one set of figures to maintain the flood protection in the original formulation, another set for the 1-in-100 year flood, and perhaps a third for the 1-in-200 year flood. In many cases, the feasibility of adding more flood space in existing reservoirs is doubtful, but the analysis would highlight the potential deficiencies in a modified climate. In some cases, there may be possible exchanges of water supply space with that in groundwater basins or new surface storage.

4.2.6 Groundwater Recharge

Natural groundwater recharge comes from streambed percolation and deep percolation of precipitation in excess of rooting zone moisture storage and the evapotranspiration of vegetation. In addition, in many basins, there is also deliberate recharge by spreading basins (artificial ponds to percolate water), delivery of water into natural watercourses for seepage and percolation, and deep percolation beyond the rooting zone on irrigated land. Even with higher CO_2 concentrations, a different (warmer) climate would likely increase the ET usage of vegetation with less left over for deep percolation. This issue is discussed in more detail in the water use section. If stream runoff becomes more flashy, that too reduces the time period for streambed seepage and percolation. Again, recharge amounts

would be strongly influenced by precipitation. If essentially historical precipitation continues, the net result probably would be a loss in the amounts historically recharged. Randall Hansen, with the U.S. Geological Survey (USGS) San Diego District office, has been studying the Santa Clara–Calleguas Basin of Ventura County, comparing historical response and some climate and long-range forecast responses. His work, which is continuing, could be a useful springboard for further research.

Research Needs

Studies of several typical groundwater basins in California should be undertaken to see how sensitive groundwater supply is to climate change. This could include some of the wetter and drier GCM scenarios. Research should focus on investigating the amounts of return flow and deep percolation of agricultural and urban applied water, and how these amounts might change in a different climate.

4.2.7 Offstream Storage

Potential impacts on offstream reservoir storage are similar to groundwater supply in many respects. The difficulty of winning approval of reservoir sites on rivers has caused water planners to turn to offstream sites, selecting a dry valley to fill with water diverted from a major river. Because of the physical limitations of conveyance systems (pumps, canals, or pipelines) bringing water from a river to the offstream reservoir, the amount of water capturable is less than it would be with a dam and reservoir on the stream. An increase in flashiness of stream runoff would reduce usable supply. This can be offset by larger diversion facilities, but at a cost. On the other hand, a wetter scenario could increase usable diversion supplies.

On snowmelt streams, the effect would probably be compounded, because snowmelt runoff is much less variable. Snowmelt runoff tends to rise relatively slowly, fluctuate, and then recede slowly. Conversion of a portion of snowmelt into winter rain runoff would yield a more variable flow, with potentially less water available between storms.

An analysis of proposed CALFED offstream storage sites is suggested, to see how much variation there is likely to be in runoff of source streams when flows are modified for global warming.

The author is not aware of any current work on this item of study.

Research Needs

An analysis of proposed new CALFED offstream storage sites is suggested to see how much variation there is likely to be in runoff of source streams when flows are modified for global warming.

4.2.8 Changes in Radiation

Greater concentrations of greenhouse gases may change incoming or reflected radiation enough to make a difference in snowpack melt. In the spring, it has been estimated that around 80% of the energy for melting snow comes from radiation. Incoming solar radiation is in the short wavelengths; reemitted radiation from the atmosphere is in the longer, infrared wavelengths. Higher concentrations of greenhouse gases, especially water vapor, could increase the infrared radiation reflected back from the atmosphere. Absolute humidity is expected to rise in a warmer world.

The University of California at Santa Barbara has conducted work measuring the effect of solar radiation input on the snowpack at a remote site in Emerald Lake basin in Sequoia National Park, but net solar radiation input to the snowpack is difficult to measure accurately in the field because of reflections from many surfaces.

Research Needs

It is recommended that careful experiments measuring radiation and its effect on snowmelt be conducted in the high Sierra snow zone. There should be enough difference between low humidity and high humidity days to see if this factor is significant. This work could build on the information developed by U.C. Santa Barbara. A more accessible site is recommended, perhaps along Highway 120 in Yosemite Park. Scripps has begun research studies in Yosemite National Park.

4.2.9 Effect of Climate Change in Other Regions

The Colorado River, which drains a huge area of the American Southwest, is a very important component of California water supply, especially in the south. Earlier studies (Nash and Gleick 1993) have indicated a high probability of change toward less runoff. Since the Colorado River water supply is already fully subscribed, if not oversubscribed, a reduction in average runoff could affect California's water supply, as well as that of the other Colorado River Basin states. In addition, hydroelectric power could be affected, especially by generation at Glen Canyon and Hoover dams, due to changes in reservoir levels.

California's long-term entitlements to Colorado River water are 4.4 million acre-feet. In recent years, California's net diversions have been around 5.2 million acre-feet, and the State is being forced to reduce its take as demands in other states build toward use of their full entitlements. Climate change in the watershed could exacerbate the water supply situation. It is also possible that a wetter scenario could improve Colorado River runoff, even to the point of generating more flood problems on the lower river.

California depends on the Pacific Northwest, including the Columbia River system, for about 10% of its electric energy supply. As seen during 2001, when Colombia River runoff is down, there is an impact on California's electric power supply and reliability.

In conclusion, the effects of climate change, especially precipitation, in the adjoining Pacific Northwest and the Colorado River watershed would have an impact on California—on electricity supply for both regions and on water supply for the Colorado River region.

Research Needs

As noted above, California may be affected by changes in annual runoff in the Pacific Northwest and Colorado River regions. It is anticipated that interested regional parties will begin new research and studies in these regions. It is recommended that the California Energy Commission and the California Department of Water Resources monitor results of these studies as they are completed and try to assess what they might mean for California water supply and electric energy imports.

4.2.10 Better Understanding of Hydrologic Variability

California climate is a sequence of wet and dry years. It would be useful to determine what climate influences, such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), are linked to drought and floods in California. The dynamics of extreme events—whether flood or drought—are not well understood, and there are questions about how well these are simulated in atmospheric models. There may be merit in extending the observed climatic record of variation by extracting high-resolution paleoclimatic data from physical indicators such as tree rings and lake sediment—especially when looking at driving forces for persistent, severe droughts. Any predictive skills that could be developed would be useful to water managers.

To the extent information can be developed on climate relationships to floods and droughts, the atmospheric GCMs should be tested to see how well these links are reproduced.

Research Needs

Researchers should make a systematic effort to look at past droughts and flood events, to categorize how they are linked to broader regional and worldwide weather patterns and to identify how they develop. There are likely to be multiple links and influences. These studies can build on research over the years by Scripps Institution of Oceanography, the Laboratory of Tree-Ring Research at the University of Arizona (in regard to past patterns determined from tree ring studies), and the National Weather Service (NWS) Climate Analysis Center.

4.3 Loss of Hydro at Foothill Reservoirs

There are essentially three elements of California hydroelectric power production: (1) run-of-the-river power plants taking advantage of unregulated or incidentally regulated river flow, (2) systems where flow is regulated by upstream power storage reservoirs where flood control is not a requirement, and (3) foothill reservoirs where power is produced more as a by-product of reservoir operations for water supply and flood control. It is

difficult to say what impact climate change would have on the first group. There may be more usable water flow; on the other hand, loss of snowmelt with its more even hydrograph (i.e., pattern of flow) may reduce hours of suitable flow. The effect on the second group of plants, where flow is regulated by upstream power reservoirs, is likely to be small. Earlier snowmelt and some winter runoff would fill the reservoirs sooner, but the operators could hold the water until the summer high electrical load season and probably produce about the same power (assuming no significant changes in annual precipitation).

The foothill groups of major multipurpose reservoirs would be expected to see the major effects. Some preliminary studies (Roos 1990) at Oroville indicated a summer season energy loss of 3 to 7 %, depending on whether operators tried to provide the same water service or reduce water releases to keep operating heads higher. The basic problem is the difficulty in filling the reservoir because of reduced snowmelt runoff after winter season flood control limits are relaxed in the late spring. Because water supply is a primary purpose of all the foothill reservoirs, an analysis of the power impact at each of the twelve major multipurpose projects could be conducted. A survey of the effect on power production for average conditions should not be very complex. The impacts probably will vary greatly from one year to another, depending on the pattern and amount of runoff. It is possible, with a wetter future climate scenario, to get an increase in hydroelectric energy production (Yao and Georgakakos 2001).

Dr. Lund at U.C. Davis is currently adapting the economic-engineering CALVIN model for power at several CVP- SWP reservoirs; some results are expected later in 2002.

To the author's knowledge, no systematic study has been made on the potential effect on hydroelectric power in California due to global warming.

Research Needs

Researchers should conduct an analysis that includes the modified monthly inflow over at least a 50-year span of hydrologic years, to better evaluate the changes in wet and dry years. Results from snow level and corresponding runoff changes and modified demands from CVP-SWP system operation are probably necessary to obtain reliable results.

4.4 Sea Level Rise

The IPCC has projected that sea level will rise between 0.1 to 0.9 meters by year 2100 (IPCC 2001). The median projection would be 0.4 to 0.5 meters—or about 1.5 feet—which means the rate in the next 100 years would more than double the rate during the twentieth century. California is not generally as vulnerable as some of the eastern and southern states, which have low shorelines. But there are areas, such as the San Francisco Bay and the Delta, which are vulnerable. Since California is tectonically active, it is the combined effect of geologic change, rising or falling land, and global sea level rise, which matters. The effect of a rising ocean would be magnified where land subsidence is occurring and

decreased where uplift is happening. Suggested items of research related to sea level rise are listed below.

4.4.1 Catalog Recent Historic Sea Level Trends along the Coast

A thorough survey of all the tide gage data and any other sea level references along the coast could produce a map containing recent decadal changes which would be helpful to land use agencies and developers along the coast.

The San Francisco Bay Conservation and Development Commission did something like this in 1988 for the Bay (SFBC and DC 1988). The California Coastal Commission has also produced a recent overview report on sea level rise (CCC 2001).

Research Needs

The objective of research in this area would be to catalog all available tide station data along the coast, in San Francisco Bay, and in the Delta. Some general information for four stations in California is contained in a Pew Center report on sea level rise (Pew 2000). Long-term data is needed (at least 20 years and preferably 50 years) to look for apparent trends in mean annual sea level. Presumably, an average of trends from San Francisco at the Golden Gate (Presidio gage) and from San Diego could be used to represent global sea level rise. Departure from that rate would be due to tectonic activity, or possibly some other effect such as oil and gas extraction. The catalog would establish a useful base to guide government and developers in the coastal zone. This survey should be conducted in the next few years.

4.4.2 Evaluate the Golden Gate Tide Gage Datum

Since the Golden Gate tide gage is the key reference point for so many sea level determinations (i.e., the central California coast, the Bay, and the Delta), it is essential that a determination of its vertical stability be made, checking for long-term vertical movement of the datum. Tools to do so may now be available by use of highly precise space geodetic techniques, such as Global Positioning Systems (GPS) and the International Terrestrial Reference Frame (ITRF), which can measure very small changes in vertical elevation. Point Blunt on Angel Island is one of the continuously operating reference stations (CORS), with an accuracy on the order of one centimeter.

Research Needs

A check on the Golden Gate tide gage datum would logically proceed in three stages: (1) compare previous precise leveling where the Golden Gate gage can be compared to nearby benchmarks (i.e., solid rock); (2) investigate whether the GPS system can be used for a precise determination of the elevation of the Golden Gate tide gage datum and its changes (if any) over time, and how long such measurements would need to be to instill confidence of a change that could be less than 2 mm (0.007 feet) per year; and (3) perform the measurements of actual tide gage datum elevations over a period of time, probably years.

The first stage could be accomplished in a year or two, the second (on which there is some doubt as to feasibility) and third could take several years of measurements.

It is recommended that the National Geodetic Survey or National Ocean Service investigate the feasibility of such a determination for the Golden Gate gage.[3] There have been claims that the apparent slow rise in sea level measured at the Golden Gate is due to settlement of the pier and tectonic movement. The precise determination, which may require several years, should lay this matter to rest.[4]

4.4.3 Effect of Higher Sea Level on Delta Levee Stability

Many levees in the Sacramento-San Joaquin River Delta are built on soft peat soil foundations. Historically, during high water at times of flooding, levees have burst with subsequent inundations of Delta islands. Sometimes this has happened during the summer, when channel stages are not unusually high. Rising sea level means channel levels in the Delta too will rise by a similar amount, increasing the risk of levee failure unless they are strengthened. Short-term changes in sea level due to El Niño events have the same effect, so changes in the frequency or intensity of El Niño events with climate change will also affect the risk of levee failure. The increase in horizontal pressure on a levee increases by the square of the increase in stage. For example, a levee withstanding four feet of water has to withstand 500 pounds of hydraulic force per linear foot of levee. But doubling the depth of water to eight feet increases the force to 2000 pounds per linear foot. Subsidence within the islands is also adding to the levee stability problem.

Research Needs

Researchers should conduct an analysis of the risk of failure for base (present) conditions, for a 0.5 feet rise (predicted at about the 2050 time frame) and a one-foot rise. Once this is done, an estimate of the change in risk due to El Niño events can be made. Some studies of levee stability were made by the Corps of Engineers in the early 1980s. A recent report was made for the CALFED Bay-Delta Program in April 2000 on seismic vulnerability of Delta levees (Torres, R. A. et al. 2000). This study showed that the greatest threat is present in the western Delta islands.

4.4.4 Salinity Intrusion

The larger factor in increasing ocean salinity intrusion in the Delta would be a longer season of controlled relatively low outflow. Model studies of the CVP-SWP system

[3] Potential contacts for work in this area would be Dr. Dennis Milbert, Chief Geodesist, National Geodetic Survey, in Silver Spring, Maryland; Marti Ikehara, California State advisor in Sacramento (office located in Caltrans); and Dr. Chris Zervas, with the National Oceanic and Atmospheric Administration (NOAA).

[4] There were some interesting reports in 2001 about measuring small changes in ground movement in the Los Angeles region with this kind of technology, including the effect of groundwater storage and extraction on land surface elevations in *Science News*, August 25, 2001, and in *Nature* magazine and also the USGS earthquake Web page.

referred to in the water supply section are needed to estimate the probable decrease in spring and early summer outflow as a result of decreased snowmelt. There is a tradeoff. Under present rules of operation, the effect in some months could be additional outflow, rather than degradation of water quality at the export pumps in the south Delta.

Scripps has done work also on salinity intrusion in the San Francisco Bay system (Knowles and Cayan 2001).

Research Needs

A separate determination of the Bay Delta system should be made with salinity models to see how much difference it would make if channels were 0.5 and 1.0 foot deeper because of ocean rise. The Scripps model may be useful in evaluating longer periods of low outflow. The more detailed modeling of smaller differences in channel depth and salinity in the Delta itself will probably require more elaborate models such as those used by DWR.

4.4.5 Silt Deposition in the Delta

The amount of silt carried into the Delta by major rivers and the amount leaving the Delta for the Bay at Chipps Island will be highly variable from year to year, depending on flood flows. The difference presumably is being deposited in Delta channels and may be enough to offset rising sea level, thereby neutralizing the depth element of additional salinity intrusion.

The USGS has been measuring sediment flow in the major rivers and the Bay. The measurement program has been conducted by scientists in the USGS Sacramento office who have been working on sediment movement.[5]

Research Needs

The amount of silt carried into the Delta by major rivers and the amount leaving the Delta for the Bay at Chipps Island should be monitored. The USGS has been measuring sediment flow in the major rivers and the Bay, and this work should continue. PIER should encourage the USGS to maintain funding of this important data collection and analysis activity.

4.4.6 Catalog of Vulnerability of Coastal Marshes and Wetlands

It is as yet unclear whether coastal marshes and wetlands (many of which are partially protected by low levees) may have problems with rising sea level and how soon such problems could arise. Cataloging historical sea level changes could provide a basis for evaluating this issue.

On its Web site, the Coastal Conservancy has information and maps of 41 coastal wetlands in southern California between the Mexican border and Point Conception in Santa Barbara

[5] Principal scientists are Randall Dinehart and David Schoellhamer.

County. This inventory is a good start and an example of what can be done for the remainder of the State. Some added analysis appears to be needed to address the vulnerability of these 41 marshes to sea level rise.

Research Needs

Projections from the recent historical sea level change would be the basis for determining whether coastal marshes and wetlands may have problems with rising sea level and how soon such problems could arise. The catalog should try to indicate whether future problems would be the result of higher water levels or more salt-water intrusion. This research should use the Coastal Conservancy's coastal wetlands data as a starting point. Remotely sensed data can provide updated information on land surface characteristics at fine scale.

4.4.7 Coastal Aquifer Salinity Intrusion

Seawater intrusion is already a problem for several California coastal basin groundwater aquifers, because water levels have been pumped below sea level inland, and there are subsurface connections between the aquifer and the sea. Higher ocean levels will increase the intrusion slightly. The simplest strategy is to keep inland water tables above sea level. In some places, a line of freshwater injection wells has halted seawater intrusion. A pumping trough (line of pumped wells) to stop the inland flow of salt water and create a seaward flow underground in a strip of land near the shore has been proposed in Ventura County as an alternative to injection wells.

Sea level rise adds to the problem, but only slightly. Oceans are not expected to rise at a rate of over 0.01 feet per year, at least to the year 2050. That rate would be about 1.5 times the apparent rate of the last several decades on the California coast. Calculating the effect of 0.01 feet per year on a fairly good-sized aquifer of 200,000 acres (about 10 by 30 miles), with a specific yield of 0.1, works out to only 200 acre-feet per year. That amount would be only a tiny fraction of the likely safe yield, which for a basin of this size could easily be over 100,000 acre-feet per year. The conclusion is that coastal aquifer additional salinity intrusion is not likely to be significant in California, but there may be a few areas where the encroachment would be a problem.

There may be more complications to underground water movement and water quality in multiple aquifer systems. The USGS office in San Diego, has made detailed studies of the Ventura County coastal aquifer, a multiple aquifer system.[6]

Research Needs

Although it does not appear to be a high climate-change priority, a test study of a multiple aquifer coastal system should be undertaken to better quantify whether a significant problem could develop due to sea level rise.

[6] Mr. Randall Hanson would be a potential contact.

4.4.8 Grade Line of Sewers and Storm Drains

In coastal and bay cities, storm drainage and treated sewage often discharge to salt water via gravity. In those cases, higher ocean levels eventually may cause some flow capacity problems. Solutions could be low-lift pumps or perhaps more pipeline capacity for drainage. Storage during high tide may be another option for certain users.

Research Needs

It would be good to identify where the gravity (or flap gate) drains are, but this is not likely to be a near-term issue, because of the slow rise in sea level estimated at less than 0.1 foot per decade.

4.4.9 Coastal Erosion

Much of the coastal erosion occurs during major storms and high tides. The sea has been eroding coastal bluffs for centuries. The process will accelerate with sea level rise. Most of the vulnerable areas have been identified. To the extent possible, it is wise to keep roads and infrastructure far enough back to provide a cushion for erosion. Shoreline protection is possible, but very expensive.

Research Needs

Changes, particularly where there are sand barriers and lagoons, are likely to be sudden, happening during major storm events. Some research in areas along the California coast judged vulnerable to rapid changes is desirable to better assess this threat (Thieler and Hammer-Klose 2001). Paleostudies reaching back to former millennia, when sea level rise was more rapid, have yielded useful information on the Texas Gulf of Mexico and East Coast. (Anderson, Rodriguez, Fletcher, and Fitzgerald 2001). Similar paleostudies may be worthwhile in California.

4.5 More Intense Precipitation Events

In a warmer world, some increase in the intensity of major precipitation events would be expected, because warm air can hold more water vapor than cooler air. Lifting of the air by mountain ranges, storm frontal activity, or convection (thunderstorms) has the potential to increase rain intensity. There is no reason to believe that California would be any more subject to hurricanes and tropical storms than today.

4.5.1 Risk of Bigger Floods and Extreme Precipitation

More intense precipitation (on the order of 10% for a 3°C rise) would generate larger floods. Another factor on streams draining high mountain areas is that many storms now produce a mix of rain with snow on the higher parts of the watershed. A warmer climate means that a greater proportion of a storm precipitation is likely to be rain, producing more direct rain runoff. Where reservoir flood control is part of the flood management structure, most storms will still be controlled to safe discharge by the dam. One of the

leading climate models suggests that El Niños may be more frequent, which could generate more frequent heavy storms in southern and central California.

Currently, reserved storage space during the winter may not be adequate for the larger storms. The result is that the degree of protection would gradually shrink. Additional flood control storage or added downstream channel conveyance capacity can be expensive. The Central Valley, in particular, has already seen a round of resizing flood protection on major rivers with numerous other studies underway. Global warming suggests that under sizing may still be a problem. Perhaps the comprehensive flood study (Corps of Engineers 2000) now being conducted by the U.S. Corps of Engineers and the (State) Reclamation Board needs to consider adding an additional allowance of say, 10%, to handle possible global warming. The cost of doing so may be in the billions.

Research Needs

As GCMs are developed and improved, researchers must analyze precipitation results to see if there is a consistent trend for more intense storms and extreme precipitation events in California. There are indications of such trends in the work of Dr. Michael Dettinger of Scripps/USGS and Dr. Norman Miller of LBNL, in their downscaling of the Hadley and Canadian GCM model runs used in the National Assessment.

4.5.2 Revise Depth-Duration-Frequency Data

Some of the most useful rainfall statistics are the rainfall depth-duration-frequency data used by many engineers and designers for storm drains, culverts, roofs, and a host of works. These are the curves, for example, which show that the 1-in-25-year storm can produce 2 inches in 2 hours at a particular place. Figure 4 shows an example for Blue Canyon northeast of Sacramento, which is a wet location. One can go to a chart like this, pick an interval of time, and determine the inches of precipitation to expect on a given return frequency.

If storm intensity increases as a result of climate change, these curves, and the structures built with their guidance, will be out of date with less protection than intended.

This kind of work is done by the DWR. Thanks to analysis of hundreds of precipitation station records by former State Climatologist James Goodridge, the DWR has a large database of short-period (24 hours or less) and long-period statistics, which is made available to requestors. The statistics are based on the historical records of precipitation, which may be gradually changing.

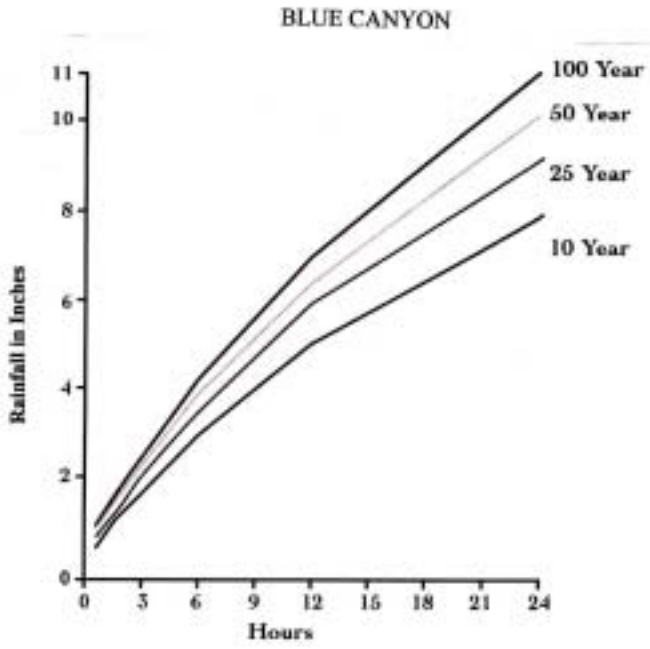

Figure 5. Depth-Duration-Frequency Curves for Blue Canyon

Source: DWR records.

Research Needs

Updating depth-duration-frequency rainfall data (or at least incorporating the data from recent storms) should be a high priority for the DWR. Practitioners may wish to incorporate a safety factor in their designs in recognition that long-term projects may be operating in a climate that can produce more intense storms.

The goal would be to prepare and maintain updated depth-duration-frequency files for the hundreds of stations in California and to post this data on the Web for Internet access. Thus designers would have ready access to the best information. This activity would require continuing funding to maintain and update the database. Preparing data for Web access should have highest priority in the next two years.[7]

It is possible that some estimates of the increase in storm intensity could be gleaned, for selected regions, from the GCM or regional climate models. It is not likely that confidence can be placed in absolute model results, but the relative comparisons of current and future GCM climate scenarios may be reasonable. When more consistent GCM precipitation results are available (probably in several years), PIER could fund a comparison study.

[7] DWR does not seem to have funding for this effort, although another funding entity could jumpstart the process during the next two years. The estimated cost would be $250,000 for the first year and $150,000 the second year.

4.5.3 Bigger Probable Maximum Floods

If extreme precipitation events are larger, one could also expect an increase in the probable maximum floods used for dam spillway design. The probable maximum flood (PMF) is the largest flood believed to be meteorologically possible in a region. It is developed by an analysis of the most severe historical storms, looking at winds, dewpoints, temperature, and storm type, then maximizing the rain producing potential by adjusting those parameters to the highest reasonable value for an area.

A warmer climate means these rare storms would have more moisture potential. Whether the wind and storm track would be the same is not certain, but a reasonable assumption is that not much change could be expected. The general southwesterly fetch storms, which currently cause the major floods, are still expected to be the type that would cause the PMF on a large watershed.

Owners of large dams periodically reevaluate their PMF and other dam safety factors. They should be made aware of the potential for somewhat larger future PMFs, especially if their spillway is only marginally acceptable. The DWR Division of Safety of Dams is in charge of the inspection of all non-federal dams in California, about 1200 in all.

Research Needs

Because GCM precipitation results are not regarded as reliable yet, there are no immediate research suggestions. In 5 to 10 years, when GCM precipitation is expected to be better, there may be a need to examine potential PMF changes where dam and spillway modification work is planned.

4.5.4 Erosion Potential

Storms with greater intensity tend to cause the most erosion. Hence, on average, greater amounts of sediment would be expected with an increase in strong precipitation events. But it may be difficult to discern the natural increase in view of all the disturbances of an increasing human population. Mountain and foothill reservoirs could see some increase in sedimentation rates.

Research Needs

The research need is to determine how vulnerable mountain watersheds would be to erosion if rainfall were to intensify. This effort is closely tied to the transition zone erosion entry under Section 4.7.2. The American River Watershed Institute in Auburn is currently partnering with the Placer County Water Agency to seek support for a paired watershed study of climate changes on Duncan and Long Canyon near French Meadows reservoir. Financial help by PIER could get the study under way. These two watersheds do have a good history of hydrologic measurements.

4.6 Water Use

There are likely to be changes in the water *use* side of the equation, as well as in water *supply*. Water consumption changes may be small, but because so much land area is involved, amounts could be very significant. Generally, a slightly warmer climate with less frost and a higher atmospheric concentration of carbon dioxide is regarded as beneficial to most food crops.

4.6.1 Change in Crop Evapotranspiration and Water Requirements

As a rule, plant evapotranspiration (ET) goes up with increasing temperature. Higher carbon dioxide levels, however, reduce water consumption (at least in laboratory tests) and seem to increase yield. In the opinion of knowledgeable researchers, the higher water consumption with warmer temperatures will probably only be partially offset by the carbon-dioxide-based reductions. The net result will be slightly higher water requirements. The situation is complicated for some of the annual crops. Here it may be possible to change the season a few weeks, which may result in no net change in water use. Tomatoes are one example. But often marketing and processing windows for produce set the planting time, limiting the farmer's flexibility.

Research Needs

The whole subject of potential crop ET and water requirements is an important area of research for university and Agriculture Extension Service people. In view of further cuts in water availability to California agriculture, changes in ET would be of great importance.

The goal would be to assess likely changes in ET in a year 2050 or 2100 scenario, with warmer average temperatures and a higher carbon dioxide content of the atmosphere. To do this, we need some reasonable median-type projections of weather by GCM modelers, and it may require new plant water consumption measurements by realistic field type experiments.

4.6.2 Indication of Recent Changes in ET

Since carbon dioxide concentrations have increased about 20% over the last 40 years, one wonders whether there is any noticeable effect on ET, especially the measured reference ET of grass, ETo. In the 1960s there were a number of well-measured grass lysimeters in various locations in California measuring directly, by weight changes, the water consumption of grass.

Research Needs

The University of California, in cooperation with DWR, should reinstall a couple of lysimeters and repeat, as closely as possible, the former measurements. Actual ET varies somewhat from year to year and day to day, depending on weather conditions. So it would probably take three to five years to see if there is a noticeable change. It is recommended that the lysimeters at Davis and the former site at Five Points in the San Joaquin Valley be reactivated to carefully measure actual water consumption for

comparison with earlier decades. The result would be field evidence of changes, if any, in plant water use due to the modest change in atmospheric carbon dioxide during the past 40 years. As a minimum, the two named lysimeters should be operated for ten years. It may take five to ten years to develop good comparable data because of the seasonal and yearly natural variations. It is also quite possible that higher carbon dioxide is a factor in the continuing improvement in California crop yields. Some university technical expertise could be directed to answering this question.

4.6.3 Change in Growing Season

Warmer climatic conditions should enable some change in the planting and growing season for annual crops. There should be more possibilities for double cropping. Many vegetables are already multiple cropped. Double cropping increases the water use of an acre; however, more produce is grown from the same acre. Market and food processing limits are also a factor in growing season determinations.

Less frost, if that happens, could increase the range of sensitive crops. For example, the orange belt in the San Joaquin Valley may be able to expand higher into the foothills and also northward. There may be some expansion too of the range of wine grape production in higher coastal and foothill valleys.

Research Needs

The California Department of Food and Agriculture should study potential cropping and growing season changes that fit a global warming scenario. As input, the climate modelers will need to be as specific as possible on changes in minimum temperatures and frost risks, as well as on the extent of extreme summer heat.

4.6.4 Effect of Changes in Winter ET on Aquifer Recharge

For many California groundwater aquifers, a significant portion of recharge comes from deep percolation of precipitation below the rooting zone, whether that of native vegetation or farmland. Temperatures several degrees warmer during the winter rainy season can be expected to increase ET, thereby drying out the soil more between storms. As a result, greater amounts of rain in subsequent storms would be needed to wet the root zone and yield excess for deep percolation. Thus, there could be fewer instances of winter percolation and a potential significant loss of natural recharge. Water users and agencies overlying groundwater basins should keep this in mind when evaluating adequacy of future supplies.

Research Needs

When future precipitation can be predicted with more confidence by the atmospheric climate models, analysis of a couple of groundwater basins in California can be made, comparing historical regimes with likely future scenarios. Since vegetation ET, whether native or planted, is an important element, this analysis should await estimates of likely changes in ET developed by research in Section 4.6.1. Because of ongoing work by

Randall Hanson, of the USGS in Ventura County groundwater basins, these basins could rank high for an initial assessment.

4.7 Other Items for Research

Items for research that do not fit well under the preceding categories are included here.

4.7.1 Water Temperature

Warmer air will make it more difficult to maintain rivers cold enough for cold-water fish, including anadromous fish. With reduced snowmelt, existing cold-water pools behind major foothill dams are likely to shrink. As a result, river water temperature could warm beyond a point that is tolerable for the salmon and steelhead that currently stay in these rivers during the summer. It is doubtful that the existing cold-water temperature standards in the upper Sacramento River could be maintained. Problems are likely for juvenile steelhead, as well.

As part of the Oroville power plants relicensing project, DWR plans to investigate existing water temperature models and possibly develop new models for Lake Oroville and the downstream Feather River. Once these tools are selected or developed, other researchers can apply them to other streams and reservoirs and begin to evaluate effects of changed climate scenarios. A need will still exist, however, to model the temperature of foothill reservoir inflow with changed climate scenarios.

Research Needs

There are several existing models of water temperature in reservoirs and downstream rivers. The primary one being used operationally is the U.S. Bureau of Reclamation monthly temperature model of the Sacramento River basin (USBR 1990).[8] This model was originally developed by the Corps of Engineers Hydrologic Engineering Center in Davis. There is a need for better models.

Researchers should analyze selected foothill reservoirs to see what a different pattern of inflow would do to temperatures in the reservoir and in the rivers below. Some have advocated planting tall trees on the riverbanks to provide more shade. Researchers should evaluate the effectiveness of doing so, as well as the conflict with flood control purposes of tall trees in leveed reaches. There may also be a need for more basic temperature data at various depths in existing reservoirs and along streams to calibrate models.

4.7.2 Transition Zone Erosion

If the snow line rises as much as 1,500 feet, a substantial zone of the Sierra and other higher mountains will see much more winter rain instead of snow. The increased direct runoff is likely to produce more erosion than the gradual runoff from melting snow. This

[8] A contact for this work is Russ Yaworsky in the Mid-Pacific Region office in Sacramento.

is obvious from the brown water typical of lower elevation river flow during a major winter storm, as opposed to the cleaner water typical of flow from spring snowmelt.

Research Needs
Researchers should study measures that could reduce winter sediment production from the transition zone. This could be an element of study that PIER could support in the proposed American River Watershed Institute paired study of two streams that was mentioned previously.

4.7.3 Water Weeds

A longer season of growth and a greater range can be expected for aquatic nuisance plants like hydrilla, pond weed (egeria densa), and water hyacinth. Cold temperatures inhibit the growth of these weeds. Currently they are controlled by mechanical means or by spraying. A special sterile triploid carp has provided good control of hydrilla in the canals of the Imperial Irrigation District. Related problems occur with invasive exotic riparian nuisance plants like arundo and salt cedar (tamarisk).

Research Needs
Research into means of control for these and other non-native aquatic weeds would be useful.

4.7.4 Increased Smog

Warmer air temperatures cause increased ozone and smog if the other atmospheric ingredients are there. The water-related issue is whether such a regime would significantly affect crop choices in some areas for farmers. The pollutants in the air may also have some effect on stream and lake water quality.

Research Needs
No immediate research is suggested on this item. But studies of atmospheric changes should be monitored and if pollution is foreseen, particularly ozone, to the extent it would significantly affect common crops, a study of potential change in cropping patterns and associated water use would be warranted.

4.7.5 Wildfires

Warmer temperatures and a longer period of dry soils during summer in the mountains could mean a greater wildfire hazard and eventual change in watershed vegetation cover. Such changes are also likely to change the runoff characteristics of the mountain watersheds, again adding sediment to the runoff. Plant life zones can be expected to shift upward. Higher carbon dioxide concentrations could promote greater chaparral growth if winter rains are adequate, increasing fuel loads. Some of the climate scenarios project more winter precipitation, especially in the southern half of California. That, along with higher carbon dioxide in the air, could further increase biomass production.

Wildfire is a natural and necessary element of many California ecosystems. Nearly a century of wildfire suppression has resulted in heavy biomass accumulations fueling a growing incidence of catastrophic, stand-replacing fires, and in widespread changes in the species composition of ecosystems. Current fire and ecosystem management policy contemplates large-scale ecosystem restoration, involving prescribed fires and mechanical fuel reductions on millions of acres and the subsequent reintroduction of sustainable fire regimes. Success of this policy depends critically on understanding past and present fire regimes, as well as understanding how climate variability and change may constrain future fire regimes and ecosystems.

Research Needs

Archival records of modern wildfire regimes need to be integrated with paleo-reconstructions of wildfires of the past in order to distinguish between the influence of climate and of management on wildfire risk. Wildfire and ecosystems management would benefit from a GIS-based model of wildfire risk that incorporates climatological and ecological changes with projections of development and population growth.

Studies of the change in wildfire risk and eventual shifts in vegetation should be undertaken. These vegetation shifts could affect runoff; greater fire frequency would probably increase sediment production, which would cause an increase in sediment buildup in downstream reservoirs. There may be wildland management practices that would counteract the trend. These practices would also need to be evaluated and tested in the field.

Again, if the American River Watershed Institute is successful in obtaining funds for its proposed paired watershed study at Duncan and Long Canyon Creeks, insights into fire induced changes may be forthcoming. Substantial portions of these two watershed were burned during the summer of 2001.

4.7.6 Increased Salinity

If temperatures go up, evaporation from reservoirs and other water surfaces will increase. Typically now, reservoir evaporation is only a few percent of total flow so the effect probably would be minor. There may not be an effect if lower reservoir levels prevail in the summer. However, if ET rates go up, a slightly greater fraction of the total moisture will transpire into the air and the drainage fraction left behind will have slightly more salts. For most of California, these kinds of water quality changes are likely to be small , but with a slight tendency toward degradation of fresh water sources. One area in California where there could be more significant problems is the lower San Joaquin River region, which may affect total maximum daily load (TMDL) limits.

Research Needs

Scientists at LBNL's Water Resources Research and Application Center in Berkeley[9] have much experience on analysis and modeling of salt and other constituents in the lower San Joaquin River system. There is merit to examining the potential for significant salinity changes on both the lower San Joaquin River and on the Colorado River. The Santa Ana River of southern California would also be a good candidate in view of its importance in recharge of the Orange County aquifer.

4.7.7 Impacts on Drinking Water Treatment

Trihalomethanes are undesirable byproducts of drinking water disinfection when chlorine is used in the presence of organic carbon. This production can be aggravated by bromide in the water supply. Urban water supplies would see a slightly greater risk of trihalomethane production in water treatment simply because the water would be warmer, which enhances trihalomethanes. Warmer water tends to have more pathogens as well, which can increase treatment costs. Solutions would be to reduce dissolved organic carbon in water supplies and possibly other methods of water treatment. However, there are many places in the world that successfully treat warmer water than California is likely to see into safe drinking water. So this should not be a major problem; satisfactory technology already exists to take care of it.

Research Needs

Because of the long range potential to affect costs and possibly methods of drinking water treatment, it would be useful to have some research on the potential effects on water treatment. A survey of practices in the southern United States and abroad should reveal how they have adapted to warmer water temperatures. Another aspect is potential changes in seasonal timing of organic carbon and bromine in Delta export water supplies.

5. Goals

The goal of the Water Resources portion of the PIER Climate Change Research Plan is to help California make decisions about water management that will protect the health and vitality of its population, ecosystems, economy, and power generation. The achievement of that goal depends on the ability to predict the effects of climate change on water supply, timing, and use.

The PIERA 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.

[9] A contact is Dr. Nigel Quinn.

5.1 Short-term Objectives[10]

The priority in water resources research should go to areas that: (1) are foundational to measuring or projecting climate change, (2) are likely to show significant effect on water resources or water use, and (3) have been identified by previous studies as being more vulnerable to problems than other areas. A second priority would be to conduct projects that are expected to yield results in a few years. The selection of the priority short-term research objections are the author's, but do reflect discussion with people in the water resources planning and project operations community.

5.1.1 Monitoring

A. Support the regular, consistent, and sustained measurement of hydrologically important variables such as precipitation and other climate data, streamflow, snowpack, and ocean and Delta tide levels.

Activities needed: (1) Support the National Weather Service's Climate Services Division in developing and operating California weather stations as part of its national climate reference network of weather stations. (2) Increase the measurements in the high Sierra snow zone, including some discrete new sites in wilderness areas.

Critical Factors for Success:

- Continued funding of the monitoring activities.

5.1.2 Depth-Duration-Frequency Data

A. Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data.

Activities needed: (1) Coordinate collection and updating depth-duration-frequency rainfall data with the Department of Water Resources. (2) Update depth-duration-frequency rainfall data. (3) Design and develop a Web-based database for dissemination of this data. (4) Maintain and update the database at intervals to be determined by DWR and PIER.

Critical Factors for Success:

- Adequate funding

[10] 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.

5.1.3 Testing Operation of the CVP-SWP System

A. Conduct a simple test of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing.

Activities needed: (1) Using DWR's CALSIM II model, run a simple test of the impact on water supply of a possible 3°C higher temperature climate scenario, assuming precipitation similar to the historical amounts, except warmer. (2) Confirm the estimates with the U.C. Davis CALVIN model.

B. Conduct detailed tests of the impact on water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume.

Activities needed: (1) Determine which model is best for developing input to the CALSIM II model, using results from watershed models such as PRMS with basic input from several GCM runs; the procedures and detailed watershed models, essentially NWSRFS, being used by Norman Miller's group in the LBNL Water Resources Research and Applications Center; or some other models that can convert GCM output into watershed runoff by month. (2) Using the selected model, run a more detailed test of the impact on water supply of a possible 3°C warmer climate scenario, conducting several runs, with varying wet and dry GCM scenarios, to produce year-by-year results over a long hydrologic base period. Include higher salinity control requirements in the western Delta as appropriate to the scenario.

Critical Factors for Success:

- The detailed tests would require a major effort by the modeling staff of DWR or any other agency that might conduct the studies with large resource inputs during the next several years.

5.1.4 Future Precipitation

A. Support the development of global climate models that can better predict future precipitation in California.

Activities needed: (1) Support of U.C. and National Laboratory experts (Scripps, UCLA, Livermore, Berkeley and elsewhere) in analyzing results of newer GCM runs by the major modeling centers of the world as they apply to California, especially in simulating historical precipitation and predicting future precipitation. Encourage feedback from these experts to the GCM modelers.

Critical Factors for Success:

- Development of models (or downscaled models) that do a reasonable job of simulating present climate patterns at the watershed level.

5.1.5 Evaluate Golden Gate Tide Gage Datum

A. Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage.

Activities needed: (1) Compare the datum elevation of the gage with nearby benchmarks sited on solid rock. (2) Compare the precise vertical elevations using a satellite GPS system.

Critical Factors for Success: The assistance of the National Geodetic Survey is essential in conducting the surveys and performing the measurements.

5.1.6 Catalog Sea Level Trends Along the Coast

A. Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast.

Activities needed: (1) Conduct a thorough survey of all the tide gage data and any other sea level references along the coast to determine apparent trends in sea level in recent decades. The map of the San Francisco Bay developed by the San Francisco Bay Conservation and Development Commission in 1988 can be a useful sample guide. The California Coastal Commission in San Francisco[11] also has data and may be willing to share in this study. Scripps Institution of Oceanography and the National Ocean Service also may be able to help.

Critical Factors for Success:

- Collection of tide gage data would require the cooperation of the several agencies mentioned above and should be documented in a detailed report.

5.1.7 Recent Changes in Evapotranspiration (ET)

A. Measure current evapotranspiration to compare current data with earlier data.

Activities needed: (1) Identify existing lysimeters in California. (2) Reinstall or reoperate lysimeters at Davis and Five Points, and maintain any other ones left from the 1960s and 1970s. (3) Maintain lysimeter operation for ten years, to account for seasonal and yearly natural variations.

Critical Factors for Success:

- Reinstatement and measurement at these two locations would require the assistance and cooperation of the University of California, Davis, and DWR land and water use analysts.

[11] Lesley Ewing is a contact.

5.1.8 Estimate Change in ET and Crop Water Requirements

A. Assess likely changes in ET in a year 2050 or 2100 scenario, with warmer average temperatures and higher carbon dioxide content of the atmosphere.

Activities needed: (1) Obtain reasonable median-type regional projections of weather, primarily temperature, from GCM modelers. (2) Have knowledgeable experts in plant water consumption at the University of California and Agricultural Extension Service and land and water use analysts in DWR estimate likely future ET rates for the major California crops by region.

Critical Factors for Success:

- Sufficient funds or grants to enable experts in government and the University system to do the necessary studies. The climate modelers need to provide likely temperatures and monthly precipitation in major agricultural areas.

5.1.9 Winter Flood Control Space

A. Conduct a systematic review and evaluation of the effect of climate change on major multipurpose flood control reservoirs.

Activities needed: (1) Conduct a systematic review and analysis of the likely increase in flood control needs with climate change on all the major flood control reservoirs in California and their ability to provide the protection in the original design, in a 1-in-100-year flood, and in a 1-in-200-year flood. (2) Determine whether it is feasible to expand flood control space in reservoirs deemed inadequate. (3) Determine whether changes in flood operation rules can help to handle bigger floods.

Critical Factors for Success:

- Some of this evaluation can be produced by the modified CALSIM II test studies of the CVP-SWP system. For the Central Valley, it would be best to await the comprehensive Flood Study findings (to use as a base).

5.1.10 Water Temperature Modeling in Rivers

A. Model water temperatures in both regulated rivers and natural streams.

Activities needed: (1) Identify rivers to model. The Feather River would be a good start in view of DWR's Oroville power relicensing study plans. (2) Collect more basic temperature data at various depths in existing reservoirs to calibrate models. (3) Model water temperatures in the rivers and streams selected. (4) Evaluate the effectiveness of potential countermeasures to unacceptable temperatures.

Critical Factors for Success:

- Development of a successful water temperature model of the Feather River and Oroville reservoir, which is anticipated as part of the power relicensing studies now underway.

5.1.11 Effect of Climate Change on Adjoining Regions

A. **Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.**

Activities needed: (1)Monitor results of anticipated studies by others on climate change effects on runoff in the Colorado River and Pacific Northwest regions. Changes there could affect California water and power supplies.

Critical Factors for Success:

- A basic assumption is that interests in the Colorado River basin or service area will sponsor new studies. Likewise, Pacific Northwest interests would be presumably doing the same in that region. If this does not happen, then California ought to sponsor analyses of likely runoff changes on the Colorado River, which would be of higher priority, because it supplies water to Southern California.

Table 3. Short-term Budget

Objective	Projected Cost ($000)
5.1.1.A Support the regular, consistent, and sustained measurement of hydrologically important variables	1500*
5.1.2.A Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data	500
5.1.3.A Conduct a simple test of the impact on water supply of the CVP-SWP system of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume and timing	600
5.1.3.B Conduct detailed tests of the impact on CVP-SWP system water supply of a possible 3°C warmer climate scenario with the expected changes in snowmelt volume, including likely upstream reservoir operational changes	1,400
5.1.4.A Support the development of global climate models that can better predict future precipitation in California	1,000
5.1.5.A Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage	100*
5.1.6.A Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast	200
5.1.7.A Measure current evapotranspiration (ET)to compare current data with earlier data	500
5.1.8.A Assess likely changes in ET in a year 2050 or 2100 scenario with warmer average temperatures and higher carbon dioxide content of the atmosphere.	300
5.1.9.A Conduct a systematic review and evaluation of flood protection adequacy in major multipurpose flood control reservoirs under projected climate scenarios	600*
5.1.10.A Model water temperatures in both regulated rivers and natural streams	400*
5.1.11.A Support monitoring of studies and research on climate change effect on runoff in the adjoining Pacific Northwest and Colorado River regions.	200*
Total Short-term Cost	**7,300**

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 total projected expenditure to complete each objective (over a three-year period).

Estimates of short-term costs to PIER and the California Energy Commission over the next three-year period are provided in Table 3. These are the author's estimates, made after consulting with others in the field, and represent approximate amounts to carry out the 12 previously listed short-term research objectives. Confidence in the cost figures is low, in view of uncertainties.

5.2 Mid-term Objectives

The foregoing items were judged of higher priority by the author, reflecting discussions with water resources specialists in State government and some local districts. It is recognized that priorities could be changed by events (such as floods and droughts) during the next couple of years. The mid-term objectives were discussed at more length in Section 4. They should begin in the 3- to 10-year time frame, although some profitable work could begin sooner if funds are available.

5.2.1 Loss of hydro at foothill reservoirs

5.2.2 Impact on reservoir recreation

5.2.3 Better understanding of hydrologic variability

5.2.4 Offstream storage (need more definitive runoff projections to do)

5.2.5 Changes in radiation

5.2.6 Delta levee stability with sea level rise

5.2.7 Catalog of vulnerability of coastal wetlands

5.2.8 Risk of bigger floods and extreme precipitation

5.2.9 Bigger probable maximum floods

5.2.10 Change in growing season

5.2.11 Water weeds

5.2.12 Effect of changes in winter ET on aquifer recharge

5.3 Long-term Objectives

Long-term research is judged of lower priority, either because of importance or because reasonable inputs in a projected changed climate would take some time to develop. These efforts are described in more detail in Section 4.

5.3.1 Natural groundwater recharge

5.3.2 Delta salinity intrusion

5.3.3 Silt deposition in the Delta

5.3.4 Coastal aquifer salinity intrusion

5.3.5 Grade line of sewers and storm drains:

5.3.6 Coastal erosion

5.3.7 Storm erosion potential

5.3.8 Transition zone erosion

5.3.9 Wildfire effects on watersheds

5.3.10 Increased river salinity

5.3.11 Impacts on drinking water treatment

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,
- solicit funds from federal and private resources to build upon their efforts, or to co-design new projects at the Energy Commission, and
- provide seed money to begin items of research, with the goal of having others continue the effort once it is started.

6.2 Opportunities

Co-sponsored efforts are already under way with EPRI. Co-sponsorship opportunities are likely with the National Weather Service, Scripps Institution of Oceanography, LBNL, Lawrence Livermore National Lab, the National Center for Atmospheric Research, the USGS, the California Department of Water Resources, the University of California at Davis, the U.S. Corps of Engineers, the State Reclamation Board, the Georgia Institute of Technology, CALFED, the University of California at Santa Barbara, the San Francisco Bay Conservation and Development Commission, National Geodetic Survey, Caltrans, NOAA, EPRI, California Coastal Conservancy, and the California Department of Food and Agriculture. Each of these organizations is interested in addressing climate issues.

The California DWR is interested in research that could affect water planning and plans to make adaptation to climate change part of its Bulletin 160 discussions and work plans. DWR also proposes, if funding permits, to be active in monitoring and processing and disseminating depth-duration-frequency rainfall data. The following specific collaborative opportunities have been identified:

Monitoring

The National Weather Service, in its newly reorganized Climate Services Division, is developing a climate reference network of 250 weather stations as a national benchmark of

long-term climate monitoring stations. Probably about five will be located in California, and PIER could cosponsor or co-fund work at those stations.

Water Supply
The California Energy Commission and EPRI are already evaluating water supply changes in California that may result from climate change.

- **Modeling Future Precipitation**
  Scripps Institution and the Lawrence Berkeley National Lab have used GCM models developed by other institutions and downscaled them into regional climate models. PIER could leverage these efforts.

  In addition, Lawrence Livermore and Lawrence Berkeley National Laboratories—in collaboration with the National Center for Atmospheric Research in Boulder and other groups—are working on a Community Climate System Model. PIER could support this work.

- **Snow Level Changes and Resulting Runoff Changes**
  The USGS, the National Weather Service, Scripps Institution of Oceanography (Climate Research Division) and LBNL have all conducted work in this area. PIER should investigate potential co-funding or collaborations with these entities.

- **Test Operation of CVP-SWP System**
  The California Department of Water Resources, the University of California at Davis, Lawrence Berkeley National Laboratory, and the Scripps Institution of Oceanography (Climate Research Division) may all offer collaborative or co-funding opportunities.

- **Impact on Reservoir Recreation**
  The California Department of Water Resources could offer some collaborative or co-funding opportunities in this area.

- **Winter Flood Control Space**
  The U.S. Corps of Engineers and the State Reclamation Board are engaged in a comprehensive study to improve flood management in the Sacramento and San Joaquin Valleys. The U.S. Bureau of Reclamation, with help from Utah State University, is testing a new approach to flood control at Folsom Reservoir.

  Dr. Konstantine Georgakakos, Managing Director of the Hydrologic Research Center in San Diego, California and research scientist at the Scripps Institution of Oceanography has been evaluating this issue, as has Dr. Aris Georgakakos, Director of the Georgia Water Resources Institute and professor at the Georgia Institute of Technology.

- **Groundwater Recharge**
  The U.S. Geological Survey has been investigating recharge in Ventura County.

- **Offstream Storage**
  Work in this area would be based on previous CALFED work; therefore, PIER should approach CALFED for collaborative and co-funding opportunities.

- **Changes in Radiation**
  The University of California at Santa Barbara has conducted work in this area. Scripps Institution of Oceanography is beginning a data gathering effort in Yosemite National Park, with the cooperation of the NPS and others.

Loss of Hydro at Foothill Reservoirs
Work is under way by Dr. Jay Lund at UC Davis adapting the CALVIN model for power production from several multipurpose reservoir hydro units.

Sea Level Rise
- **Cataloging Recent Historic Sea Level Trends along the Coast:** The San Francisco Bay Conservation and Development Commission, the California Coastal Commission and Scripps Institution of Oceanography.
- **Evaluation of the Golden Gate Tide Gage Datum:** National Geodetic Survey; Caltrans; and NOAA
- **Higher Sea Level on Delta Levee Stability:** EPRI, DWR, CALFED, Scripps Institution of Oceanography
- **Salinity Intrusion:** Scripps Institution of Oceanography and the Department of Water Resources
- **Silt Deposition in the Delta:** U.S. Geologic Survey
- **Catalog of Vulnerability of Coastal Marshes and Wetlands:** California Coastal Conservancy
- **Coastal Aquifer Salinity Intrusion:** Department of Water Resources
- **Grade Line of Sewers and Storm Drains:** Major San Francisco Bay Area cities and East Bay Municipal Utility District
- **Coastal Erosion:** California Coastal Commission

More Intense Precipitation Events
- **Risk of Bigger Floods and Extreme Precipitation:** U.S. Corps of Engineers and The (State) Reclamation Board
- **Revise Depth-Duration-Frequency Data:** The Department of Water Resources
- **Bigger Probable Maximum Floods:** DWR Division of Safety of Dams
- **Erosion Potential:** American River Watershed Institute

Water Use

- **Change in Crop Evapotranspiration and Water Requirements:** Universities and Agriculture Extension Services
- **Indication of Recent Changes in ET:** University of California at Davis
- **Change in Growing Season:** California Department of Food and Agriculture
- **Aquifer Recharge:** Perhaps U. S. Geological Survey or DWR

Other Items for Research

- **Water Temperature:** DWR in its Oroville power relicensing study
- **Transition Zone Erosion:** Perhaps American River Watershed Institute
- **Water Weeds:** Irrigation districts
- **Increased Smog:** California Department of Food and Agriculture
- **Wildfires:** U.S. Forest Service, American River Watershed Institute, Scripps Institution of Oceanography
- **Increased Salinity:** Central Valley Regional Water Quality Control Board
- **Impacts on Drinking Water Treatment:** Metropolitan Water District of Southern California

7. Areas Not Addressed by This Roadmap

The suggested research plan has not intentionally avoided any aspects of California water resources associated with climate change.

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Appendix A
Current Status of Programs

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

Current Status: California

California Department of Water Resources

- The California Department of Water Resources has several studies underway. First is the California Water Plan Update, Bulletin 160–03, to be published in 2003. Second is the relicensing study for the Oroville power plants scheduled to be complete in 2005. Third would be proposed processing and Web dissemination of updated depth-duration-frequency rainfall data. Fourth, in cooperation with The Reclamation Board, participation in the Comprehensive Flood Study in the Sacramento and San Joaquin River basins, with the feasibility report scheduled for late 2002. The U.S. Army Corps of Engineers is the major partner in the Comprehensive Study.

California Energy Commission

- In cooperation with the Electric Power Research Institute, the Energy Commission has undertaken an ambitious program to evaluate the potential effects of climate change under different GCM scenarios in California. Items of study include hydrology, water resources, agriculture, energy and timber, and coastal resources.

University of California

- The California Applications Program *Improved Weather and Climate Forecast Information for California* is an ongoing program involving many researchers in the University of California and National Laboratory System who have been, and are doing, a wide variety of research on weather, weather forecasting, climate, and climate change. Much of the funding has come from NOAA. This program began in 1998 and is continuing. The program is administered by the Climate Research Division, Scripps Institution of Oceanography, in La Jolla (Dr. Daniel Cayan, director).

CALFED

- This is an ongoing cooperative Bay-Delta program of many federal and State agencies working on California water and environmental problems, with emphasis on the Delta. It is expected that the Program will invest $1 to 5 million per year for the next 10 years on climate change implications.

California Water Resources Research and Applications Center, Lawrence Berkeley National Laboratory, University of California.

- This group has been making a number of water resources studies and modeling studies, which include climate change. The most recent is a Climate Change Sensitivity Study of California Hydrology by Dr. Norman Miller and Kathy Bashford, assisted by Eric Strem of the NWS California-Nevada River Forecast Center in Sacramento, which is part of a California Energy Commission study administered by EPRI. The Center also receives funding from the U.S. Department of Energy.

U.S. Geological Survey

- The USGS has a number of important monitoring studies dealing with stream runoff, water quality, groundwater, coastal erosion, and climate change induced runoff changes on several California rivers, salinity in the San Francisco Bay, sedimentation in the Delta, Ventura County groundwater, and paleostudies of past climate. Many of these are continuing.

Hydrologic Research Center (San Diego) and Georgia Water Resources Institute (Atlanta)

- Konstantine and Aris Georgakakos have been investigating reservoir operations for some time. Recent studies have involved probabilistic forecasting, weather forecasting and climate change. They have proposed a five-year project, INFORM, for research development technology transfer and a demonstration program to users of the climate information for water resources management. Funds are being sought from the NOAA Office of Global Programs.

Current Status: Regional and National

U. S. Global Change Research Program

- The Global Change Research Program was established under the auspices of the President's National Science and Technology Council in 1989 and authorized by Congress in 1990. It is coordinated by a multi-agency Subcommittee on Global Change Research established by the Council's Committee on Environmental and Natural Resources. Research studies are conducted by nine federal agencies. The National Assessments for the nation and for a number of regions were funded by USGCRP. The Program seeks to provide a sound scientific understanding of the human and natural forces that influence the Earth's climate system—and thus provide a sound scientific basis for national and international decision making on global change issues. It seeks to observe, understand, predict, and assess the critical natural and human-induced dynamic states and trends of the Earth's global environmental system across a wide range of time and spatial scales.

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).

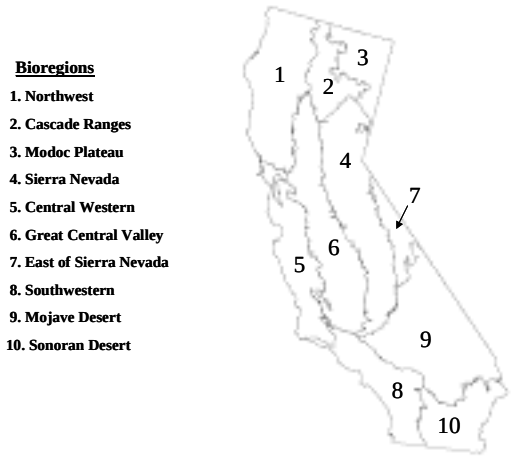

Figure 1. Bioregions of California

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).

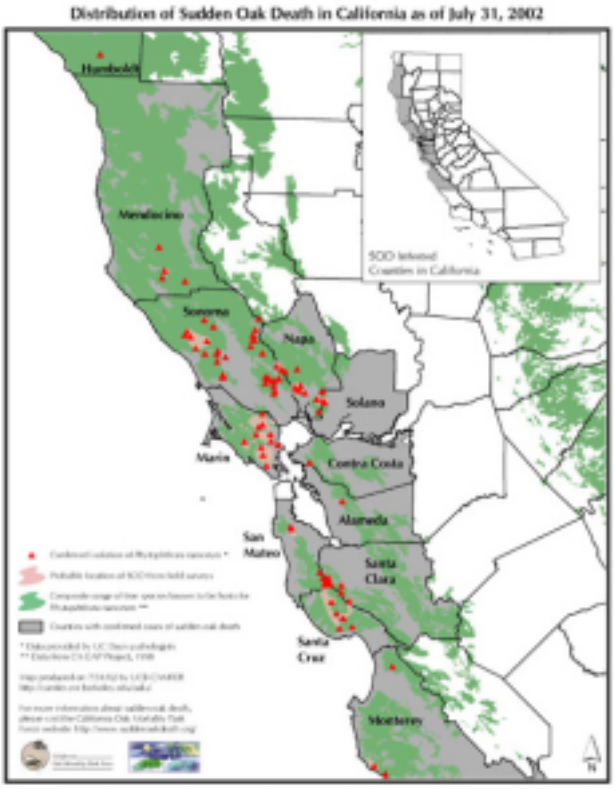

Figure 3. Distribution of Sudden Oak Death

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.

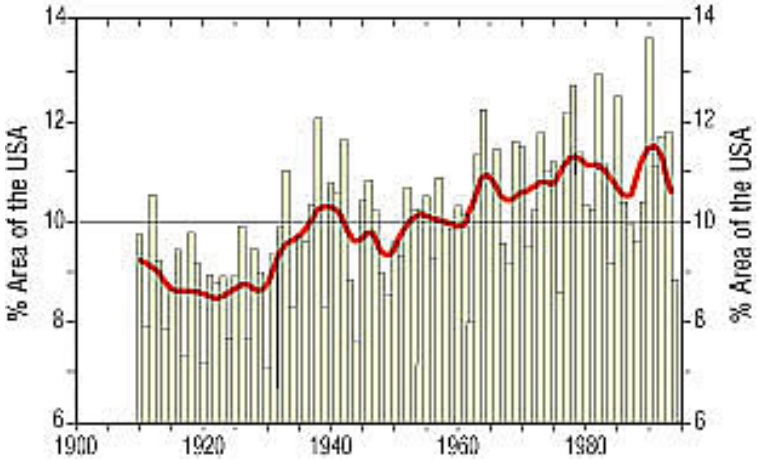

Figure 4. Extreme Precipitation Events in the United States
The area (expressed in percentage) of the United States, excluding Alaska and Hawaii, with an unusually large amount of total annual precipitation coming from extreme precipitation events (those with more than 5.08 cm {2 inches} of rainfall {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,

[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.

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 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

Attachment IV

Carbon Sequestration in California's Terrestrial Ecosystems and Geologic Formations

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Executive Summary

Carbon sequestration in terrestrial ecosystems and geologic formations provides a significant opportunity for California to address global climate change. The physical size of its resources (e.g., forests, agriculture, soils, rangeland, and geologic formations) and the expertise in California provides a substantial foundation for developing carbon sequestration activities. Furthermore, the co-benefits of carbon sequestration—such as improved soil and water quality, restoration of degraded ecosystems, increased plant and crop productivity, and enhanced oil recovery—are significant. In fact, carbon sequestration often represents a "no regrets" strategy, because implementing carbon sequestration provides multiple benefits even without the advent of global climate change. Nevertheless, several research issues need to be addressed to determine more accurately the potential of carbon sequestration in California. The California Energy Commission's Public Interest Energy Research (PIER) Program will need to collaborate and coordinate this research with other key organizations in California, nationally, and internationally.

Six major research objectives have been identified for the PIER Program to address:

1. Establish the California Carbon Sequestration Network
2. Improve the Understanding of Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations
3. Identify and Assess the Technical Feasibility and Carbon Impacts of Carbon Sequestration Strategies in California
4. Evaluate the Cost-Effectiveness of Carbon Sequestration Strategies in California
5. Evaluate the Environmental and Social Impacts of Carbon Sequestration Strategies in California
6. Develop Guidelines for the Design, Implementation, Monitoring, Evaluation, Reporting, Verification, and Certification of Carbon Sequestration Projects in California

The resources needed to address these issues are anticipated to be significant, and the PIER Program will need to be selective in funding the first set of activities. The PIER Program seeks to leverage these efforts with other organizations, to enable California to address all of the above objectives.

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

Objective	**Projected Cost ($000 per year)**
Establish the California Carbon Sequestration Network	15
Improve the Understanding of Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations	
• Improve the understanding of carbon flux	250
• Improve the understanding of carbon sequestration in soils	250
• Improve the understanding of carbon sequestration in biomass and bioenergy	250
• Improve the understanding of geologic sequestration	250
Identify and Assess the Technical Feasibility and Carbon Impacts of Carbon Sequestration Strategies in California	
• Forestry carbon sequestration strategies	400
• Agricultural, rangeland, and soil carbon sequestration strategies	400
• Bioenergy carbon sequestration strategies	400
• Geologic carbon sequestration strategies	400
Evaluate the Cost-Effectiveness of Carbon Sequestration Strategies	
• Develop carbon supply curves for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California	400
• Conduct special economic studies of bioenergy	600
Evaluate the Environmental and Social Impacts of Carbon Sequestration Strategies in California	
• Conduct an environmental analysis of bioenergy strategies in California	150
• Conduct an environmental analysis of soil carbon sequestration strategies in California	150
• Conduct an environmental analysis of geologic carbon sequestration strategies in California	150
• Quantify the environmental and social benefits and costs of carbon sequestration strategies in California	150
• Evaluate the impacts of carbon sequestration on wildfires	150
• Conduct a life-cycle analysis of urban carbon-based residuals	150
Develop Guidelines for the Design, Implementation, Monitoring, Evaluation, Reporting, Verification, and Certification (DIMERVC) of Carbon Sequestration Projects in California	150
Total Short-term Cost per Year	**4,665**

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 on a per-year basis over three years.

The Public Interest Energy Research (PIER) Climate Change Research Plan also identifies mid-term (3–10 year) and long-term (10–20 year) goals, some of which build on the short-term work listed above.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 an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

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. *Section 4: Current Research and Research Needs* surveys current projects addressing carbon sequestration in terrestrial ecosystems and geologic formations 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 this area of climate change research that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being done to address carbon sequestration in terrestrial ecosystems and geologic formations.

Acronyms

ARS	Agricultural Research Service (USDA)
ANL	Argonne National Laboratory
BNL	Brookhaven National Laboratory
BDT	Bone Dry Tons
CH_4	Methane
CO_2	Carbon dioxide
CARD	Center for Agricultural and Rural Development (Iowa State University)
CASMGS	Consortium for Agricultural Soils Mitigation of Greenhouse Gases
CC	Conservation Compliance
CDF	California Department of Forestry and Fire Protection
CREP	Conservation Reserve Enhancement Program (USDA)
CRP	Conservation Reserve Program (USDA)
CSiTE	Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (USDOE)
CTA	Conservation Technical Assistance (USDA)
CTIC	Conservation Technology Information Center
DIMERVC	Design, Implementation, Monitoring, Evaluation, Reporting, Verification and Certification
EPRI	Electric Power Research Institute
EQIP	Environmental Quality Incentive Program (USDA)
ERS	Economic Research Service (USDA)
FACE	Free Air CO_2 Enrichment program
FPP	Farmland Protection Program (USDA)
GHG	greenhouse gas
GtC	Gigaton of carbon (10^9 tons of carbon)
GTI	Gas Technology Institute (formerly, the Gas Research Institute)
INS	Inelastic Neutron Scattering
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
LIBS	laser-induced breakdown spectroscopy
LANL	Los Alamos National Laboratory
MMT	million metric tons
MMTC/yr	million metric tons of carbon per year
MMTCE	million metric tons of carbon equivalent
N_20	Nitrous oxide
NASA	National Aeronautics and Space Administration
NRCS	Natural Resources Conservation Service (NRCS)
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PIER	Public Interest Energy Research
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)

SOC	soil organic carbon
SWP	Small Watershed Program (USDA)
SCM system	Soil carbon measurements system
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WHIP	Wildlife Habitat Incentive Program (USDA)
WRP	Wetland Reserve Program (USDA)

1. Issue Statement

It is necessary to develop data, methods, and tools that researchers and decision makers can use to sequester carbon, in order to reduce the release of carbon dioxide to the atmosphere while promoting the health, sustainability, and productivity of California's forests, agriculture, rangelands, geologic formations, and natural ecosystems.

2. Public Interest Vision

Carbon sequestration in terrestrial ecosystems and geologic formations provides a significant opportunity for California to address global climate change. The physical size of its resources (e.g., forests, agriculture, soils, rangeland, and geologic formations) and the expertise in California provides a substantial foundation for developing carbon sequestration activities. Furthermore, the co-benefits of carbon sequestration—such as improved soil and water quality, restoration of degraded ecosystems, increased plant and crop productivity, and enhanced oil recovery—are significant. In fact, carbon sequestration often represents a "no regrets" strategy—implementing carbon sequestration provides multiple benefits, even without the advent of global climate change.

Nevertheless, researchers need to address several issues to determine more accurately the potential, benefits, and costs of sequestering carbon in California's terrestrial ecosystems and geologic formations, as well as to identify the most promising sequestration methods and their optimal implementation. Researchers must better understand carbon sequestration processes and mechanisms, identify and assess the technical feasibility and carbon impacts of carbon sequestration practices in California, evaluate carbon sequestration economics for the State, evaluate the potential environmental and social impacts of implementing carbon sequestration strategies, and develop standardized guidelines that those who implement sequestration strategies can use to receive credits in emissions trading markets.

The California Energy Commission's Public Interest Energy Research (PIER) Program will need to collaborate and coordinate this research with other key organizations in California, nationally, and internationally. The development of an entity to oversee and coordinate California's carbon sequestration efforts would facilitate partnerships, leverage resources, and coordinate research

3. Background

3.1 Global Warming and the Need for Carbon Sequestration

Evidence for global climate change is accumulating, and there is a growing consensus that the global temperature is believed to be rising due to human activity that releases carbon dioxide (CO_2) to the atmosphere (i.e., global warming) (IPCC 2001a). The major culprits are thought to be fossil fuel burning, cement production, and changes in carbon sequestration caused by land use, such as lack of regeneration after wood harvesting,

extended shifting cultivation, drainage, and soil erosion (*ibid.;* Lal and Bruce 1999). For example, during the period 1850–1998, approximately 405 gigatons of carbon (GtC)[1] was emitted as CO_2 into the atmosphere as a result of fossil fuel burning and cement production (67%) and land use and land use change (33%), predominantly from forested areas (IPCC 2000).

In California, CO_2 emissions in the state account for about 85% of in-state greenhouse gas (GHG) emissions,[2] and 98.2% of those emissions are attributed to the combustion of fossil fuels (Franco 2002). In terms of total CO_2 emissions from fossil fuel combustion in California in 1999, transportation accounts for the largest portion of emissions (59%), followed by power production (16%), non-power-production industrial activities (12%), the residential sector (9%), and the commercial sector (4%).

In order to reduce carbon emissions into the atmosphere, research is expected to continue in California to (1) develop new carbon-free electricity generating technologies, (2) substitute lower carbon or carbon-free energy sources for existing sources, (3) increase the energy efficiency of fossil-based generation, and (4) reduce the demand for energy by improving the overall energy efficiency of equipment and services. Nevertheless, fossil fuels will continue to be used to generate power and fuel transportation in the foreseeable future. Accordingly, California needs to investigate all the options available to reduce net fluxes of carbon into the atmosphere and increase storage of atmospheric carbon in reservoirs such as trees and other vegetation, soils, and geologic formations (e.g., oil fields, coal beds, and aquifers).[3]

For example, terrestrial ecosystems offer significant potential to capture and store carbon at modest social costs: a U.S. Department of Energy (USDOE) white paper recently stated that terrestrial offsets represented the only set of commercially mature technologies that had the capability to reduce the concentrations of GHG in the atmosphere (USDOE 2001a). Furthermore, the Intergovernmental Panel on Climate Change's Second Assessment Report estimated that about 60 to 87 GtC could be conserved or sequestered in forests by the year 2050 and another 23 to 44 GtC could be sequestered in agricultural soils (IPCC 1996). Toward the end of this time interval, the mitigation impact could approach a maximum rate of 2.2. GtC/year. Recognizing the importance of carbon sequestration in combating global climate change, the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) established the principle that carbon sequestration can be used by participating nations to meet their respective net emission reduction targets for CO_2 and other greenhouse gases (UNFCCC 1997). Finally, in the 2002 California State Legislature, Senate Bill 812 proposes that the California Climate Action Registry take action on establishing a

[1] 1 GtC = 10^9 tons carbon.
[2] The other sources of GHG emissions are methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.
[3] *Carbon flux* is the exchange of carbon between carbon aquatic and terrestrial pools and the atmosphere.

carbon inventory for forestry (this bill is still under discussion). Such inventories are essential to defining and directing carbon sequestration research in the state.

3.2 Carbon Sequestration Basics

The purpose of carbon sequestration is to keep anthropogenic carbon emissions from reaching the atmosphere by capturing them, isolating them, and diverting them to secure storage, and/or to remove CO_2 from the atmosphere by various means and store it (USDOE 1999). Converting atmospheric carbon into biomass or soil organic matter (known as carbon sinks,[4] reservoirs, or pools) eliminates its impact as a greenhouse gas until it is again released into the atmosphere. There are at least six ways of removing CO_2 from the atmosphere and storing it or keeping anthropogenic carbon emissions from reaching the atmosphere (*ibid.*):

- Sequestration in terrestrial ecosystems
- Sequestration in geologic formations
- Sequestration in the oceans
- Separation and capture of CO_2 from the energy system
- Advanced biological processes
- Advanced chemical processes

This paper focuses on the first two methods: sequestration in terrestrial ecosystems and in geologic formations. Future papers may address one or more of the remaining issues.

3.2.1 Sequestration in Terrestrial Ecosystems

Terrestrial ecosystems, including forests, vegetation, soils, farm crops, pastures, tundra, and wetlands, act as huge natural biological scrubbers for CO_2. Carbon can be sequestered in terrestrial ecosystems by means of a variety of techniques, including increasing photosynthetic carbon fixation of trees and other vegetation, reducing decomposition of plant residues and soil organic matter, reversing land use changes that contribute to global emissions, and creating energy offsets through the use of biomass for electricity generation, fuels, or beneficial products (e.g., furniture) (USDOE 1999). The terrestrial ecosystem presently sequesters about 2 GtC per year globally.

Terrestrial ecosystems provide only temporary storage for carbon, because carbon may be released by anthropogenic and natural disturbances, and forest products and litter can decay over a finite period of time. The temporal nature of carbon storage in forests implies that its primary role will be to sequester carbon for finite time periods, which will allow the implementation of more long-term options for the avoidance of GHG emissions, and stabilization of climate change (Sathaye et al. 2001). The substitution of products from sustainably managed forests for carbon-intensive and other forest

[4] The term *sink* is used to mean any process, activity, or mechanism that removes a greenhouse gas from the atmosphere. Examples include: farmland, rangeland, and forests.

products, or for carbon-intensive fuels, however, offers an opportunity for the long-term removal of GHG emissions (*ibid*.).

As illustrated in Table 1, California is composed of a variety of terrestrial ecosystems. The great majority of this acreage offers opportunities for carbon sequestration. The impacts on forest and agricultural ecosystems will be addressed in a future chapter of the PIER Global Climate Change Research Plan.

Table 1. Statewide Habitat Types in California, by Owner (thousand of acres)

Habitat Type	Private	U.S. Forest Service	Bureau of Land Mgmt.	National Park Service	Other Public	Total
Conifer Forest	6,432	10,644	394	1,108	426	19,004
Conifer Woodland	458	1,051	482	220	151	2,363
Hardwood Woodland	4,292	310	239	36	309	5,188
Hardwood Forest	2,901	1,287	176	134	193	4,691
Shrub	5,433	5,673	2,261	319	878	14,565
Herbaceous (Rangeland)	9,621	233	496	43	526	10,919
Desert	4,298	200	10,253	4,678	4,119	23,548
Wetland	334	69	12	22	103	540
Agriculture	11,201	4	42	(< 500 acres)	174	11,421
Barren	229	918	203	680	254	2,283
Urban	4,606	17	29	8	250	4,909
Water						1,486
Total	**49,805**	**20,406**	**14,587**	**7,247**	**7,384**	**100,915**

Source data: California Department of Forestry and Fire Protection, Fire and Resource Assessment Program (http://frap.cdf.ca.gov/projects/frap_veg/count_state_habitat.pdf)
Note: Some columns may not total exactly, due to rounding.

3.2.1.1 Sequestration in Forests

Forests play an essential role in the global carbon cycle. Tree growth in forests serves as an important means to capture and store atmospheric CO_2 in vegetation, soils, and forest products. Forests occupy one-third of the U.S. land mass (747 million acres) and, in 1999, sequestered 310 million metric tons of carbon (Wayburn et al. 2000). About 31% of California is covered by forest ecosystems (Horwath et al. 2001). Much of this forestland is in federal, state, and urban parklands. Although most California forests are not managed nearly as intensively as agricultural sites, they do offer the substantial advantage of providing excellent long-term carbon storage in long-growing, woody species (i.e., for thousands of years, barring natural disasters).

Changes in management of existing forested lands can increase the amount of carbon per unit of area, and restoration of trees in riparian areas offer another very good opportunity. However, forest loss appears to be growing exponentially in California, where more forest land was lost between 1982 and 1997 than during the previous thirty years (1950 to 1980) (Best and Wayburn 2001). In fact, the U.S. Forest Service expects the greatest loss in the next fifty years to come from the Pacific Region: e.g., close to 20% (12 million acres) of non-

industrial forest land is expected to be lost to development in California during this time period (*ibid*.).

The California Department of Forestry and Fire Protection, through its Fire and Resource Assessment Program (FRAP), conducts an ongoing Land Cover Mapping program with the USDA Forest Service (USFS). This monitoring detects ongoing changes in vegetative cover in California, to help identify shifts in carbon storage capacity in the state.

There are basically three categories of forest management practices that can be employed to curb the rate of increase in carbon dioxide in the atmosphere (Brown et al. 1996; Watson et al. 1996). These categories are: (1) management for carbon conservation, (2) management for carbon sequestration and storage, and (3) management for carbon substitution (Table 2).

Table 2. Types of Forestry Carbon Sequestration Projects

Carbon conservation management	• Forest reserves /reduced deforestation • Modified forest management • Reduced degradation (e.g., from fires and pests)
Carbon substitution management	• Biomass for energy generation • Substitution for fossil-fuel based products
Carbon sequestration and storage management	• Afforestation • Reforestation • Urban forestry • Agroforestry • Natural regeneration • Biomass enrichment • Forest product management

Source: Adapted from Watson et al. (1996).

The goal of carbon conservation management is primarily to conserve existing carbon pools in forests as much as possible through options such as controlling deforestation, protecting forests (forest preservation), modified forest management (e.g., reduced impact logging, hardwood control, sound silvicultural practices, firewood harvests, more efficient use of wood, and fertilization), and controlling other anthropogenic disturbances such as fire and pest outbreaks ("reduced degradation"). Because harvest or conversion to non-forest use releases substantial quantities of carbon into the atmosphere (potentially, for an extended period), avoiding or delaying harvest or conversion (particularly in old-growth forests) provides the most significant near-term carbon gains.

The goal of carbon sequestration and storage management is to expand the storage of carbon in forest ecosystems by increasing the area or carbon density of natural and plantation forests and increasing storage in durable wood products. Thus, this includes afforestation (i.e., the planting of trees in areas where trees have been absent in recent times), reforestation (i.e., the planting of trees where trees had recently been, but currently are absent), urban forestry (i.e., the planting of trees in urban or suburban settings), and agroforestry (i.e., planting and managing trees in conjunction with agricultural crops). Other activities include natural regeneration, biomass enrichment, and forest product management.

Carbon substitution management aims at increasing the transfer of forest biomass carbon into products (e.g., construction materials and biofuels) that can replace fossil-fuel-based energy and products, cement-based products, and other building materials. This type of management includes short-rotation woody biomass energy plantations.

Several studies have shown that growing trees to sequester carbon could provide relatively low-cost net emission reductions for the United States (Adams et al. 1993; Callaway and McCarl 1996; Newell and Stavins 1999; Parks and Hardie 1995; Richards, Moulton, and Birdsey 1993; and Stavins 1999). The U.S. Forest Service estimates that if the full spectrum of existing technologies and management systems were implemented nationwide, carbon storage in forests and forest products would increase by 50% over current levels. A recent study using NASA-developed satellite data indicate that current levels of carbon sequestration in North American forests is about 140 million tons of carbon a year (MMTC/yr)—approximately 11% of the United States' annual emissions (Myneni et al. 2001).

3.2.1.2 Sequestration in Agriculture

In 1996, U.S. agricultural activities were responsible for emissions of 114.1 million metric tons of carbon equivalent (MMTCE),[5] or between 6 and 7% of total U.S. GHG emissions (USDA 1999). Agricultural activities contribute CO_2 emissions primarily through combustion of fossil fuels, decomposition of soil organic carbon, and biomass burning. Principal agricultural activities that may lead to an increase in carbon sequestration are numerous (Table 3) (Cole et al. 1995; Lal 1997a and 1997b; Lal and Bruce 1999).

Agriculture represents over 11% of California's land base (Table 1). In this report, agriculture includes irrigated pasture, row crops, orchards, and other agricultural enterprises. If one were to add herbaceous/rangeland acreage (unirrigated grasslands used for grazing), agriculture and rangeland represent over 22% of California's land base (Table 1).

[5] *MMTCE* is used when counting multiple greenhouse gases. For example, methane is 23 times as potent a greenhouse gas as CO_2 and can be converted to a "CO_2 equivalent" using this factor.

Table 3. Types of Agricultural Carbon Sequestration Projects

• Conservation tillage[6] and residue management	• Range and land management
• Cover crops	• Pest and disease control
• Improved crop rotations	• Control of invasive species
• Irrigation and water management	• Soil fertility improvement
• Crop mix alteration	• Restoration of degraded soils
• Conservation buffers	• Restoration of salt-affected soils
• Crop fertilization alteration (including organic amendments)	

A portion of the plant biomass produced during agricultural production is harvested; however, varying amounts are returned to the soil in the form of residue, and different crops or varieties of crops can be selected to enhance residue production. Also, crops can be grown specifically to produce organic material for the soil (e.g., cover crops) during times, such as winter, when conventional agricultural products cannot be grown. Buffer strips surrounding agricultural fields can also be managed for carbon sequestration.

Some agricultural production is associated with perennial vegetation that will sequester carbon and can be manipulated by management strategies. Some examples are orchards that provide wood for stocks on fine firearms or range vegetation that has not reached climax and has the potential for increased above-ground growth with less grazing. Agro-forestry (shrubs and trees associated with landscaping) also contributes to carbon sequestration, as well as reduced carbon emissions and heat sink reduction. Marginal lands or areas that are reverting from agriculture back to natural ecosystems also have the potential to sequester carbon.

Agriculture is intimately linked to soils: agricultural ecosystems contain 2.6 times more carbon in soil than in vegetation (USDOE 2001a). The agricultural activities noted above often result in improved soil carbon sequestration, as noted in the next section.

3.2.1.3 Sequestration in Soils

Major loss of soil organic carbon follows conversion of virgin forest and grassland to cropland and subsequent anthropogenic activities, such as plowing, biomass burning, residual removal, drainage, low fertilizer input, lack of or low level of application of organic amendments, summer fallowing, and the low frequency of incorporating cover crops in a rotation cycle (Lal and Bruce 1999).

The rate of carbon accumulation and release in soils varies with many site-specific factors, such as: chemical and physical characteristics of the soil, precipitation, above- and below-ground biology, temperature, solar radiation, atmospheric chemistry and processes,

[6] *Conservation tillage* refers to any tillage and planting system that maintains at least 30% of the oil covered by residue after planting to reduce water erosion (Lal and Bruce 1999).

landscape characteristics, site history (including past management practices), time, and current land use (USDA 1999). Soils having the greatest potential to sequester carbon are those that are below their carbon carrying capacity, meaning young soils and soils that have been depleted of carbon due to management practices. Because the large majority of U.S. and California cropland has been in production for several decades, their large initial release of carbon has already occurred and current releases are now very low—estimates range between 2.7 and 15 million metric tons of carbon annually (Gephart et al. 1994; Lal et al. 1998). Thus, simply reducing practices that lead to carbon losses could increase carbon storage in soils. California's agricultural soils show additional promise for sequestration, because many are managed year round. In fact, their intense management increases their value and the efficacy of using them as a carbon sequestration tool.

Soil conservation (e.g., converting marginal lands to compatible land use systems, restoring degraded soils, and adapting best management practices) reduces soil erosion and increases the organic matter content of soils (USDA 1998). Use of winter cover crops and improved cropping rotations can increase the amount of plant material available to form soil organic matter.[7] Conversion from continuously cultivated cropland to improved pasture could also create a large short-term carbon sink. Although conservation tillage (e.g., minimum tillage, mulch tillage, ridge tillage, and no-till) is not yet widespread in California, these strategies appear to offer a substantial potential for increasing carbon sequestration in soil. Conservation tillage reduces soil disturbance and loss—as well as energy use—but does not impact crop yields or quality. In fact, over 36% of U.S. farmers use conservation tillage already, and in Iowa the percentage is even higher—over 60% (Kurkalova et al. 2001).

Collectively, U.S. and California soils (especially, agricultural soils) have a relatively high potential for being managed to store additional carbon. In fact, soil carbon sequestration is considered by some to be the best long-term option for carbon storage in terrestrial systems, because most forms of soil organic matter have a longer residence time than plant biomass (USDOE 1999). Soil is predicted to constitute as much as 73% of the carbon sequestration potential available in the world (Horwath et al. 2001). United States cropland soils alone currently sequester 15 to 20 MMTC/yr, with the capacity to sequester 60–150 MMTC/yr more (Pew 2001). Grazing lands potentially could add an additional 50 MMTC/yr (*ibid.*). Another estimate predicts that U.S. agricultural soils could sequester between 75–200 million metric tons of carbon annually (Lal et al. 1998). It is estimated that 20–40% of targeted emission reductions can be met by agricultural soil carbon sequestration alone. In fact, some research has estimated that increases in agricultural soil carbon sequestration could delay the need for more technically complex solutions for another 35 years, possibly saving $100 million or more (Edmonds et al. 1996, 1997). This option is appealing, because the agricultural infrastructure already exists to make use of research findings that would enhance the cost-effectiveness of existing practices and soil conservation programs.

[7] For example, one recent study showed a 36% increase in soil organic carbon over 12 years when conventional agricultural practices were changed to cover crop/organically managed cropping practices (Horwath et al. 2001).

3.2.1.4 Bioenergy

Bioenergy is energy derived from biomass. Biomass may be produced from purpose-grown crops or forests, from urban carbon-based residuals, or as a byproduct of forestry, sawmilling, and agriculture. Biomass can be utilized directly for heat energy or converted into gas or electricity for energy production (especially, small modular biomass systems, sized from 5 kW to 5 MW).[8] Currently, biomass sources account for 3% of our nation's total energy consumption (USDOE 2001c). There are over 1,085 bioenergy facilities in the United States, with a total capacity of approximately 12,295 MW; California has 170 of these plants, with a total capacity of approximately 997 MW (NREL 2002). Net carbon emissions from bioenergy generation of a unit of electricity are 10 to 20 times lower than emissions from fossil-fuel-based electricity generation (Boman and Turnbull 1997; Mann and Spath 2000; Matthews and Mortimer 2000).

In California, crops such as sugar beet, corn, sunflower, and woody hybrids can be used for biofuels (Horwath et al. 2001). Bioenergy is also produced in the forestry sector. With short-rotation forests for bioenergy, harvesting occurs approximately every 5–12 years, and regeneration is accomplished through replanting or coppicing[9] (USDOE 1994). Longer–rotation plantations and natural forests can also be used for producing biomass for power generation (Carpentieri et al. 1993; Hall 1997; McLain 1998; Perlack et al. 1991; Russell et al. 1992; Swisher 1994; Swisher and Renner 1996). Thus, the cultivation of bioenergy resources such as short-rotation forestry can mitigate climate change, not only by replacing fossil fuels in the energy system, but also by storing additional terrestrial carbon in trees. Furthermore, to the extent that harvests are sustainable, the biomass fuel supplied from the same land can continue to prevent carbon emissions indefinitely in the future.

Carbon-based residuals can also be a source of biofuel, while offering multiple benefits. Over 25 million tons of carbon-based residues are landfilled in California each year, contributing to the overall emissions of CO_2 and methane. Finding efficient, cost-effective means of using a portion of these residues as biofuel could replace CO_2 emissions from fossil-fuel plants, as well as those from the landfills (Friedman 2002).

California's biomass resource is much larger than what is currently being used. As shown in Table 4, total biomass in wastes and residues exceed 56 million bone dry tons (BDT) per year—ten times the current use to date (Springsteen 2000). Of this, 16 million BDT can be considered available, with a much larger fraction available if forest fuel-reduction programs and energy crops production were to be developed in California (Springsteen 2000).

[8] Biomass can also be used for fuels (ethanol and renewable diesel) for transportation and in chemical manufacture. These subject areas are not the focus of this roadmap.
[9] The practice of cutting a tree or bush near the ground to promote the generation of more sprouts.

Table 4. Biomass Wastes in California

Source	Gross Production (MM BDT/yr)	Current Use (BDT/yr)		Amount Available (MM BDT/yr)
		Fuel (1)	Other (2)	
Lumber mill	5.5	1.75	3.25	0
Forest slash	4.5	0.25	0	2.5
Forest thinnings	3.8	0.25	0	1.4
Wood agricultural	2	0.75	0	1.4
Urban wood	3.2	1	0.5	0.7
Urban yard	3.9	0.2	0.5	1.2
Waste paper	13	0.2	4	2.5
Waste plastic	2.5	0.1	0.1	0.8
Field crops	4.5	0.1	0	2.8
Sewage sludge	0.7	0.1	0	0.6
Shells, pits, hulls	1	0.4	0.2	0.5
Livestock manure	12	0.1	0	2
Total	56.6	5.2	8.55	16.4

Notes: (1) Used in biomass and municipal waste combustion units.
(2) Uses include particle board, plywood, animal bedding, fertilizer, landscaping.
Source: Springsteen 2000.

3.2.2. Sequestration in Geologic Formations

Geologic sequestration is a form of direct sequestration, where CO_2 is captured from large point sources of anthropogenic emissions, transported, and injected into underground formations. Some of these underground formations have structure, seals, porosity, and other geologic properties that make them ideal for long-term CO_2 storage. Geologic formations are likely to be the first large-scale option to be considered for CO_2 storage, because developers of geologic storage technologies can draw on the experience gained from oil, gas, coal, and water-resource management (USDOE 2002a). For example, the petroleum industry is currently injecting 30 million tons of CO_2 per year into geologic formations for improving oil recovery (USDOE 2002b). Geologic sequestration also has cost advantages, because many power and industrial power plants are located near suitable geologic sites.

Carbon dioxide can be sequestered in geological formations by three principal mechanisms (Table 5). Geologic formations under consideration for mitigating CO_2 emissions include depleted oil and gas wells, unmineable coal seams, organic-rich shales, aquifers, and deep saline groundwater systems.

Table 5. Types of Geologic Carbon Sequestration Mechanisms

• Hydrodynamic trapping[10]
• Solubility trapping[11]
• Mineral-trapping[12]

Research has produced a large range of estimates for global geologic sequestration: e.g., 140 to 310 GtC for depleted gas wells and 40 to 190 GtC for depleted oil wells (IEA 2002). The estimates for CO_2 sequestration in U.S. geologic formations are sizeable, too: 1 to 130 GtC in deep saline reservoirs, 10 to 25 GtC in natural gas reservoirs, 0.3 GtC/year in active gas fields, and 10 GtC in enhanced coal-bed methane production (NETL 2001). A study of geologic sequestration options for California suggests that oil reservoirs, gas fields (in the near term), and brine formations (in the long term) present the most promising geologic reservoirs for carbon in the state (Benson 2000). The sequestration of carbon in California oil fields may be an especially attractive option if it is implemented with enhanced oil recovery.

3.3 Co-benefits of Carbon Sequestration

Carbon sequestration is not the only benefit that would result from implementing practices that increase the amount of carbon in California lands. Many carbon management strategies also deliver environmental, productivity, energy, and economic benefits (Table 6). For example, improved forestry and agricultural management practices will reduce soil erosion, resulting in the reduction of loss of nutrients and the improvement of water quality. Increasing the acreage of protected forests will improve wildlife habitats and increase biodiversity. Establishing forestry plantations will lead to more biomass products, rural economic development, and a reduced dependence on oil imports (where wood is used for bioenergy). And injecting carbon dioxide into oil or natural gas reservoirs will enhance oil recovery, leading to a reduced dependence on oil imports.

[10] CO_2 is trapped as a gas or supercritical fluid under a low-permeability caprock, similar to the way that natural gas is trapped in gas reservoirs or stored in aquifers.
[11] CO_2 dissolves into the fluid phase (e.g., petroleum).
[12] CO_2 reacts either directly or indirectly with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix (e.g., formation of calcium, magnesium, and iron carbonates).

Table 6. Co-benefits of Carbon Sequestration

Environmental	Economic/Productivity/Energy
Improved salmonid and wildlife habitat	Enhanced methane recovery from coal beds
Improved soil and water quality	Increased plant and crop productivity
Reduction in soil erosion and runoff	More biomass products
Decreased nutrient loss	Development of exportable technologies
Decreased water and pesticide use	Enhanced oil recovery from oil or natural gas reservoirs
Reduced concentrations of GHGs (methane[13] and nitrous oxide[14])	Reduced dependence on oil imports (enhanced national energy security)
Restored degraded ecosystems	Decreased energy use[15]
Increased biodiversity	Rural economic growth
Increased water conservation	
More sustainable land use and food production	

Sources: Pew 2001, USDOE 1999, USDA 1998.

3.4 The PIER Focus

Global climate change and the role of atmospheric carbon in a changing climate is inextricably linked to electricity production in California. Both in- and out-of-state fossil power plants emit CO_2 while producing electricity for California consumers. Those emissions contribute to climate change, which in turn affects the state's ability to *produce* power (e.g., through changes in the timing and strength of precipitation, which can affect hydroelectric production), as well as the state's *demand* for power (e.g., through hotter temperatures that require an increased demand for cooling).

The mission of the PIER Program is to conduct public interest energy research that seeks to improve the quality of life for California's citizens by providing environmentally sound, safe, reliable, and affordable energy services and products. Evaluating carbon sequestration opportunities and implementing efficient, cost-effective, and environmentally sound projects that produce multiple benefits addresses those goals.

[13] Through bioenergy projects.

[14] Through changes in crop mix, fertilization, and tillage practices. However, it is possible that NO_X could increase without proper controls.

[15] Trees in cities lower the albedo (i.e., reflectivity) of the urban surface and allow for evapotranspiration, thereby resulting in cooler temperatures and less demand for air conditioning. In Modesto, researchers performed a benefit-cost analysis of energy and CO_2 reductions attributable to the city's municipal urban forest (McPherson et al. 1999). Results indicated that the benefits residents obtained from Modesto's public trees exceeded the city's management costs by a factor of nearly two. This study concluded that Modesto's urban trees provided tangible air quality, flood control, energy conservation, aesthetic, and CO_2-reduction benefits, and further predicted that the city could claim credits for these benefits as CO_2 trading markets develop.

Carbon sequestration in terrestrial ecosystems and geologic formations is a global, interdisciplinary effort that draws from and builds upon a wide pool of state, regional, national, and international research. Many of the PIEREA efforts identified in this roadmap build upon or are connected with this large body of work, in an effort to both avoid duplication and to develop stronger state capabilities to address these issues. PIEREA seeks to leverage the best technical knowledge about carbon sequestration from the broader community with the knowledge and expertise of California's resource agencies, to enable the state to assess and exploit its carbon sequestration options to the fullest.

4. Current Research and Research Needs

Successful carbon sequestration must: (1) be effective and cost-competitive with other carbon management options, (2) provide stable, long-term storage (i.e., it must be predictable and reliable), (3) be measurable and verifiable, (4) avoid and/or minimize adverse environmental and socioeconomic impacts; and (5) be acceptable to the public (USDOE 1999). In order to achieve these goals, California research needs to:

1. Improve the understanding of processes and mechanisms involved in carbon sequestration in terrestrial ecosystems and geologic formations in California
2. Identify and assess technical feasibility and carbon impacts of carbon sequestration practices in California
3. Evaluate the economics of implementing carbon sequestration strategies in California
4. Evaluate the environmental and social impacts of implementing carbon sequestration strategies in California
5. Develop guidelines for the design, implementation, monitoring, evaluation, reporting, verification, and certification of carbon sequestration projects in California
6. Develop the California Carbon Sequestration Network (CCSN)

These research areas are interrelated and the results from one research area will inform the other areas (e.g., improved methods will provide better estimates of carbon sequestration potential). These activities do not have to be conducted sequentially: for example, for some forest types, there may be sufficient information for identifying and assessing carbon sequestration practices. Finally, although not a research activity per se, the California Carbon Sequestration Network should be established soon, as described in Section 4.6.

The following discussion outlines the status of current work in these areas and identifies scientific and research gaps and research issues. For more detailed information on specific projects, see Appendix A.

4.1 Improve the Understanding of Processes and Mechanisms of Carbon Sequestration in California

Estimating the technical feasibility and the potential for increasing carbon sequestration in terrestrial ecosystems is difficult, because the biogeochemical dynamics that control the flow of carbon among plants, soils, and the atmosphere are poorly understood (USDOE 1999). Researchers will need to review existing mechanistic information about carbon sequestration potential, determine how relevant it is to California, and determine if there is missing information uniquely associated with California. Technological advances (including the use of remote sensing by aerial and satellite-based technology) will be needed for the comprehensive measurement of CO_2 fluxes and carbon stocks (above and below ground) at a range of scales in terrestrial ecosystems (USDOE 2001a). Similar studies will be needed to improve the measurement of CO_2 in geologic formations, in order to understand the behavior and the predictability of CO_2 in geologic storage.

All research addressing carbon sequestration processes will have to account for California's changing vegetative landscape under climate change. To direct their research effectively, plant physiologists and foresters will need information and input from climate change eco-modelers and analysts focusing on the state's changing landscape.

4.1.1 Carbon Flux

One important area for improving our understanding of carbon is the measurement of the rate of exchange between carbon aquatic and terrestrial pools (also known as *sinks* or *reservoirs*) and the atmosphere (known as *carbon flux*). This flux is measured to quantify the movement of carbon and to identify significant carbon repositories. This research topic has been the focus of much activity in recent years in California: (1) AmeriFlux is collecting carbon flux data at over 60 sites in North, Central, and South America, and six of these sites are in California; (2) the California Energy Commission, the Electric Power Research Institute, the California Department of Forestry and Fire Protection (CDF), and Winrock International are planning to conduct field studies to measure carbon flux in an area in California, both with and without carbon sequestration methods; and (3) studies on grassland are under way at Stanford University, where researchers at the Field Lab of the Carnegie Institution of Washington are studying carbon flux in grasslands and other flora at the Jasper Ridge Biological Preserve (see Appendix A for more details).

Related types of studies on carbon flux have been conducted outside of California, by the following organizations: EUROFLUX, FLUXNET, CarboEurope, Colorado State University (in collaboration with the U.S. Department of Agriculture's (USDA) Agricultural Research Service), Texas A&M, and Oak Ridge National Laboratory (ORNL), University of Nebraska, and the U.S. Forest Service (see Appendix A for more details).

Research Needs

- It is unclear whether AmeriFlux's six California sites are sufficient for obtaining accurate data on carbon flux in California's key ecosystems. Researchers need to assess this capability and determine if additional sites are warranted.
- Research needs to evaluate the adequacy of existing ecosystem models for estimating carbon flux in California's ecosystems. If needed, these models will be modified and calibrated with field data from California ecosystem. In some cases, new ecosystems models may need to be developed and calibrated with California field data.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) carbon flux data collection activities in California, (b) California-based field studies of carbon flux, and (c) carbon flux and ecosystem modeling in California. Researchers should make the databases on these efforts accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare case studies of the "best" carbon flux field studies and modeling.

Proposed research to address these research needs is described in Section 5.1.2.A.

4.1.2 Soils

Although the studies of soil productivity and associated topics are old research endeavors, researchers still have only a rudimentary understanding of the biogeochemical processes that control turnover times[16] in both forestry and agricultural soils (USDOE 1997). For example, research is needed to improve our understanding of the physical, chemical, and biological processes involved in conversion of plant material to carbon-containing compounds that are chemically and physically inert. Changes in soil carbon are difficult to measure, because of soil variability and lack of historical information on how soils have been managed. Sequential changes in soil carbon can be measured over time, but the slow rate of change makes such measurement difficult (USDA 1998). Nevertheless, because of the significant potential for sequestering carbon in soils, a great deal of work on this topic is ongoing. This research will aid understanding of the mechanisms by which agricultural practices (such as tillage, fertilization, pesticide and herbicide application, crop rotation, irrigation fallowing, and erosion control) influence carbon storage and which of these practices, or combinations of practices, will lead to enhanced carbon storage without unduly interfering with agricultural productivity or causing ecological harm.

The development of new field-deployable, laser-based instruments for measurement and characterization of soil carbon will revolutionize the practice of soil carbon science and allow for a more accurate accounting for terrestrial carbon sequestration, as well as for verification of soil carbon sequestration projects. These instruments will need to be calibrated to a wide variety of soils and tested in the field. Because they are so highly

[16] Turnover time is the time required to convert organic carbon to inorganic forms such as CO_2.

managed, there is a great deal of variety in California's agricultural soils, and researchers must measure many locations to capture all of the agricultural soil diversity.

Modeling of soil carbon will also have an important role. Researchers will need to evaluate existing models of carbon budgets and carbon sequestration (such as the CENTURY model) and assess their applicability for use in California. Once promising models are selected, researchers will need to apply these models to California at a county level (or some equivalent scale) for monitoring carbon flow. Land use, soil types, and climatic zones are extremely variable in California; therefore, small-scale modeling is necessary to establish data that researchers can evaluate to develop larger-scale modeling scenarios. Long-term field experiments will need to be conducted for validating soil carbon models.

Researchers throughout the United States are using models and taking measurements to predict the effects of environmental conditions and management practices on sequestration of carbon in soils. A number of studies have been, and are being, conducted in California: (1) the University of California's (UC) Kearney Foundation of Soil Science supports basic and applied research throughout the UC system on topics related to soil carbon in managed and natural ecosystems in California; (2) the Sustainable Agriculture Farming Systems (SAFS) project (1988 to 2001) at UC Davis compared conventional agricultural management systems to low input and organic management systems, with respect to each system's impacts on soil carbon, nutrients, productivity, soil biota, weeds and pests, and economics; and (3) UC Davis' Long-Term Research Agricultural Systems (LTRAS) project is measuring changes in soil carbon with various management systems (see Appendix A for more details).

Several related studies on soil carbon have been conducted outside of California, including the following organizations: the Consortium for Agricultural Soil Mitigation of Greenhouse Gases (CASMGS) (including Michigan State University and Colorado State University); the Pacific Northwest National Laboratory (PNNL); the University of Alberta; Texas A&M; Ohio State University; USDA; University of Nebraska; Iowa State University; and the USDOE Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE) (see Appendix A for more details).

Research Needs

- An understanding of the biogeochemical processes that control turnover times in California forestry and agricultural soils is critical. Researchers need to assess this understanding, and if warranted, conduct additional field studies in California on these processes.
- It is unclear whether sufficient field studies have been conducted on analyzing carbon sequestration strategies in forestry and agriculture on soil carbon. There is a need to assess these studies and determine if additional field studies are warranted.

- Improved technologies for measuring carbon in soils have been developed in recent years. Research needs to study the application of these technologies to the measurement of soil carbon in selected agricultural and forestry soils.
- Research needs to evaluate the adequacy of existing soil carbon models for estimating carbon in California's soils. If needed, these models will be modified and calibrated with field data from California soil ecosystems. In some cases, new soil carbon models may need to be developed and calibrated with California field data.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) California-based field studies of conversion of plant material to soil carbon, (b) California-based field studies of the influence of carbon sequestration strategies in forestry and agriculture on soil carbon, (c) California-based field studies on the application of new techniques for the measurement of carbon agriculture and forestry soils; and (d) California-based field studies on soil carbon models. Databases on these efforts should be made accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare case studies of the "best" carbon soil carbon field studies, sequestration activities, technologies, and models.

Proposed research to address these research needs is described in Section 5.1.2.B.

4.1.3 Biomass and Bioenergy

Comprehensive analyses of carbon sequestration through the use of biomass fuels entail measurement research in four areas: (1) plant sciences (e.g., optimal types of biomass to use); (2) production and collection of the biomass (e.g., agricultural practices and harvesting,); (3) transportation of the biomass to the power plant (e.g., proximity to generation source, ease of handling, method of transport);[17] and (4) processing and conversion of biomass into power and fuels (e.g., raw feedstock, gas, or liquid for combustion or chemical reaction in a fuel cell) (USDOE 2001c).

At the national level, the National Renewable Energy Laboratory (NREL) serves as the primary focus for USDOE programs in biomass conversion, but other biomass activities are managed through Oak Ridge, Argonne, and Sandia National Laboratories. USDOE's Biomass Power Program is developing prototypes of small modular biopower systems.

Research Needs

For plant sciences research, studies will be needed for improving the understanding of the inherent plant metabolism and regulation of carbon flow, enabling design of particular characteristics (e.g., higher oil content or more or less lignin), depending on the targeted use of the crop or vegetation in bioenergy. For production and collection, research will be needed for: (1) improving productivity in terms of yield per acre and yield per unit input,

[17] The distance that biomass must be transported from its point of sequestration to the point of generation is an important cost element of the total system (USDOE 1997). Therefore, reducing that distance or the associated transport costs would improve the economic prospects for all of the CO_2 extraction/sequestration systems.

and (2) more efficient systems for the design, production, and handling of dedicated crops. For processing and conversion, research is needed for developing economical new techniques for separating plant components and for delivering and processing urban carbon-based residuals, more effective conversion processes for biomass materials, improved fermentation processes, improved biopower systems (e.g., gasification and pyrolysis, gas cleanup, and ash use), and successful demonstrations of existing or near-term technologies (e.g., biomass combustion and steam systems for power, and gasification for power and fuels). Most importantly, research is needed for improving theory and practice of sustainable forestry and agriculture to maintain biodiversity and ecosystem functions while also increasing yields of biomass for energy. Large test areas could be used to examine the potential of biomass development in California (Jacobs 2002).

- There is a need to review and assess the current understanding of plant metabolism, regulation of carbon flow, and ways of improving plant and tree productivity.
- It is unclear whether sufficient California-based field studies have been conducted on plant metabolism, regulation of carbon flow, and ways of improving plant and tree productivity. Research needs to assess these studies and determine if additional field studies are warranted.
- The design, production, and handling of dedicated crops for biomass are some of the key elements in the biomass industry. Case studies are needed for improving these processes.
- The techniques for separating plant components, conversion processes for biomass materials, fermentation processes, and biopower systems are other key elements in the biomass industry. Technology and field studies are needed for developing economical new techniques for separating plant components and for delivering and processing urban carbon-based residuals, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems.
- Biomass and bioenergy projects will not be successful in the long term if the forestry and agriculture practices supporting these projects are not sustainable. Hence, there is a need to improve the theory of sustainable forestry and agriculture practices for biomass/bioenergy. In addition, researchers need to conduct demonstrations of sustainable forestry and agriculture practices for biomass/bioenergy.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) California-based field studies on plant metabolism and regulation of carbon flow for biomass, (b) California-based field studies on improving plant productivity for biomass, (c) efficient systems for design, production, and handling of dedicated crops for biomass in California; and (d) economical new techniques for separating plant components, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems. Databases on these efforts should be made accessible on the Wide World Web.

- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on: (a) improving plant productivity for biomass, (b) efficient systems for design, production, and handling of dedicated crops for biomass in California, (c) economical new techniques for separating plant components, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems, and (d) sustainable agricultural and forestry practices for biomass and bioenergy.

Proposed research to address these research needs is described in Section 5.1.2.C.

4.1.4 Geologic Formations

Lawrence Berkeley National Laboratory (LBNL) has a geologic carbon sequestration project (the GEO-SEQ Project) that is being implemented with ORNL and other partners. They are investigating safe and cost-effective methods for geologic sequestration of CO_2. At the national level, the USDOE has identified geological sequestration as an important component of it carbon sequestration program. Several offices at USDOE are conducting research in this area, including the Office of Science and the Office of Fossil Energy. In addition to LBNL's project, other projects are being conducted by Texas Tech University, University of Utah, Battelle Laboratories, the University of Texas, and Sandia National Laboratory and Los Alamos National Laboratory (LANL). The U.S. Geologic Service (USGS) also has a geologic sequestration project.

There are several areas requiring better information on geologic sequestration, including the following (USDOE 2002a):

- Research is needed to improve our understanding of (1) equilibria between multi-component gases, oil, and water; (2) long-term effects of CO_2 on oil and gas reservoir properties; (3) multiphase fluid movement, phase transition, density and viscosity effects, and geochemical reactions at the micro scale; (4) the effects of hydraulic issues, such as lateral and vertical migration, well integrity, caprock integrity, permeability, pressure buildup, sweep efficiency, density and viscosity effects, and storage capacity at the injection-well scale; (5) formation of complex carbonates in deep saline formations; (6) fate and transport of CO_2 in the subsurface; and (7) the impacts of additional chemicals or microorganisms to be injected to ensure safe and effective sequestration.
- Research is needed to collect data on (1) stress-related changes to integrity of caprock and reservoir; (2) reservoir properties and capacity of saline aquifers; (3) CO_2 vertical and lateral migration in saline aquifers; (4) solubility and mineral trapping in brine systems in saline aquifers; (5) location and integrity of abandoned wells; (6) long-term corrosion effects; and (7) long-term interactions of CO_2 and storage reservoirs.

The monitoring and verification of CO_2 storage is costly (USDOE 2002a). Hence, there is a need to develop reliable, cost-effective, and affordable technology, models, and methods for monitoring and verifying/validating geomechanical models of carbon sequestration in

geologic formations (*ibid.*). These tools would be used to determine the ability of abandoned oil and gas fields, for example, to sequester CO_2 for long periods. These methods will also be used for monitoring subsurface CO_2 concentrations, phase behavior, and reaction products to ensure the effectiveness and safety of geologic sequestration. These tools will also be used in field tests for monitoring of (1) CO_2 storage in oil and gas reservoirs and aquifers, (2) natural CO_2 seepage, (3) CO_2 leakage mitigation, and (4) economically feasible corrosion resistant materials.

Research Needs

- The understanding of carbon flow in geologic formations is limited and needs to be improved, especially to address the following areas: (a) equilibria between multi-component gases, oil, and water; (b) long-term effects of CO_2 on oil and gas reservoir properties; (c) multiphase fluid movement, phase transition, density and viscosity effects, and geochemical reactions at the micro scale; (d) the effects of hydraulic issues, such as lateral and vertical migration, well integrity, caprock integrity, permeability, pressure buildup, sweep efficiency, density and viscosity effects, and storage capacity at the injection-well scale; (e) formation of complex carbonates in deep saline formations; (f) fate and transport of CO_2 in the subsurface; and (g) the impacts of additional chemicals or microbiota to be injected to ensure safe and effective sequestration.
- To improve our understanding of these issues, researchers need to conduct field studies in different geologic formations. These studies will collect information on the following types of data: (a) stress-related changes to integrity of caprock and reservoir; (b) reservoir properties and capacity of saline aquifers; (c) CO_2 vertical and lateral migration in saline aquifers; (d) solubility and mineral trapping in brine systems in saline aquifers; (e) location and integrity of abandoned wells; (f) long-term corrosion effects; and (g) long-term interactions of CO_2 and storage reservoirs.
- Research needs to asses the methods for verifying and validating geomechanical models of carbon sequestration in geologic formations and, if needed, develop more reliable, cost-effective, and affordable methods.
- Researchers need to apply existing and new methods for monitoring of: (a) CO_2 storage in oil and gas reservoirs and aquifers, (b) natural CO_2 seepage, (c) CO_2 leakage mitigation, and (d) economically feasible corrosion resistant materials.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) California-based field studies on carbon dynamics in geologic sequestration, (b) methods and technologies for monitoring carbon storage, leakage, and seepage in geologic formations, and (c) economically feasible corrosion resistant materials for geologic sequestration. Databases on these efforts should be made accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on: (a) field studies on carbon dynamics in geologic sequestration and

(b) methods and technologies for monitoring carbon storage, leakage, and seepage in geologic formations.

Proposed research to address these research needs is described in Section 5.1.2.D.

4.2 Identify and Assess the Technical Feasibility and Carbon Impacts of Carbon Sequestration Strategies in California

There are numerous options for sequestering atmospheric carbon in vegetation, soils, and geologic formations. However, there is a need for a systematic and comprehensive assessment of carbon management opportunities to help forest, agricultural, rangeland, and natural resource managers to identify and compare options for a particular California region or application.

The California Energy Commission is collaborating with EPRI on a project to measure, classify, and quantify carbon market opportunities in the United States. Sponsors of the project will receive tools, data sets, and methodologies to evaluate and formulate carbon strategies and to design and implement practical near-term projects. The effort is also establishing baselines for participants' projects, developing a national land classification system, and constructing a database containing information on the size and cost of carbon storage opportunities in one region of the United States. The funding entities participating in this project will select the region of study.

4.2.1 Forest Carbon Sequestration Strategies

Several studies on forest carbon sequestration strategies have been conducted outside of California, including those conducted by the following organizations: Michigan State University, the USDA Forest Service, University of Maine, and the Woods Hole Research Center (see Appendix A for more details). California-specific forest carbon sequestration studies can build upon this work.

Research Needs

Because of the expanse of forests in California, researchers need to conduct an assessment of carbon sequestration opportunities in representative forests (using Table 2 as a start for possible activities). Once this information is obtained, then an assessment of the technical potential of carbon sequestration in forests needs to be conducted. The assessments should include an analysis of technical and programmatic barriers preventing carbon sequestration in forests.

Examples of potential carbon sequestration studies in California include: (1) restoring oaks on California savanna rangelands, because these areas may offer more carbon sequestration potential than riparian areas; (2) restoring the species balance in the coast redwood/Douglas-fir ecotype, because these conifers store more carbon per acre than tan oak, and carbon is stored longer with conifers (because the harvested wood from those trees tends to go into longer-lasting products such as lumber, rather than used as

firewood, which is often the case with tan oak); (3) species restoration (or maintenance) using timber stand improvement practices (e.g., culling and thinning), which increase growth and survival by making more moisture and nutrients available to each remaining tree; (3) afforestation of agricultural land.

- Because most studies of forestry carbon sequestration strategies have been conducted outside California, it is important to review the current status of forestry carbon sequestration strategies and assess the applicability and feasibility of implementing the identified forestry sequestration strategies for California's forestry ecosystems. Where needed, researchers will need to conduct field studies and geographic information systems (GIS) studies of forestry sequestration strategies in selected forests.

- In order to estimate the total potential of carbon sequestration in forests in California, research is needed to quantify the carbon-per-unit impacts of each strategy for each forestry ecosystem.

- The technical potential of carbon sequestration cannot be realized, due to technical and programmatic barriers facing carbon sequestration. Accordingly, research is needed to identify any technical or programmatic barriers preventing the use of carbon sequestration strategies in California's forests, and to recommend solutions for reducing or overcoming these barriers.

- The California carbon sequestration community needs to be kept informed of, and have access to: (a) descriptions of California-based forestry carbon sequestration strategies, and (b) California-based field studies and demonstrations of forestry carbon sequestration strategies. Databases on these efforts should be made accessible on the Wide World Web.

- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on forestry carbon sequestration strategies and projects.

Proposed research to address these research needs is described in Section 5.1.3.A.

4.2.2 Agricultural, Rangeland, and Soil Carbon Sequestration Strategies

Two studies in California have examined the effects of different agricultural practices on soil carbon. The Sustainable Agriculture Farming Systems (SAFS) project at UC Davis (1988 to 2001) compared conventional agricultural management systems to low input and organic management systems, with respect to each system's impacts on soil carbon, nutrients, productivity, soil biota, weeds and pests, and economics. Currently, UC Davis' LTRAS project is measuring changes in soil carbon with various management systems.

Several related studies on agriculture, rangeland, and soil carbon sequestration strategies have been conducted outside of California, including those conducted at the following organizations: Texas A&M University, Purdue University, Kansas State University,

Colorado State University, USDA's Natural Resources Conservation Service, USDOE's CSiTE, and CASMGS members (see Appendix A for more details).

Research Needs

Because of the expanse of agriculture, rangeland, and agricultural soils in California, an assessment of carbon sequestration opportunities (using Table 3 as a start for possible activities) in representative crops, rangeland, and soils needs to be conducted. Once this information is collected, then an assessment of the technical potential of carbon sequestration in crops, rangeland, and soils needs to be conducted. The assessments should include an analysis of technical and programmatic barriers preventing carbon sequestration in crops, rangeland, and soils.

- Because most studies of agriculture, rangeland, and soil carbon sequestration strategies have been conducted outside California, it is important to review the current status of these carbon sequestration strategies and assess the applicability and feasibility of implementing the identified carbon sequestration strategies for California's agriculture, rangeland, and soil ecosystems. Where needed, researchers will need to conduct field studies and GIS studies of agriculture, rangeland, and soil carbon sequestration strategies in selected ecosystems.
- In order to estimate the total potential of carbon sequestration in agriculture, rangeland, and soil in California, research is needed to quantify the carbon-per-unit impacts of each strategy for each ecosystem.
- The technical potential of carbon sequestration cannot be realized, due to technical and programmatic barriers facing carbon sequestration. Accordingly, research is needed to identify any technical or programmatic barriers preventing the use of carbon sequestration strategies in California's agriculture, rangeland, and soil, and to recommend solutions for reducing or overcoming these barriers.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) descriptions of California-based agriculture, rangeland, and soil carbon sequestration strategies, and (b) California-based field studies and demonstrations of agriculture, rangeland, and soil carbon sequestration strategies. Databases on these efforts should be made accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on agriculture, rangeland, and soil carbon sequestration strategies and projects.

Proposed research to address these research needs is described in Section 5.1.3.B.

4.2.3 Bioenergy Strategies

We are not aware of any research studies being conducted in California on bioenergy's relation to carbon sequestration, although some bioenergy projects are being developed with the assistance of the PIER program. At the national level, the National Renewable

Energy Laboratory (NREL) serves as the primary focus for DOE programs in biomass conversion, but other biomass activities are managed through Oak Ridge, Argonne, and Sandia National Laboratories.

Research Needs

Because of the potential benefits of bioenergy in California, researchers need to conduct an assessment of bioenergy opportunities. Once this information is collected, then an assessment of the technical potential of bioenergy needs to be conducted. The assessments should include an analysis of technical and programmatic barriers preventing bioenergy.

- Most studies of bioenergy strategies have been conducted outside California, so it is important to review the current status of these strategies and assess the applicability and feasibility of implementing the identified strategies for California. Where needed, researchers should conduct field studies of bioenergy strategies in selected ecosystems.
- In order to estimate the total potential of bioenergy in California, research is needed to quantify the carbon-per-unit impacts of bioenergy.
- The technical potential of bioenergy cannot be realized, due to technical and programmatic barriers facing bioenergy. Accordingly, research is needed to identify any technical or programmatic barriers preventing the use of bioenergy in California, and to recommend solutions for reducing or overcoming these barriers.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) descriptions of California-based bioenergy strategies, and (b) California-based field studies and demonstrations of bioenergy strategies. Databases on these efforts should be made accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on bioenergy strategies and projects.

Proposed research to address these research needs is described in Section 5.1.3.C.

4.2.4 Geologic Carbon Sequestration Strategies

Lawrence Berkeley National Laboratory has a geologic carbon sequestration project (the GEO-SEQ Project) that is being implemented with ORNL and other partners. They are investigating safe and cost-effective methods for geologic sequestration of CO_2. At the national level, the USDOE has identified geological sequestration as an important component of its carbon sequestration program. Several offices at USDOE are conducting research in this area, including the Office of Science and the Office of Fossil Energy. In addition to LBNL's project, other projects are being conducted by Texas Tech University, University of Utah, Battelle Laboratories, the University of Texas, and Sandia National Laboratory, and LANL. The USGS also has a geologic sequestration project.

Research Needs

Because of the potential benefits of geologic carbon sequestration in California, an assessment of geologic carbon sequestration opportunities (see Table 5) needs to be conducted. Once this information is collected, then an assessment of the technical potential of geologic carbon sequestration needs to be conducted. The assessments should include an analysis of technical and programmatic barriers preventing geologic carbon sequestration (e.g., conflicts between optimizing recovery of oil and maximizing long-term storage of CO_2, reluctance of industry to consider storage of CO_2 in depleted gas reservoirs, limited experience with CO_2 storage and saline aquifer field operations, etc.).

- Most studies of geologic carbon sequestration strategies have been conducted outside California, so it is important to review the current status of these strategies and assess the applicability and feasibility of implementing the identified strategies for California. Where needed, researchers will need to conduct field studies of geologic carbon sequestration strategies in selected ecosystems.
- In order to estimate the total potential of geologic carbon sequestration in California, research is needed to quantify the carbon-per-unit impacts of geologic carbon sequestration.
- The technical potential of geologic carbon sequestration cannot be realized, due to technical and programmatic barriers facing geologic carbon sequestration. Accordingly, research is needed to identify any technical or programmatic barriers preventing the use of geologic carbon sequestration in California, and to recommend solutions for reducing or overcoming these barriers.
- The California carbon sequestration community needs to be kept informed of, and have access to: (a) descriptions of California-based geologic carbon sequestration strategies, and (b) California-based field studies and demonstrations of geologic carbon sequestration strategies. Databases on these efforts should be made accessible on the Wide World Web.
- In order to disseminate lessons learned on this topic, researchers should prepare "best case studies" on geologic carbon sequestration strategies and projects.

Proposed research to address these research needs is described in Section 5.1.3.D.

4.3 Evaluate the Cost-Effectiveness of Carbon Sequestration Strategies[18]

The California Energy Commission is working with: (1) EPRI to examine the costs and benefits of GHG reduction in California, and (2) Winrock International to develop supply curves for carbon sequestration markets in California. Lawrence Berkeley National Laboratory has developed supply curves of forestry carbon sequestration, but for developing countries (Sathaye et al. 2001).

[18] This work will be coordinated with other economic analyses as suggested in the chapter in the PIER Climate Change Research Plan, "The Economics of Climate Change Mitigation and Adaptation in California."

Two related studies on evaluating the cost-effectiveness of carbon sequestration strategies have been conducted outside of California, involving USDOE's CSiTE and Pacific Northwest National Laboratory (PNNL) (see Appendix A for more details).

Research Needs

Once the technical potentials have been identified, researchers will need to assess the economic and market potentials of carbon sequestration in California, including an analysis of the technical and programmatic barriers (identified in the previous section) preventing the use of carbon sequestration. The economic analysis will need to account for many factors, including those associated directly with sequestration, as well as those associated with related ecosystem changes, land and water use, opportunity costs of the land, business practices, and regulatory factors. The major output from this analysis will be supply curves of sequestered carbon, which would be updated as the results from field studies and modeling exercises are disseminated.

Researchers may need to conduct some economic analyses of specific inputs to the economic models. As an example, in evaluating the economics of bioenergy, research projects may include the following: (1) improved understanding of the economics of energy crop cultivation and utilization from the perspective of the farmer or forester; (2) improved understanding of the collection, processing, and distribution infrastructure that will be necessary for large-scale biomass utilization, including analysis of the cost impact of distance between processing sites and biomass concentrations; (3) improved understanding and optimization of life-cycle emissions, energy rations, and costs through life-cycle assessments; (4) studies of the economic feasibility of biorefinery modules in reducing costs of biomass collection and transport; (5) models of broad-scale biobased products and bioenergy market development, identifying the impacts of different economic scenarios and the most effective drivers and incentives within each scenario; and (6) models of rural development to support production, processing, and utilization of biomass.

- In order to compare carbon sequestration strategies with other carbon management options, researchers need to develop carbon supply curves for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California. Both "technical potential" and "achievable potential" should be modeled. This work should be coordinated with the work undertaken in the other chapters in the PIER Global Climate Change Research Plan.
- In order to develop these supply curves, researchers should collect and analyze technical and cost estimates of carbon savings.
- These carbon supply curves should be compared with similar carbon supply curves for other carbon management options, in order to determine whether forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies should be pursued in California.

- Researchers should identify the technical, programmatic, and market barriers to agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies and report them in a white paper.
- The California carbon sequestration community needs to be kept informed of, and have access to, carbon supply curves in California. Databases on these efforts should be made accessible on the Wide World Web.
- Researchers need to prepare special economic studies on specific topics dealing with forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California. One area of special import concerns bioenergy.

Proposed research to address these research needs is described in Section 5.1.4.

4.4. Evaluate the Environmental and Social Impacts of Carbon Sequestration Projects in California

We are not aware of any research on these topics in California. Some researchers outside of California may be addressing these issues as part of other projects identified previously.

Research Needs

To optimize co-benefits and ensure environmental health, research will need to evaluate carbon sequestration from a whole-system approach that examines all of the complex environmental interactions associated with these strategies. We expect most carbon sequestration projects to provide multiple environmental benefits (e.g., Table 6). However, the quantification (and possible monetization) of these benefits is needed for conducting life-cycle assessment of carbon sequestration projects. In addition, environmental costs will need to be evaluated, especially in the following areas:

- Bioenergy projects: Large-scale tree plantations. (e.g., eucalyptus or pine). Planted in even-aged stands, plantations require intensive preparation of the soil, fertilization, regular spacing of trees, mechanical or chemical weeding, use of pesticides, and mechanized harvesting in short rotations. Because of the rapid growth of the species planted, they draw heavily from local water resources. And they generally lead to a loss of biodiversity on the lands they occupy because of their uniform structure and the use of non-native species in monoculture. They also may displace people living on the land and lead to fewer jobs in the areas. Research is needed for analyzing measures to promote biodiversity of intensively managed plantations (e.g., the adoption of longer rotation times, use of native tree species, and reduced chemical inputs) (IPCC 2001b).
- Urban carbon-based residuals. Currently, more than 37.5 millions tons of solid wastes are buried in the state's landfills annually (CIWMB 2000). Approximately 15–20% of the solid waste collected in California municipalities for disposal is woody material that can be segregated from mixed wastes and processed into high-quality biomass fuels (Morris 2000). And urban-derived compost can complement cropping and soil management systems that seek to retain carbon in the soil. Research is needed on the

following activities: (1) life-cycle analysis of gasification, hydrolysis, and other conversion technologies that use solid waste as feedstock for bioenergy projects, compared with landfilling and other management techniques for solid waste; (2) life-cycle analysis of using compost in final landfill cover as a means of reducing methane emissions; (3) life-cycle analysis of using urban-derived compost and mulch in enhancing carbon sequestration in the soil in agricultural and horticultural applications; and (4) life-cycle analysis of landfill gas-to-energy projects.

- Soil carbon sequestration. Soil carbon sequestration may have some potential adverse effects on the emissions of other GHGs, notably nitrous oxide (N_2O). Where the carbon accumulation requires additional amounts of nitrogen as fertilizer or manure, it carries the risk of increased N_2O emissions (IPCC 2001b). Furthermore, some carbon-conserving practices such as reduced tillage may increase N_2O emissions by favoring higher soil moisture content, which can lead to the anaerobic conditions that enhance N_2O emissions (*ibid.*). And for some areas, the potential for contamination of groundwater and surface waters from increased nutrient and fertilizer use needs to be examined.
- Geologic sequestration. The environmental acceptability of the storage of carbon dioxide in geologic formations must be demonstrated.
- Wildfires and carbon sequestration. Carbon sequestration may lead to an increased potential for wildfires and related damage, due to the increased amount of vegetation, crops and trees set aside for sequestering carbon. On the other hand, because of improved management practices and the use of biomass for bioenergy projects, the potential for wildfires may be lessened.
- Because of the possible significant environmental impacts of carbon sequestration projects in California, researchers need to conduct environmental analyses on bioenergy, soil, and geologic carbon sequestration projects. If possible, they should quantify the environmental and social benefits and costs. In addition to identifying the positive and negative environmental impacts, recommendations are needed for reducing the negative environmental impacts associated with each of these projects.
- A special study is needed for evaluating the positive and negative impacts of the different carbon sequestration projects on wildfires in California.

Proposed research to address these research needs is described in Section 5.1.5.

4.5 Develop Guidelines for the Design, Implementation, Monitoring, Evaluation, Reporting, Verification, and Certification (DIMERVC) of Carbon Sequestration Projects in California

The U.S. government has indicated that it does not intend to ratify the Kyoto Protocol (see Section 3.1),[19] and California presently does not have an emissions trading program or a climate change registry that includes carbon sequestration projects. However, some of this may change in the near future. For example, the California State Legislature is discussing Senate Bill 812 that would require the California Climate Action Registry (Registry) to establish a carbon inventory for forestry.[20] Voluntary carbon emissions trading programs have been established internationally and are beginning in Illinois, Indiana, Iowa, Michigan Minnesota, Ohio, and Wisconsin in 2002. For example, nearly three dozen U.S. Midwestern companies plan to launch the Chicago Climate Exchange by the third quarter of 2002 to cut regional emissions of six greenhouse gases.[21] Credits would be given for U.S. and overseas emissions offsets projects. And the economic impacts of emissions trading could be large. Preliminary research estimates that a carbon credits market for U.S. agriculture potentially could be worth $1–5 billion per year for the next 30–40 years. In fact, this market is already being developed, as evidenced by recent contracts from Canadian and American utilities to purchase six million metric tons of sequestered carbon from Iowa farmers (CASMGS 2001). Because this roadmap is taking a long-term approach, it proposes research on guidelines for the design, implementation, monitoring, evaluation, reporting, verification, and certification (DIMERVC) of carbon sequestration projects in California, so that private and public organizations could be prepared for participating in the Registry or in emissions trading programs.

As part of the development of the DIMERVC guidelines, research will need to address key measurement issues related to carbon sequestration projects, such as baselines, additionality, leakage, and permanence:

Baselines and Additionality For joint implementation and Clean Development Mechanism projects implemented under the Kyoto Protocol (Articles 6 and 12, respectively), the emissions reductions from each project activity must be "additional to any that would otherwise occur," also referred to as "additionality criteria" (Articles 6.1b and 12.5c). Other future emissions trading systems may also require additionality. Determining additionality requires a baseline for the calculation of carbon sequestered, i.e., a description of what would have happened to the carbon stock had the project not been implemented. Additionality and baselines are inextricably linked and are a major source of debate. Determining additionality is inherently problematic because it

[19] The Kyoto Protocol makes provision for Annex I Parties to take into account afforestation, reforestation, and deforestation and other agreed land use, land-use change, and forestry (LULUCF) activities in meeting their commitments under Article 3 (IPCC 2000).
[20] The Registry currently focuses on energy projects.
[21] Chicago Climate Exchange (www.chicagoclimatex.com).

requires resolving a counter-factual question: What would have happened in the absence of the specific project?

Future changes in carbon stock may differ from past levels, even in the absence of the project, due to growth, technological changes, input and product prices, policy or regulatory shifts, social and population pressure, market barriers, and other exogenous factors. Consequently, an accurate carbon accounting method is essential, and the calculation of the baseline needs to account for likely changes in relevant regulations and laws, changes in key variables (e.g., population growth or decline, economic growth or decline, deforestation, development of markets for wood products, and how future land use patterns (e.g., gradual deforestation) affect the carbon cycle). For example, for a forest protection project, a simple baseline would try to account for how many acres might be lost in a year, how the loss would occur (e.g., through burning or timber harvest), what biomass would replace the forest, and whether the forest would return after the land has been abandoned. Ideally, the baseline would track this information annually and constitute a full carbon accounting (i.e., measure stocks and flows of carbon in each of the different carbon pools in the different ecosystems), to help ensure that carbon was not counted twice.

Leakage is the loss of overall sequestration benefits due to displacement. Leakage occurs if success in protecting or increasing carbon in one place hastens the release of carbon elsewhere. For example, if logging is stopped in one area, but logging occurs on a different parcel of land as a result, the overall amount of logging is not reduced. Similarly, if conserving and doubling the size of a teak forest (for example) increases prices and spurs the sale and harvest of teak in another forest, there is no net gain. Leakage originates when projects reduce access to land, food, fiber, fuel and timber resources without offering alternatives. Calculating leakage is complicated by the myriad factors that affect the supply and demand of products.

Permanence refers to whether or not the carbon stored at the time of a trading agreement, for example, will continue to be stored in the future. This is a major research issue for the U.S. Department of Energy (USDOE 1999). A recent study questioned the proposition that forest soil can sequester carbon for long periods of time, and contended that long-term net carbon sequestration is unlikely (Schlesinger and Lichter 2001). There is a possibility that any carbon accumulated or protected in the biosphere might be released at a later time, due to changes in land ownership, public policy, commitment by the landowner, climate, or natural disturbances, such as fire or pests. Hence, there is a need to assess project risks and to develop risk management strategies. The relative importance of different types of risk to carbon sequestration and storage varies by project location and by type of project (Ellis 2001; Wayburn et al. 2000). The following types of risks will need to be addressed:

- **Naturally-occurring risks.**[22] Naturally-occurring events that can partially or completely reverse carbon sequestration include fires, pest or fungal attack, floods, droughts, hurricanes, volcanoes, earthquakes, and landslides. The risk of one of these events (such as a hurricane) occurring on the site of a particular project during a particular period may be more difficult to predict than others (such as pest attack). Consequently, protective action may be more applicable for some risks than others. Analysis of some forestry GHG-mitigation projects has quantified some of these risks (SGS 2000a, 2000b, 2000c).

- **Human-induced risks.** Human-induced risks include fire, encroachment, and deforestation.

In California, LBNL has been one of the international leaders in developing guidelines for evaluating carbon sequestration projects (Vine et al. 1999).

Several related studies have been conducted outside of California, including the following organizations: the UNFCCC, USDOE's CSiTE, the World Resources Institute, and the World Council on Sustainable Business Development (see Appendix A for more details).

Research Needs

- If private and public organizations in California are to participate in a revised Registry or in emissions trading programs, research will need to be conducted on several key measurement and evaluation issues related to carbon sequestration, such as additionality, baselines, leakage, and permanence.
- Based on the research work above, Web-based guidelines need to be developed on the design, implementation, monitoring, evaluation, reporting, verification, and certification of carbon sequestration projects in California.

Proposed research to address these research needs is described in Section 5.1.6.

4.6 Develop the California Carbon Sequestration Network (CCSN)

PIEREA should develop a California Carbon Sequestration Network (CCSN) in order to establish state public-private partnerships to facilitate science and technology development and public outreach appropriate to each major sequestration region. This network would include a focus on providing information to the public. The CCSN would involve academia, national laboratories, energy producers and users, and state and local agencies. The network would help provide state-specific scientific data and options to ensure the use of environmentally sound practices and the long-term safety of the sequestration alternatives being considered. The network would include the evaluation and selection of sequestration sites, field tests, and verification and validation of

[22] In the U.S., historically, the risk of loss to inventory from natural risks is less than 1% over time (Wayburn et al. 2000).

sequestration approaches. And working with PIEREA, this network could track the progress of research projects and suggest new projects.[23]

5. Goals

The goal of the carbon sequestration component of the PIER Climate Change Research Plan is to help California sequester and store CO_2 in terrestrial ecosystems and geologic formations while fostering additional economic and environmental benefits. The achievement of that goal will depend on the development of reliable methods, tools, and data that will enable decision makers to more accurately predict the carbon sequestration effectiveness and economic viability of various strategies.

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[24]

5.1.1 Establish the California Carbon Sequestration Network

Activities needed: (1) Establish the California Carbon Sequestration Network (CCSN).

Critical Factors for Success:

- Participation of the full range of stakeholders: academia, national laboratories, nonprofits, energy producers, energy users, and state and local agencies.
- A willingness and ability among participants to reach consensus on how best to facilitate science and technology development and public outreach.

5.1.2 Improve the Understanding of Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations in California

[NOTE: Much of this research will be "basic science research" that will be funded by national (and possibly international)

[23] USDOE is proposing a similar, but more ambitious, network for geologic sequestration, called the Regional Carbon Sequestration (RCS) network (USDOE 2002). For example, USDOE is proposing five RCS region-specific demonstrations ($100 million for each demonstration, or approximately $500 million for the duration of the RCS network (6 years). Each regional effort would be a cost-shared partnership between regional public and regional industrial entities, with the expectation that they would become self-sustaining by the end of the tenth year. Another research network that might provide assistance to the CCSN is the Tropical Forestry and Global Change Research Network (F-7) (Sathaye et al. 2001). The main goal of the F-7 network is to estimate the (1) GHG emissions from participating and neighboring countries, (2) potential for emissions avoidance and carbon sequestration, and (3) monetary and other costs and benefits of forestry mitigation options. The network also is focused on assessing project opportunities, including the issues of baselines, additionality, leakage, and monitoring and verification (*ibid.*).

[24] 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.

organizations. PIEREA funding will be used to augment funding for those projects that focus on California ecosystems and formations.]

A. Improve the understanding of carbon flux.

Activities needed: (1) Review the current status of carbon flux data collection by AmeriFlux in California and determine the need for additional sites; (2) if needed, add additional carbon flux sites in ecosystems that are not being monitored; (3) review the current status of field studies collecting carbon flux data and determine the need for additional sites; (4) if needed, add additional field studies in ecosystems that are not being monitored; (5) review the current status of ecosystem models for estimating daily fluxes of CO_2 from different ecosystems and assess their applicability for California ecosystems; (6) modify existing ecosystem models for California ecosystems and calibrate with field data; (7) develop new ecosystem models for California ecosystems and calibrate with field data; (8) prepare Web-accessible databases on: (a) carbon flux data collection activities in California, (b) California-based field studies of carbon flux, and (c) carbon flux and ecosystem modeling in California;[25] and (9) prepare "best case studies" of carbon flux data collection and analysis in California.

B. Improve the understanding of carbon sequestration in soils.

Activities needed: (1) Review the current understanding of the biogeochemical processes that control turnover times in California forestry and agricultural soils, focusing on the conversion of plant material to carbon-containing compounds that are chemically and physically inert; (2) if needed, conduct additional field studies on the conversion of plant material to carbon-containing compounds that are chemically and physically inert; (3) review the current status of field studies on how carbon sequestration strategies in forestry and agriculture (see Tables 2 and 3) influence carbon storage; (4) if needed, conduct additional field studies on how carbon sequestration strategies in forestry and agriculture influence carbon storage; (5) review the current status of techniques measuring carbon in soils; (6) conduct field studies in the application of new techniques (especially remote sensing and inexpensive, portable systems) for the measurement of carbon in California agriculture and forestry soils; (7) review the current status of soil carbon models for estimating carbon from different soil ecosystems and assess their applicability for California soils; (8) modify existing soil carbon models for California soils and calibrate with field data; (9) develop new soil carbon models for California soils and calibrate with field data; (10) prepare Web-accessible databases on: (a) California-based field studies of conversion of plant material to carbon-containing compounds that are chemically and physically inert, (b) California-based field studies on the influence of carbon sequestration strategies in forestry and agriculture on carbon storage in soils, (c) California-based field studies on the application of new techniques

[25] Web-accessible databases are mentioned throughout this section. Research should explore the opportunity for a *integrated* Web-accessible database containing multiple data elements (e.g., flux, soil carbon, land use, and others).

for the measurement of carbon agriculture and forestry soils, and (d) California-based field studies on soil carbon models; and (11) prepare "best case studies" on soil carbon field studies, sequestration activities, technologies, and models.

C. Improve the understanding of carbon sequestration in biomass and bioenergy.

Activities needed: (1) Review the current understanding of plant metabolism and regulation of carbon flow; (2) if needed, conduct additional California-based field studies on plant metabolism and regulation of carbon flow; (3) review the current understanding of improving productivity; (4) if needed, conduct additional California-based field studies on improving plant productivity for biomass; (5) review the current status of efficient systems for the design, production, and handling of dedicated crops for biomass; (6) if needed, conduct additional California-based field studies on developing more efficient systems for the design, production, and handling of dedicated crops for biomass in California; (7) review the current status of techniques for separating plant components, conversion processes for biomass materials, fermentation processes, and biopower systems; (8) if needed, conduct California-based technology and field studies on developing economical new techniques for separating plant components, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems; (9) improve theory and conduct demonstrations of sustainable forestry, and agriculture and urban carbon-based residuals practices for biomass/bioenergy; (10) prepare Web-accessible databases on: (a) California-based field studies on plant metabolism and regulation of carbon flow for biomass, (b) California-based field studies on improving plant productivity for biomass, (c) efficient systems for the design, production, and handling of dedicated crops for biomass in California, and (d) economical new techniques for separating plant components, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems; and (11) prepare "best case studies" on: (a) improving plant productivity for biomass, (b) efficient systems for design, production, and handling of dedicated crops for biomass in California, and (c) economical new techniques for separating plant components, more effective conversion processes for biomass materials, improved fermentation processes, and improved biopower systems.

D. Improve the understanding of geologic sequestration.

- *Activities needed:* (1) Review the current understanding of the following issues for California geologic formations: (a) equilibria between multi-component gases, oil, and water, (b) long-term effects of CO_2 on oil and gas reservoir properties, (c) multiphase fluid movement, phase transition, density and viscosity effects, and geochemical reactions at the micro scale, (d) the effects of hydraulic issues, such as lateral and vertical migration, well integrity, caprock integrity, permeability, pressure buildup, sweep efficiency, density and viscosity effects, and storage capacity at the injection-well scale, (e) formation of complex carbonates in deep

saline formations, (f) fate and transport of CO_2 in the subsurface, and (g) the impacts of additional chemicals or microbiota to be injected to ensure safe and effective sequestration; (2) if needed, conduct field studies in different geologic formations to assess each of the issues; (3) collect field studies to collect data on the following issues: (a) stress-related changes to integrity of caprock and reservoir, (b) reservoir properties and capacity of saline aquifers, (c) CO_2 vertical and lateral migration in saline aquifers, (d) solubility and mineral trapping in brine systems in saline aquifers, (e) location and integrity of abandoned wells, (f) long-term corrosion effects, and (g) long-term interactions of CO_2 and storage reservoirs; (4) review the status of methods for verifying and validating geomechanical models of carbon sequestration in geologic formations; (5) if needed, develop more reliable, cost-effective, and affordable methods for verifying and validating geomechanical models of carbon sequestration in geologic formations; (6) apply existing and new methods for monitoring of: (a) CO_2 storage in oil and gas reservoirs and aquifers, (b) natural CO_2 seepage, (c) CO_2 leakage mitigation, and (d) economically feasible corrosion resistant materials; (7) prepare Web-accessible databases on: (a) California-based field studies on carbon dynamics in geologic sequestration, (b) methods and technologies for monitoring carbon storage, leakage, and seepage in geologic formations, and (c) economically feasible corrosion resistant materials for geologic sequestration; and (8) prepare "best case studies" on: (a) field studies on carbon dynamics in geologic sequestration, and (b) methods and technologies for monitoring carbon storage, leakage, and seepage in geologic formations.

Critical Factors for Success:

- Adequate funding for monitoring, field studies, and model evaluation and development.
- Resources adequate for monitoring key ecosystems and sites.
- Ability of models to accurately portray California ecosystems and to model soil carbon.
- Accurate methods for measuring carbon and carbon flux
- Cooperation among public and private stakeholders that allows access to data and land.
- Cooperative efforts between state agencies and industry to evaluate geologic sequestration potential at industrial sites.

5.1.3 Identify and Assess the Technical Feasibility and Carbon Impacts of Carbon Sequestration Strategies in California

A. Forestry carbon sequestration strategies.

Activities needed: (1) Review the current status of forestry carbon sequestration strategies (see Table 2); (2) assess the applicability and feasibility of implementing the identified forestry sequestration strategies for California's forestry ecosystems, including an assessment of how these initiatives would promote or interfere with

other agency goals; (3) where needed, conduct field studies of forestry sequestration strategies in selected forests; (4) quantify the carbon-per-unit impacts of each strategy for each forestry ecosystem; (5) identify any technical or programmatic barriers preventing the use of carbon sequestration strategies in California's forests; (6) prepare Web-accessible databases on: (a) forestry carbon sequestration strategies in California, and (b) California-based field studies and demonstrations of forestry carbon sequestration strategies; and (7) prepare "best case studies" of forestry carbon sequestration strategies and projects.

B. Agriculture, rangeland, and soil carbon sequestration strategies.

Activities needed: (1) Review the current status of agriculture, rangeland, and soil carbon sequestration strategies (see Table 3); (2) assess the applicability and feasibility of implementing the identified agriculture, rangeland, and soil sequestration strategies for California, including an assessment of how these initiatives would promote or interfere with other agency goals; (3) where needed, conduct field studies and GIS studies of agriculture, rangeland, and soil sequestration strategies in selected geographic areas; (4) quantify the carbon-per-unit impacts of each strategy for each agriculture, rangeland, and soil ecosystem; (5) identify any technical or programmatic barriers preventing the use of carbon sequestration strategies in California's agriculture, rangelands, and soils; (6) prepare Web-accessible databases on: (a) agriculture, rangeland, and soil carbon sequestration strategies in California, and (b) California-based field studies and demonstrations of agriculture, rangeland, and soil carbon sequestration strategies; and (7) prepare "best case studies" of agriculture, rangeland, and soil carbon sequestration strategies and projects.

C. Bioenergy carbon sequestration strategies.

Activities needed: (1) Review the current status of bioenergy carbon sequestration strategies; (2) assess the applicability and feasibility of implementing the identified bioenergy sequestration strategies for California, including an assessment of how these initiatives would promote or interfere with other agency goals; (3) where needed, conduct field studies of bioenergy sequestration strategies in selected geographic areas; (4) quantify the carbon-per-unit impacts of each bioenergy strategy for each area; (5) identify any technical or programmatic barriers preventing the use of bioenergy carbon sequestration strategies in California; (6) prepare Web-accessible databases on: (a) bioenergy carbon sequestration strategies in California, and (b) California-based field studies and demonstrations of bioenergy carbon sequestration strategies; and (7) prepare "best case studies" of bioenergy carbon sequestration strategies and projects.

D. Geologic carbon sequestration strategies.

Activities needed: (1) Review the current status of geologic carbon sequestration strategies (see Table 5); (2) assess the applicability and feasibility of implementing the identified geologic sequestration strategies for California's geologic formations,

including an assessment of how these initiatives would promote or interfere with other agency goals; (3) where needed, conduct field studies of geologic sequestration strategies in selected geographic areas; (4) quantify the carbon-per-unit impacts of each strategy for each geologic formation; (5) identify any technical or programmatic barriers preventing the use of geologic carbon sequestration strategies in California's geologic formations; (6) prepare Web-accessible databases on: (a) geologic carbon sequestration strategies in California, and (b) California-based field studies and demonstrations of geologic carbon sequestration strategies; and (7) prepare "best case studies" of geologic carbon sequestration strategies and projects.

Critical Factors for Success:

- Adequate funding and resources for field studies of key ecosystems and sites.
- Cooperation among public and private stakeholders that allows access to data and land.
- Accurate methods for measuring carbon-per-unit impacts of each sequestration strategy.

5.1.4 Evaluate the Cost-Effectiveness of Carbon Sequestration Projects[26]

A. Develop carbon supply curves for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California.

Activities needed: (1) Review the technical estimates of carbon savings from forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California; (2) where needed, develop cost estimates for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California; (3) develop two carbon supply curves for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California: "technical potential" and "achievable potential" (market penetration should be modeled for a range of market interventions to produce estimates of achievable potential, and associated costs should include programmatic costs);[27] (4) compare supply curves with supply curves of other carbon management strategies in California; (5) identify any technical, programmatic, or market barriers preventing the use of carbon sequestration strategies in California; (6) prepare Web-accessible databases on carbon supply curves in California; and (7) prepare a white paper on technical, programmatic, or market barriers preventing the use of carbon sequestration strategies in California.

[26] This work will be coordinated with other economic analyses, as suggested in the PIER Climate Change Research Plan chapters, "The Economics of Climate Change Mitigation and Adaptation in California" and "Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources."

[27] As suggested in the PIER Climate Change Research Plan chapter, "Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources."

B. Conduct special economic studies of forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California.

Activities needed: (1) Collect and analyze costs to farmers and foresters on energy crop cultivation in California (including collection, processing, and distribution costs that will be necessary for large-scale biomass utilization); (2) conduct life-cycle assessment of bioenergy strategies in California;[28] (3) conduct a study of the economic feasibility of biorefinery modules in reducing costs of biomass collection and transport in California; (4) conduct a study of the economic feasibility of using urban carbon-based residuals for bioenergy production; (5) develop models of broad-scale biobased products and bioenergy market development, identifying the impacts of different economic scenarios and the most effective drivers and incentives within each scenario; and (6) develop models of rural development to support the production, processing, and utilization of biomass.

Critical Factors for Success:

- Agreement among stakeholders as to the methods used to assign value and determine carbon sequestration cost-effectiveness.
- Cooperation among public and private stakeholders that allows access to data and land.

5.1.5 Evaluate the Environmental and Social Impacts of Carbon Sequestration Strategies in California[29]

A. Conduct an environmental analysis of bioenergy projects in California.

Activities needed: (1) Review the literature on the environmental impacts of large-scale tree plantations; (2) evaluate the environmental impacts of soil preparation, fertilization, chemical weeding, pesticides, and short rotations on biodiversity and aquatic ecosystems in California; (3) evaluate the environmental impacts of using urban carbon-based residuals for bioenergy production; and (4) develop recommendations for reducing negative environmental impacts associated with bioenergy projects in California.

B. Conduct an environmental analysis of soil carbon sequestration projects in California.

Activities needed: (1) Review the literature on the environmental impacts of soil carbon sequestration projects; (2) evaluate the environmental impacts of soil carbon sequestration projects in California (especially N_2O and contamination of

[28] This work will be coordinated with other life-cycle analyses identified in the PIER Environmental Area Research Plan. Life-cycle assessments for other carbon sequestration strategies might be conducted.

[29] This work will be coordinated with other economic analyses as suggested in the PIER Climate Change Research Plan chapters, "The Economics of Climate Change Mitigation and Adaptation in California" and "Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources."

groundwater and surface waters from increased nutrient and fertilizer use); and (3) develop recommendations for reducing negative environmental impacts associated with soil carbon sequestration projects.

C. Conduct an environmental analysis of geologic carbon sequestration projects in California.

Activities needed: (1) Review the literature on the environmental impacts of geologic carbon sequestration projects; (2) evaluate the environmental impacts of geologic carbon sequestration projects in California; and (3) develop recommendations for reducing negative environmental impacts associated with geologic carbon sequestration projects.

D. Quantify the environmental and social benefits and costs of carbon sequestration projects.

Activities needed: (1) Review the literature on the environmental and social benefits and costs of carbon sequestration projects; (2) quantify the environmental and social benefits and costs of carbon sequestration projects in California; and (3) prepare a Web-accessible database and white paper that quantifies the environmental and social benefits and costs of carbon sequestration projects.

E. Evaluate the impacts of carbon sequestration on wildfires.

Activities needed: (1) Review the literature on the causes of wildfires and possible impacts of carbon sequestration on wildfires; (2) for selected carbon sequestration projects in California, examine the possible implications of these strategies to wildfires; and (3) prepare a white paper on carbon sequestration and wildfires.

F. Conduct a life-cycle analysis of urban carbon-based residuals.

Activities needed: (1) Review the literature on the environmental and social impacts of using urban carbon-based residuals for bioenergy project feedstock, using landfill cover to reduce methane emissions, enhancing carbon sequestration in the soil in agricultural and horticultural applications, and landfill gas-to-energy projects; (2) evaluate the environmental and social impacts of using urban carbon-based residuals for the above activities; and (3) develop recommendations for reducing negative environmental and social impacts associated with the use of urban carbon-based residuals.

Critical Factors for Success:

- Cooperation among public and private stakeholders that allows access to data.

5.1.6 Develop Guidelines for the Design, Implementation, Monitoring, Evaluation, Reporting, Verification, and Certification (DIMERVC) of Carbon Sequestration Projects in California[30]

Activities needed: (1) Review the literature on existing and proposed guidelines for the design, implementation, monitoring, evaluation, reporting, verification, and certification (DIMERVC) of carbon sequestration projects; (2) conduct research on key measurement and evaluation issues related to carbon sequestration, such as additionality, baselines, leakage, and permanence; and (3) develop Web-based DIMVERC guidelines for carbon sequestration projects in California.

Critical Factors for Success:

- Cooperation among public and private stakeholders that allows access to data.
- Coordination with the California Climate Action Registry and among other entities interested in developing guidelines.

[30] This work will be coordinated with other economic analyses, as suggested in the PIER Climate Change Research Plan chapters, "The Economics of Climate Change Mitigation and Adaptation in California" and "Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources."

Table 7. Short-term Budget

Objective	Projected Cost ($000 per year)
5.1.1 Establish the California Carbon Sequestration Network	15
5.1.2 Improve the Understanding of Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations	
5.1.2.A Improve the understanding of carbon flux	250
5.1.2.B Improve the understanding of carbon sequestration in soils	250
5.1.2.C Improve the understanding of carbon sequestration in biomass and bioenergy	250
5.1.2.D Improve the understanding of geologic sequestration	250
5.1.3 Identify and Assess the Technical Feasibility and Carbon Impacts of Carbon Sequestration Strategies in California	
5.1.3.A Forestry carbon sequestration strategies	400
5.1.3.B Agricultural, rangeland, and soil carbon sequestration strategies	400
5.1.3.C Bioenergy carbon sequestration strategies	400
5.1.3.D Geologic carbon sequestration strategies	400
5.1.4. Evaluate the Cost-Effectiveness of Carbon Sequestration Strategies	
5.1.4.A Develop carbon supply curves for forestry, agricultural, rangeland, soil, bioenergy, and geologic carbon sequestration strategies in California	400
5.1.4.B Conduct special economic studies of bioenergy	600
5.1.5 Evaluate the Environmental and Social Impacts of Carbon Sequestration Strategies in California	
5.1.5.A Conduct an environmental analysis of bioenergy strategies in California	150
5.1.5.B Conduct an environmental analysis of soil carbon sequestration strategies in California	150
5.1.5.C Conduct an environmental analysis of geologic carbon sequestration strategies in California	150
5.1.5.D Quantify the environmental and social benefits and costs of carbon sequestration strategies in California	150
5.1.5.E Evaluate the impacts of carbon sequestration on wildfires	150
5.1.5.F Conduct a life-cycle analysis of urban carbon-based residuals	150
5.1.6 Develop Guidelines for the Design, Implementation, Monitoring, Evaluation, Reporting, Verification, and Certification (DIMERVC) of Carbon Sequestration Projects in California	150
Total Short-term Cost per Year	**4,665**

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 on a per-year basis, over three years.

5.2 Mid-term and Long-term Objectives

The work for future years will continue and advance the work in the short-term. In particular, the following activities are apt to continue, most likely in ecosystems that were not targeted in the short term:

- Additional field studies
- Additional "best case studies"
- Development of new and improved models
- Improved data and databases on sequestered carbon and costs of sequestered carbon

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 CASMGS, CSiTE, the Conservation Reserve Program, USDOE, USDA, USEPA, and others, and

- solicit funds from USDOE, USDA, USEPA, and others to build upon their efforts, or to co-design new projects at the Energy Commission.

6.2 Opportunities

Co-sponsored efforts are under way with EPRI at this time. Co-sponsorship opportunities are likely with CASMGS, CSiTE, the Conservation Reserve Program, the Kearney Foundation for Soil Science, CDFA, and the USDOE. Each of these organizations is interested in addressing terrestrial sequestration of carbon.

7. Areas Not Addressed by This Roadmap

This roadmap does not address the following issues:

- Carbon sequestration policy issues. This is a research roadmap and does not focus on policy development.
- Valuation of carbon under emission trading and its impact on the amount of carbon sequestered. This topic is considered in the PIER Climate Change Research Plan chapter, "The Economics of Climate Change Mitigation and Adaptation in California."
- Direct carbon sequestration from generation sources. The focus of this roadmap is on terrestrial ecosystem and geologic sequestration.

- Impacts on agriculture and forestry from climate change. These issues will be addressed in future PIEREA climate change Agriculture and Forestry roadmaps.[31]
- Changes in future climate. Because of the extreme difficulty and complexity in predicting such changes, the roadmap activities herein must use a static approach that examines the issues based on what is known currently.
- Other GHG emissions. The focus of this roadmap is on CO_2, although future roadmaps may consider other emissions as part of sequestration activities (e.g., methane).

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[31] These roadmaps will include the following topics: (1) increased CO_2 levels will promote vegetation growth, and as a result, increase the amount of biomass sequestration; and (2) nitrate fertilization from NO_X emissions and nitrate deposition will promote plant growth.

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Appendix A
Current Status of Programs

This section outlines those efforts that most closely address the carbon management aspect of the climate change issue and its impact on California.

Current Status: California

California Energy Commission

- The PIEREA program is currently conducting a project with the Electric Power Research Institute to examine global climate change and its potential impacts and costs on California. Part of this project is examining alternative proposals for reducing GHGs in terms of costs and benefits. (Contract No. 500-97-043)
- PIEREA is currently working closely with the California Department of Forestry and Fire Protection (CDF), EPRI, and Winrock International to develop a first order of magnitude carbon sequestration supply curve for the California forestry sector. The project is also conducting measurement and design of monitoring activities to assess carbon credits from potential projects in California forests.

The California Department of Fire and Forestry (CDF)

- Through its Fire and Resource Assessment Program (FRAP), CDF is conducting an ongoing monitoring program with the USDA Forest Service (USFS) to detect changes in vegetative cover in California, to identify shifts in carbon storage capacity in the state. The Land Cover Mapping program's mapping methodology captures forest vegetation characteristics using automated, systematic procedures that map large areas with minimal bias. Vegetation data are maintained and updated at the CDF-FRAP and USDA Forest Service Pacific Southwest Region's Remote Sensing Lab.
  - For more details, see http://frap.cdf.ca.gov/projects/land_cover/mapping/index.html

The Carnegie Institution of Washington

- Researchers at the Field Lab of the Carnegie Institution of Washington (at Stanford University) are studying carbon flux in grasslands at the Jasper Ridge Biological Preserve. Researchers manipulate temperature, atmospheric carbon dioxide, precipitation, and nitrogen deposition to simulate ecosystem responses from global change. Researchers also conduct continuous measurement of the fluxes of water vapor and carbon dioxide from the grassland to the atmosphere, to better understand how the grassland responds to its changing environment and use that knowledge in future modeling. The Field Lab's research is ongoing.

Kearney Foundation of Soil Science, University of California at Davis

- The current five-year mission of the Kearney Foundation is "Soil Carbon and California Terrestrial Ecosystems." The Kearney Foundation's 2001–2006 goals are to:

understand the mechanisms and processes governing the storage and flow of carbon in soils that support California's ecosystems; quantify the impacts of anthropogenic inputs of water, nutrients, pollutants, and physical disturbances on transformations and transport of carbon in soils; assess the roles of soils in emissions and consumption of greenhouse carbon gases; identify and analyze strategies and policy options for soil carbon management that optimize natural resource utilization and mitigate adverse effects of global climate change. The Kearney Foundation has funded the following two-year efforts, which begin in 2002:

- **Quantitative and Qualitative Assessment of Soil Organic Carbon in Native and Cropland Soils in California.** (Department of Environmental Sciences, UC Riverside) This project will collect paired native and irrigated California cropland soils from sites where records of cropping history are available. Researchers will determine the difference in carbon storage and dynamics associated with bulk soil and with various size fractions of aggregates in native soils and in soils managed under different cropping systems in California.
- **Climate and Parent Material Controls Over Carbon Storage and Dynamics in California Upland Soils.** (Department of Earth System Science, UC Irvine) This project will use the California Soil-Vegetation Survey in combination with gridded climate surfaces to quantify statistically the relationship between soil carbon and parent material across a matrix of climate and vegetation types. The final product will be an estimate of the capacity of soils in the Sierra Nevada and Cascade regions to store or release carbon under future scenarios of change in climate or vegetation productivity.
- **Identification of Microbes Responsible for Acetate Consumption in Soils under Different Wetting Regimes.** (Department of Environmental Sciences, UC Riverside) For this project, researchers will use a new stable isotope probing (SIP) method to link the activity of acetate catabolism with the identity of the organisms performing this process. Once the method is optimized, they will use it to identify the components of the microbial community that are critical for acetate consumption in soil microcosms. This work will help clarify the processes governing carbon storage in soils, quantify the impacts of anthropogenic inputs on soil carbon dynamics, and assess the roles of soils in greenhouse gas flux.
- **Plant Species Composition, Soil Biology, and Carbon Storage in Grasslands.** (UC Davis/UC Berkeley) This project is examining how plant species composition affects soil carbon dynamics and carbon storage in grasslands with different management histories. The work focuses on plants with different rooting attributes and on their contribution to soil carbon retention in grasslands with different vegetation and past tillage history. Researchers will conduct soil profile analysis of carbon pools in roots and various organic matter fractions, carbon mineralization activity, and soil CO_2 concentrations and efflux. Researchers will suggest management scenarios to enhance carbon storage in California grasslands.
- **Management Protocols for Soil Carbon Sequestration in San Joaquin Valley Agroecosystems.** (UC Davis) This research will determine carbon loss and

stabilization and the effect of soil carbon management using reduced tillage on nitrogen availability in a cotton-tomato rotation. It will compare conservation (ridge- and strip-) tillage and conventional tillage practices in a crop rotation that is common to the San Joaquin Valley's west side, in terms of soil carbon sequestration, farm productivity, and profitability, and will widely disseminate information related to the study's objectives and outcomes.

- **Carbon Flow Through Root and Microbial Respiration in Vineyards and Adjacent Oak Woodland Grassland Communities.** (UC Davis) This research will examine the mechanisms affecting carbon storage and fluxes, the impacts of management on carbon storage and fluxes, and the effects of soil carbon on nutrient cycling. Researchers will monitor soil CO_2 emission from undisturbed oak woodland grasslands and adjacent lands converted to vineyards, and partition the CO_2 into respiration derived from root plus rhizosphere respiration, soil organic matter oxidation, and litter decomposition. This study complements a parallel investigation examining root population dynamics; therefore, it will provide comprehensive information on carbon flow.
- **Carbon Flow From Roots to Microbes to Soil Humic Substances.** (UC Berkeley) Using 13C-analysis, researchers will follow below-ground carbon as it moves from plant root exudates and debris into the microbial community and its components, and finally into operationally defined soil humic components. Researchers will plant Avena barbata in a California annual grassland soil under enriched $13CO_2$ to uniformly label plant materials. This study will demonstrate how microbial communities of differing composition and activity alter the outcome of the humification of below-ground plant debris, and how living plants control these effects.
- **The Quantity and Controls on Soil Carbon in California and United States.** (UC Berkeley) Researchers are using a GIS framework to quantify the amount, and spatial patterns, of organic and inorganic soil carbon in California and the United States. The work is using the national STATSGO soil database, is employing new algorithms to estimate missing data, and is incorporating an explicit estimate of the possible range in soil carbon storage values based on STATSGO data calculations. Researchers will compare generated maps and data to digital data that loosely correlate to "factors of soil formation" to understand, at a coarse scale, the controls on soil carbon patterns. Researchers hope to link the CENTURY multi-pool soil carbon model to a GIS framework in order to (ultimately) refine the model to regional and national scales, and to address questions of how soil carbon will respond to climatic and land use perturbations.
- **Erosion Removal and Redistribution of Soil Organic Carbon in Upland Ecosystems.** (UC Berkeley) This research is combining intensive soil sampling and analyses with geomorphic modeling to reconstruct how the landscape-scale distribution of soil organic carbon storage develops over time. At two 0 order watersheds with contrasting geology, researchers will excavate soil pits in differing erosional/depositional area, determine soil bulk density and carbon and nitrogen,

develop detailed watersheds topographic maps, and model the rates of soil carbon erosion/deposition in the watersheds. The results from the 0 order watersheds will also be scaled to higher order watersheds.

- **Sequestering C in Stable Soil Organic Matter Fractions: How Important is fertilizer-N in Sequestering C?** (UC Davis) In cooperation with the Sustainable Agriculture Farming Systems project at UC Davis, researchers are determining the relative contribution of residue-N and fertilizer-N in soil organic matter (SOM) pools, and quantifying the differences in carbon and nitrogen sequestration pathways between a conventionally managed and an organic system. This research will help devise management practices to enhance carbon and nitrogen sequestration and the build-up of SOM in fertilized agro-ecosystems in California and beyond.
- **Enhancing Inorganic Carbon Sequestration by Irrigation Management in California.** (UC Davis) This project is examining the extent of carbonate precipitation in effluent-irrigated fields through reconnaissance surveys, identifying factors that control soil carbonate dissolution/precipitation under effluent irrigation, and determining die effluent irrigation management that maximizes inorganic carbon sequestration in arid region soils. Research will determine whether or not inorganic carbon is an effective means to sequester carbon and will identify the most effective irrigation scheme based on a new understanding of the basic soil processes.
- **Controls of Canopy Activities on Roots and Soil Carbon Dynamics in a Young Ponderosa Pine Forest.** (UC Berkeley/UC Santa Cruz) This project combines the ongoing canopy scale and soil chamber gas flux measurements at the Blodgett Forest research site with measurements of root dynamics using a minirhizotron approach, and addresses the issue of aboveground controls on root turnover and soil carbon sequestration. It will increase understanding of below-ground carbon fluxes in forest ecosystems, and of the role of roots in below-ground carbon dynamics, to help researchers assess the contribution of forests as global C processors.
- **Soil Organic Matter Does Not Break Itself Down. The Implications of Exoenzyme activity on C Flow and Microbial Carbon and Nitrogen Limitation in Soil.** (UC Santa Barbara) Two contradictions are apparent in the understanding of soil organic matter processing: 1) microbes often appear C limited, even in C-rich soils, and 2) C-based studies often conclude C limitation, while N-based studies often conclude N-limitation. Researchers have developed a model that helps explain such contradictions. This project will test five hypotheses that grow from the model predictions, and researchers will analyze the exoenzyme kinetics of soil organic matter breakdown and how non-linear enzyme kinetics produces carbon limitation even in the midst of plenty, how the disconnection between actual polymer breakdown and microbial growth affects the response to stress events, and how enzyme-driven C flow interacts with possibly nitrogen-limited microorganisms to produce counterintuitive responses to C and N additions.

- **The Role of Methane- and Ammonia-Oxidizing Bacteria in the Emission of Greenhouse Gases from Agricultural Soils.** (UC Riverside) This project is determining the physiological mechanism of greenhouse gas production by methane-oxidizing bacteria (MOB) and ammonia-oxidizing bacteria (AOB) in agricultural soils by: characterizing the physiological responses of pure cultures to changes in CH_4, NH_3, NO_2, and O_2 concentrations; developing molecular tools for quantifying changes in populations of MOB, AOB, and their functional genes; and applying both the physiology and molecular tools developed to soil microcosms, to assess how MOB and AOB respond within a soil matrix when perturbed by changes in nutrient composition.
- **Carbon Sequestration by Smectite Clay Minerals in Soils.** (UC Berkeley) This project is investigating the hypothesis that smectite clay minerals can sequester soil humus effectively against microbial oxidation by a mechanism that involves the encapsulation of alkyl compounds in fulvic acid, with subsequent movement of the alkyl-fulvic acid complex into smectite interlayers, where the alkyl component is then protected against microbial attack by hydrophobic interactions. Results should provide insight as to how carbon can be sequestered more effectively in California soils and how these soils can be managed to enhance their content of recalcitrant organic matter.
- For more details, see http://kearney.ucdavis.edu/

Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory

- In the GEO-SEQ Project, LBNL and LLNL (along with Oak Ridge National Laboratory and other partners) are investigating safe and cost-effective methods for geologic sequestration of CO_2. Targeted tasks address the following: (1) siting, selection, and longevity of the optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO_2 (NETL 2001). This three-year study will focus on geologic sequestration of CO_2 in formations such as brine reservoirs, depleted oil reservoirs, and coal beds.

San Diego State University

- The Global Change Research Group at San Diego State conducts climate change work at the Mediterranean CO_2 Research Facility (MedCO_2RE) at the Sky Oaks Biological Field Station. This facility contains Free Air CO_2 Enrichment (FACE) rings, large-scale CO_2 field chambers, and CO_2-controlled growth chambers, which researchers use to study carbon changes attributable to climate change, among other things. The group is evaluating the possibility of using natural releases of CO_2 in FACE research in the Inyo forest. They are also preparing an aircraft to determine the CO_2, water vapor, and energy fluxes of arctic tundra and chaparral.

Current Status: Regional, National, and International

AmeriFlux

- AmeriFlux is a consortium of university and government researchers collecting data on carbon flux in North, Central, and South America. The AmeriFlux program is led by Dr. David Hollinger at U.S. Forest Service, Durham, New Hampshire.
  - http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm

Battelle Laboratories

- Battelle Laboratories is evaluating and examining factors that affect the geological and geochemical storage of CO_2 in deep saline formations in the Midwestern United States (NETL 2001).

CARBOEUROPE

- CARBOEUROPE is a group of projects from various entities that focus on the prototype development of a reliable, consistent monitoring system, which will allow researchers to calculate the full carbon balance of Europe (including the sink of the biosphere) at all relevant scales. This three-year effort began in 2001, and it is being coordinated by the Max-Planck-Institute for Biogeochemistry.
  - www.bgc-jena.mpg.de/public/carboeur/cluster/index_c.html

Carnegie Mellon University

- Carnegie Mellon is developing a state-of-the-art computer model to assess CO_2 sequestration options and costs at local, regional, and national levels.

Consortium for Agricultural Soil Mitigation of Greenhouse Gases (CASMGS)

The Consortium for Agricultural Soil Mitigation of Greenhouse Gases (CASMGS) is composed of researchers from a variety of universities and Battelle-Pacific Northwest National Laboratory. The consortium's goal is to provide the tools and information needed to implement soil carbon sequestration programs to lower the accumulation of greenhouse gases in the atmosphere, while providing income and incentives to farmers and improving the soil. Research is funded through the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, the U.S. Department of Energy, and the National Science Foundation. The consortium focuses on the following activities:

- Basic research on processes and mechanisms of soil carbon sequestration
- Development and assessment of best management practices
- Prediction and assessment of carbon sequestration and GHG emissions
- Measurement and monitoring of greenhouse gas emissions and emission reductions
- Outreach and technology transfer

Relevant research results to date for each consortium participant are outlined below.

- For more details, see the CASMGS Web site at www.casmgs.colostate.edu/.

Colorado State University

- In collaboration with the USDA's Agricultural Research Service (ARS), Colorado State University (CSU) estimated CO_2 emissions and sinks from U.S. agricultural soils and incorporated them into the national inventory of greenhouse gases compiled by EPA.
- The Natural Resource Ecology Laboratory at CSU developed the CENTURY model, which is a general model of plant-soil nutrient cycling that has been used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests, and savannas. It has been used to evaluate U.S. carbon levels as part of the National Assessment of the Potential Consequences of Climate Variability and Change. Current efforts are evaluating continental carbon fluxes for the past three decades. CSU also developed a daily time step version of the CENTURY ecosystem model (DAYCENT) in collaboration with the Soil-Plant-Nutrient Research Unit of ARS, to estimate *daily* fluxes of carbon dioxide, nitrous oxide, and methane from agricultural grassland and forest soils. The model was tested against field data and compared with other trace gas flux models, and has been used to study trade-offs between carbon sequestration and other greenhouse gas emissions for various agricultural management practices.
- In collaboration with USDA's Natural Resource Conservation Service (NRCS), CSU is using the CENTURY model to conduct state-level assessments of carbon sequestration rates and potentials for Iowa, Indiana, and several other states. As part of this effort, a computer model is being developed to use in forecasting and management decision making when implementing carbon-sequestering practices at the farm level.
- In collaboration with USDA's Economic Research Service, CSU is analyzing the sensitivity of carbon sequestration potentials to constraints on management adoption rates.

Montana State University

- Montana State University, in cooperation with CSU and the University of Nebraska, assessed economics of carbon sequestration in Northern Great Plains agricultural lands and found that changes from crop-fallow to continuous cropping of grains could sequester 12 MMT carbon in Montana at a cost that would be competitive with non-agricultural sources of carbon reduction.

Ohio State University

- Ohio State University (OSU) participants, together with collaborators from the NRCS and ARS, have organized several conferences since 1996 to evaluate various aspects of soil and agriculture in relation to carbon sequestration, and have published books on the subject.

Michigan State University

- Michigan State University, CSU, and six other cooperating institutions are establishing the framework to validate and model carbon sequestration in different soils and management systems. Tracer-bioassay techniques are indicating they can provide meaningful measurements that can field validate carbon sequestration.
- Studies on afforestation of agricultural land showed great potential for sequestering carbon, improving wildlife habitat, and reducing pollution. A study of one reforested site showed that 53 years of forest growth sequestered 1.1 tons of carbon per year, with two-thirds in the vegetation and one-third in the soil (CASMGS 2001).

Iowa State University

- Researchers estimated the expected cost of sequestering carbon in agricultural soils under different government-based and market-based approaches, and found that if all crop producers in the Midwestern United States adopted conservation tillage, then an additional 14 million metric tons of carbon would be sequestered, at a cost of approximately $170 million.

Texas A&M University

- Researchers measured CO_2 fluxes in prairies in North Dakota, Oklahoma, and Texas, using micrometeorological techniques to quantify changes in soil and biomass carbon in grassland and cropping systems. Measurements showed that all three grasslands were sequestering carbon, in amounts ranging from 0.9 to 4.9 metric tons per hectare per year, which suggests that these grasslands are potential CO_2 sinks.
- Similar measurements were taken over three fields dominated by different warm-season grasses (Bermuda grass, tallgrass native prairie, and sorghum) at Temple, Texas. Results substantiated other evidence that conversion from continuously cultivated cropland to improved pasture could create a large short-term carbon sink.
- Department of Soil and Crop Sciences researchers have demonstrated the effectiveness of conservation tillage in increasing soil organic carbon and various organic matter fractions.
- Analysts in Texas A&M's Department of Agricultural Economics investigated agricultural alternatives for GHG mitigation. In cooperation with Iowa State and CSU, they are now examining the role of soil carbon sequestration in the total array of greenhouse gas mitigation efforts. This study considers carbon dioxide, nitrous oxide, and methane, and its economic results will be carried into a detailed environmental analysis using Iowa State's Center for Agricultural and Rural Development (CARD) modeling systems.

Purdue University

- Research at Purdue University focuses on soil carbon processes with different crop rotation and tillage practices. Researchers have estimated the impact of management practices on carbon sequestration and carbon and nitrogen cycling in agricultural systems. Some programs are investigating the stability and nature of carbon in soil and others are evaluating plant genomics and lignin formation with an eye towards plant modification. Purdue works in collaboration with the Conservation Technology Information Center (CTIC).

Pacific Northwest National Laboratory (PNNL)

- The PNNL, Oak Ridge National Laboratory, and the Council for Agricultural Science and Technology, conducted a workshop on the science, monitoring, and policy issues of soil carbon sequestration in 1998. The workshop was sponsored by EPA, USDOE, USDA, Monsanto, and the National Aeronautics and Space Administration (NASA). Workshop participants identified research needs on mechanisms of carbon stabilization and turnover in soil aggregates, landscape effects on carbon sequestration, use of genetic engineering to enhance plant productivity and carbon sequestration, environmental impacts of soil carbon sequestration, and the role of soil carbon sequestration in controlling desertification.
- Researchers at PNNL, the University of Alberta, and Texas A&M revised algorithms of the EPIC model (originally designed in the 1980s to quantify the costs of soil erosion and benefits of soil erosion research and control in the United States) to improve the description of carbon and nitrogen transformations as influenced by climate, soil, management, and erosion dynamics.
- PNNL has computed the economic value of a successful program of soil carbon capture and sequestration, to better understand the role of soils in a larger program of carbon management.
- Researchers at PNNL, OSU, and the USDA and have assessed the impact of agricultural practices on the transport and fate of soil carbon. University of Alberta and PNNL researchers used a mathematical approach to reconstruct changes in soil carbon observed over half a century.

Kansas State University

- Kansas State University has been studying the carbon sequestration potential of tallgrass prairie. Under elevated CO_2 levels, the soil contained 6% more carbon than when compared with ambient conditions. Greater carbon concentrations were found under elevated CO_2 conditions than under ambient conditions, which suggests that the tallgrass prairie can sequester carbon in response to rising atmospheric CO_2.
- Carbon flux and soil carbon storage have also been examined in different management strategies of tallgrass prairie and wheat ecosystems in conjunction with University of Nebraska.

- Kansas State University has also been evaluating soil carbon with different cultivated agricultural management strategies.

Council of Western State Foresters

- When the Council of Western State Foresters met in February 2002, they discussed carbon sequestration issues and strategies for helping to reduce the rate of atmospheric CO_2 accumulation. They concluded that increasing forestland area, improving forest management and productivity, and the greater adoption of agroforestry by agriculture were effective strategies that they would support.

EPRI

EPRI has been assessing the technical and economic aspects of carbon management in its Target 48: *Carbon Capture and Sequestration.*

- Target 48 is conducting a three-year plan, which began in 2002, to address carbon sequestration. Addressing both direct and indirect sequestration, this effort is (1) conducting an analysis of current developments in carbon sequestration, (2) looking at the economics of carbon sequestration, (3) evaluating carbon sequestration research priorities, (4) examining carbon sequestration through sink enhancement, and (5) conducting research, development, and demonstrations for selected subject areas.
- Quantifying Carbon Market Opportunities in the United States. This project—conducted in collaboration with Winrock International and others—is measuring, classifying, and quantifying carbon market opportunities in the United States (Winrock 2001). Sponsors of the project will receive tools, data sets, and methodologies to evaluate and formulate carbon strategies and to design and implement practical near-term projects. The effort is also establishing baselines for participants' projects, developing a national land classification system, and constructing a database containing information on the size and cost of carbon storage opportunities in one region of the United States.

EPRI has also conducted research on biomass crops for energy production for a number of years. This work is currently being performed under Target 84.4: *Biomass Energy,* with the current focus on optimal technologies and strategies for firing biomass to produce electricity.

EUROFLUX

- The European community established the EUROFLUX, which involves long-term flux measurements of CO_2 and water vapor at 15 forest sites in the United Kingdom, France, Italy, Belgium, Germany, Sweden, Finland, Denmark, The Netherlands, and Iceland for three years. This data is now available through FLUXNET.
  - http://www.daac.ornl.gov/FLUXNET/euro_db.html.

FLUXNET

- FLUXNET is a global network of micrometeorological tower sites that use eddy variance methods to measure the exchanges of CO_2, water vapor, and energy between terrestrial ecosystem and atmosphere. At present, over 150 tower sites are operating on a long-term and continuous basis. Researchers also collect data on site vegetation, soil, hydrologic, and meteorological characteristics at the tower sites. FLUXNET includes data from AmeriFlux and EUROFLUX sites, as well as some in Asia, Australia, and New Zealand.
  - http://www.daac.ornl.gov/FLUXNET/

Massachusetts Institute of Technology

- MIT's Laboratory for Energy and the Environment hosts a Carbon Sequestration Initiative, formed by a consortium of energy and industrial companies. This group focuses most of its research on direct carbon sequestration.
  - http://sequestration.mit.edu/

Texas Tech University

- Texas Tech University and its research partners are using nuclear magnetic resonance well-logging techniques to identify suitable geologic formations for CO_2 storage. Understanding hydraulic fracturing will enable researchers to predict the behavior of gas in targeted formations to minimize the number of injection wells, while increasing the injected gas volume (NETL 2001).

University of Iowa

- A recent research project at the University of Iowa examined subsides for conservation tillage (Kurkalova et al. 2001). The research developed a modeling strategy to directly compute the subsidies needed for adoption; divided the subsidy into the profit loss (or gain) from adoption and the adoption premium due to uncertainties; calculated a supply curve of conservation tillage for a sample of Iowa farmers; and analyzed the subsidies' role in improving environmental performance and as a tool for income transfers to farmers.

University of Kansas

- The University of Kansas is developing a digital database that catalogs CO_2 source-to-sequestration information in five Midwestern states (IL, IN, JY, KS, and OH).

University of Maine, the Woods Hole Research Center, and USDA/Forest Service

- The University of Maine, the Woods Hole Research Center, and the USDA/Forest Service are conducting a project that is evaluating the carbon sequestration consequences of shelterwood cuts at the Howland Integrated Forest Study Area in Maine. The study is removing approximately 30% of the basal area of the overstory trees. Researchers will measure the whole-ecosystem carbon exchange associated with this strategy, using micrometeorological and measurement equipment.

University of Nebraska

- Researchers at the University of Nebraska are conducting a project focusing on carbon sequestration in dryland and irrigated agro-ecosystems in Nebraska. They will investigate carbon sequestration within three major agro-ecosystems, focusing on: (1) quantifying annual amounts of carbon sequestered and the associated interannual variability, at the landscape level, employing eddy covariance flux systems year-round, (2) quantifying soil carbon changes using geo-referenced soil samples, and (3) developing reliable, cost-effective procedures for predicting annual carbon sequestration and changes in soil carbon stocks at the scale of a single production field, using detailed crop yield mapping. The project will also measure plant photosynthesis and respiration, and soil carbon respiration in detail. It will examine interannual variability in carbon sequestration in terms of biophysical and physiological controlling factors, and quantify "carbon costs" of applied energy-dependent inputs (e.g., N fertilizer, irrigation, grain drying), and changes in N_2O and CH_4 emissions and integrate these results into net carbon sequestration values.

University of Texas

- Researchers at the University of Texas at Austin's Bureau of Economic Geology are developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. A regional U.S. data inventory of saline water-bearing formations is also being developed (NETL 2001).

University of Utah

- Researchers at the University of Utah are leading an effort to conduct an in-depth study of deep saline reservoirs in the Colorado Plateau and Rocky Mountain region. The study will enable researchers to determine how much CO_2 can be stored, what happens to the stored gas, and the long-term environmental risks associated with the storage (NETL 2001).

U.S. Department of Agriculture

- Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), the Wildlife Habitat Incentive Program (WHIP), the Farmland Protection Program (FPP), the National Research Initiative (NRI) Competitive Grants program, the Environmental Quality Incentive Program (EQIP), the Small Watershed Program (SWP), Conservation Compliance (CC), and Conservation Technical Assistance (CTA), the Wetland Reserve Program (WRP), the Stewardship Incentive Program (SIP), Forestry Incentives Program (FIP), and the Secretary's conservation buffer strip initiative are all working to help increase soil organic carbon. USDA research is focusing on understanding the role of agricultural ecosystems in the global carbon cycle.
    - USDA is conducting a project on pasture management strategies for sequestering soil carbon. The project will integrate the measurement of soil organic carbon (SOC) sequestration in pasture management systems with soil quality, water quality, and animal performance and productivity in a unique combination of

replicated water catchments with diverse plant genetic resources. The work will determine the rate and magnitude of SOC accumulation under three important management variables: (1) plant genetic source, (2) poultry litter versus inorganic fertilizer application, and (3) grazing of cattle versus haying.

- **Agricultural Research Service (ARS).** ARS has used technology to measure CO_2 emissions from soil during tillage and analyzed the rates of storage of atmospheric carbon dioxide as organic carbon in soils following the adoption of conservation practices. ARS researchers have also measured the rates of CO_2 assimilation of rangelands to help climate modelers develop better estimates of future atmospheric carbon dioxide levels.
  - www.usda.gov/oce/gcpo/sequeste.htm.
- **Agricultural Research Service (ARS).** CASMGS participants at the Soil-Plant-Nutrient Research Unit of ARS studied stable carbon isotopes to evaluate rates and processes of carbon sequestration in crop and rangeland soils. In collaboration with USDA/NRCS, samples were collected throughout the historic grasslands of the United States to determine how soil carbon is affected by cropping and soil management systems. A regional study of carbon sequestration rates on CRP lands across 13 states showed that CRP sequesters about 900 kg of carbon ha-1 yr-1, a rate at which, under full U.S. enrollment, the CRP alone could offset about 30% of all CO_2 emissions resulting from U.S. agriculture. In addition, much additional basic research is being conducted on soil carbon pools, isotopic methods and standardization, and effects of long-term cropping systems and nitrogen fertilization on soil carbon sequestration.
- **Economic Research Service.** Researchers at ERS have catalogued current GHG emissions from U.S. agriculture to project impacts of climate change mitigation policies on U.S. agriculture. GHG mitigation research supported the 1999 USDA analysis of how the Kyoto Protocol would affect U.S. agriculture. ERS and CSU are collaborating to integrate the most up-to-date economic and biophysical modeling systems and apply these new tools to evaluate the performance of a wide range of GHG mitigation policies on U.S. agriculture.
- **National Agroforestry Research Center.** The Center has studied the potential carbon sequestration of agroforestry practices in Nebraska, such as living snow fences, windbreaks, riparian forest buffers, and center pivot irrigation corners, and determined that the potential for carbon storage using these techniques was large.
- **National Research Initiative's Competitive Grants Program.** The Soils and Soil Biology section of this program is currently funding work examining the impact of CO_2 fertilization on soil carbon in forests (at Boston College), the response of fine root chemistry to elevated CO_2 and ozone (at Michigan Technological University), and the temporal coupling of soil nitrogen processes with net CO_2 exchange and long-term carbon storage (at the University of Wyoming).
- **Natural Resources Conservation Service (NRCS).** NRCS has developed models to link farm practices to carbon sequestration and to assess regional and national carbon sequestration rates. The Forest Service is developing management

practices to increase sequestration and implementing these practices on national forests.
  - www.usda.gov/oce/gcpo/sequeste.htm.
- **National Resources Inventory (NRI)** This database contains over 800,000 field sites across the United States. Data is collected every five years. Data fields include: land use, cropping history, soils, irrigation, and land set aside.
- **USDA Forest Service, Pacific Southwest Research Station, Center for Urban Forest Research.** Researchers performed a benefit-cost analysis of energy and CO_2 reductions attributable to Modesto's municipal urban forest (McPherson et al. 1999), and found that the benefits residents obtained from public trees exceeded city management costs by a factor of nearly two. This study found that Modesto's urban trees provided tangible air quality, flood control, energy conservation, and CO_2 reduction benefits, and predicted that the city could claim credits for these benefits as CO_2 trading markets develop.

U.S. Department of Energy

- USDOE's Carbon Sequestration program addresses the entire carbon sequestration life cycle of capture, separation, transportation, and storage or reuse, as well as research needs for methane and nitrous oxide. The program has six elements:
  - Cost-effective CO_2 capture and separation processes.
  - CO_2 sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.
  - Direct injection of CO_2 into the deep ocean and stimulation of phytoplankton growth.
  - Improved full life-cycle carbon uptake of terrestrial ecosystems.
  - Advanced chemical, biological, and decarbonization concepts.
  - Models and assessments of cost, risks, and potential of carbon sequestration technologies.

- USDOE's Office of Science/Office of Biological and Environmental Research established CSiTE (The USDOE Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems.) CSiTE performs fundamental research that will lead to acceptable methods for enhancing carbon sequestration in terrestrial ecosystems. Currently, the Office is conducting the following research:
  - **Ecosystem Dynamics.** This work involves evaluation and modeling of ecosystem dynamics at several well-instrumented test sites, including mine lands, croplands, and rangelands. USDOE is conducting an economic analysis of carbon storage and land reclamation options as a function of land management strategy, to understand the relationships of carbon sequestration and land management practices to the economics of carbon management. The project is using the laser-induced breakdown spectroscopy (LIBS) technology developed at Los Alamos National Laboratory to determine the elemental composition of materials. Using LIBS, elements in soil, including carbon can be determined rapidly using portable instrumentation. This project began in 2001 and runs through 2004.

- **Terrestrial Sequestration of Carbon Dioxide.** This research is investigating the use of forest biomass and various waste materials (including coal combustion by-products) incorporated into the soil to restore its quality, increase long-term carbon sequestration, and enhance short- and long-term productivity and sustainability. The study is taking place in South Carolina. Preliminary results indicated that solid carbon in the mulching treatments has migrated to deeper soils.
- **Carbon Sequestration Potential.** CSiTE is starting an analysis of a U.S. site by looking at the existing land and its uses, and performing a modeling analysis to see what sequestration options are feasible. This analysis will account for social, environmental, and economic issues.
- **Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration.** This project, conducted with The Nature Conservancy, Winrock International, and a number of other organizations, seeks to refine the tools and methodologies for cost-effective, verified measurements of the long-term potential of various carbon sequestration and land use emissions avoidance strategies, and test those tools and methodologies in the field. The project seeks to: (1) improve carbon offset estimates produced in both the planning and implementation phases of projects; (2) build valid and standardized approaches to estimate project carbon benefits at a reasonable cost; and (3) lay the groundwork for implementing more projects to provide new test ground for increasing knowledge on how to sequester significant amounts of carbon from the atmosphere. The project began in 2001 and is scheduled to be completed in 2004.
- **Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Combustion By-products.** This research, conducted by ORNL, PNNL, OSU, and Virginia Polytechnic Institute, is evaluating field sites where amendments of solid by-products from fossil-fuel combustion, paper production, and biological waste-treatment facilities have been applied, to identify and quantify the key factors leading to successful carbon sequestration and reclamation of degraded lands. The work focuses on: (1) the extent and nature of the sequestered carbon, (2) microbial communities and their influence on greenhouse gas (CO_2, CH_4, N_2O, NO_X) emissions, and (3) redox, alkalinity, toxic metals, and key soil physical properties. Long-term field studies will then be designed and site(s) recommended for the demonstration and further optimization of this approach. This work was scheduled to conclude at the end of 2001.

- USDOE's Biomass Power Program is developing prototypes of small modular biopower systems. In addition to collecting energy performance data, they are also collecting data on air emissions. They have established a Community Demonstration Program to demonstrate the feasibility of using small modular biomass systems to produce energy with wood chips from forest fuel reduction activities. Six sites will be chosen in two-year demonstrations. See www.eren.doe.gov/biopower.

- USDOE is also conducting carbon sequestration research through its national laboratories:

  - **Brookhaven National Laboratory (BNL).**
    - The Free Air CO_2 Enrichment (FACE) program, which is an open-air, long-term field experiment that enables the microclimate around growing plants to be modified to simulate climate change conditions. These experiments enable researchers to measure photosynthesis and carbon sequestration under these changed conditions to determine how these processes will behave in a CO_2-enriched atmosphere of the future. Studies have focused on cotton, wheat, and pine trees.
      - http://www.face.bnl.gov/face1.htm
    - Brookhaven is also developing a flexible, noninvasive method for monitoring and verifying temporal changes in soil carbon in situ. The method is based on Inelastic Neutron Scattering (INS) of fast neutrons from the carbon nucleus and detection of the subsequently emitted 4.4 MeV gamma rays. Preliminary results suggest that the requirement to measure changes of 100 gC/m^2 can be met with a precision of about 5%. The proposed system will allow multiple and sequential measurements in a static mode, covering area of about 2 m^2 or a scan of large areas. The project's two major objectives are: (1) to construct a prototype of a field deployable Soil Carbon Measurements (SCM) system, and (2) to characterize, calibrate and test the SCM system in the FACE) facility at Duke Forest, North Carolina, where laboratory carbon measurements of soil core samples are currently in progress. Researchers will collaborate with Dr. William H. Schlesinger (Duke University), Soil Scientist at the FACE experiment, Dr. George Hendrey (BNL) leader of the FACE experiment, where the field measurements in soil will be performed, and with Dr. Hugo Rogers, Plant Physiologist, (National Soil Dynamics Laboratory, Auburn, Alabama) where extensive calibrations will be carried out.

- **Los Alamos National Laboratory (LANL).** Researchers at LANL are conducting a project entitled *Field-Portable Spectroscopy Measurements of In Situ Soil Carbon: Inventories, Spatial Heterogeneity, and Dynamics in Semiarid Environment*. This work will use laser-induced breakdown spectroscopy (LIBS) to measure total soil carbon, and Raman spectroscopy to differentiate organic and inorganic soil carbon. Researchers will develop an integrated instrument for field use, demonstrate it by measuring carbon inventories through time in semiarid field sites, and use it to measure changes in soil carbon at sites in response to carbon sequestration practices and/or climate. It is expected that the instrument will be able to measure soil carbon at hundreds of points in a day, which could help resolve problems associated with the high degree of heterogeneity in distribution of soil carbon. Instrument development and testing will also produce data to improve understanding of carbon inventories, dynamics, spatial heterogeneity, and sequestration strategies in semiarid lands.

- **Oak Ridge National Laboratory (ORNL).**
  - ORNL is conducting a project to better understand the genetic and molecular control of processes that determine sequestration success, including photosynthetic uptake of CO_2 from the atmosphere and aspects related to securely storing that carbon in chemical forms that are resistant to microbial degradation and allocating carbon preferentially to roots where it can better contribute to soil carbon sequestration. The study will take advantage of a genetically well-characterized population of hybrid poplars growing in the Pacific Northwest. For every individual in this population, researchers will determine the chemical composition of leaves and roots, and the fraction of total carbon allocated to roots. Researchers will compare these traits against a genetic map that is being established for hybrid popular, to identify genes important to carbon sequestration.
  - A collaboration between ORNL and the Institute of Energy Research, in Graz, Austria, has developed the Graz/Oak Ridge Carbon Accounting Model (GORCAM) to calculate net carbon fluxes to and from the atmosphere as a result of land management and biomass utilization strategies. This spreadsheet model accounts for changes of carbon stored in vegetation, plant litter and soil; reduction of carbon emissions because biofuels replace fossil fuels; carbon storage in wood products; reduction of carbon emissions from wood products replacing energy-intensive materials like steel or concrete; waste wood recycling or burning; and auxiliary fossil fuels used for the production of biofuels and wood products.
    - www.joanneum.ac.at/GORCAM.htm

- ORNL recently completed a FACE experiment on a sweetgum monoculture in Oak Ridge, Tennessee. Among the results were indications that that above-ground wood production was 35% greater in CO_2-enriched plots during the first year only, and that the increased carbon uptake was allocated to fast-turnover pools (such as leaf mass and fine root production)—not to woody biomass.
  - www.esd.ornl.gov/facilities/ORNL-FACE/
- In the 1990s, ORNL measured and modeled CO_2 exchange between the forest and the atmosphere. The project continually measured fluxes of trace gases between the forest and atmosphere, using an eddy covariance method; measured canopy microclimate to interpret CO_2 flux measurements; measured leaf photosynthesis to parameterize the seasonal photosynthesis model; and used the biophysical CANOAK model to ingrate fluxes of multiple years and examine physiological and biophysical controls on canopy-atmosphere CO_2 exchange. The model computations over the study period indicated that net CO_2 uptake by the subject forest ranged from 450 to 620 g C m^{-2} y^{-1}.
  - www.esd.ornl.gov/programs/WBW/WBW_Forest.html

- **Sandia National Laboratory and Los Alamos National Laboratory.**
  - SNL and LANL have partnered with an independent producer to investigate down-hole injection of CO_2 into a depleted oil reservoir. Researchers will use a comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts to understand, predict, and monitor the geomechanical, geochemical, and hydrogeological processes involved. The observations will be used to calibrate, modify, and validate the modeling and simulation tools (NETL 2001).

U.S. Global Change Research Program

- The U.S. Global Change Research Program, established in 1989, is a U.S. federal government interagency organization that coordinates climate change research.

Attachment V

Developing Greenhouse Gas Mitigation Supply Curves for In-State Sources

Mike Rufo
XENERGY Inc.

PIER Environmental Area

September 2002

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Executive Summary

Objectives and PIER Vision

The key objective of this greenhouse gas (GHG) emission reduction supply curves roadmap is to contribute to advancements in the science of supply curve development, particularly as applied to understanding GHG emissions reductions opportunities in California. To achieve this goal, it will also likely be necessary to develop GHG reduction supply curves for California in cases where such curves are otherwise unavailable.

Part of the long-term vision of this roadmap is to develop the technical information necessary to ensure that California's policy makers can effectively respond to any GHG-reduction commitments made on its behalf by the United States. Even absent a national commitment to international agreements such as the Kyoto Protocol, California might decide to adopt its own GHG mitigation goals for the state. Already, the State has created a California Climate Action Registry to help companies and organizations doing business in California establish GHG emissions baselines against which future GHG emission reduction requirements could be applied. State policymakers will need robust and credible estimates of GHG mitigation costs and impacts in order to develop GHG mitigation strategies, policies, programs, and, possibly, regulations.

This roadmap seeks to advance the state-of-the-art of supply curve development, as well as improve the applicability and functionality of such curves for policy making and macroeconomic modeling. The strengths and limitations of supply curves vary significantly by greenhouse gas type and by sector; however, virtually all supply curves developed to date can be improved with respect to their methods, data limitations, and models.

Background

"Supply curves" have been utilized in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. These early conservation supply curves were intended to graphically illustrate the amount of energy *savings* that could be achieved through widespread implementation of energy conservation measures, as well as the costs of achieving those savings. In this way, conservation supply curves were designed to allow direct comparison of the costs of saving a unit of energy with the costs of producing it. Generally, the vertical axis of the curve represented the cost of each conservation measure, usually in dollars per unit of energy saved, while the horizontal axis represented the total amount of energy savings available. Measures are ordered on a marginal, least-cost basis.

Over the last ten years, the energy conservation supply curve framework was adapted and applied to the problem of characterizing the costs and benefits of various GHG mitigation strategies. In these GHG mitigation supply curves, costs are generally expressed in dollars per ton of carbon-equivalent reduction and plotted against the total amount of carbon-equivalent reduction that can be achieved by implementing the mitigation measures.

Despite some inherent weaknesses and limitations in the supply curve approach, it has been adopted in many GHG mitigation studies for several reasons. First, supply curves are an effective way of presenting the combined results of individual measure analyses into a simple graphical format that is intuitively easy to understand. This is important because many GHG mitigation supply curve studies often include cost and impact data on hundreds or thousands of individual technologies and practices. A second reason supply curves have proved useful to GHG researchers is that their results can be directly incorporated into a number of existing energy and economic forecasting models. These models use GHG mitigation supply curves as inputs to estimates of the total macroeconomic costs associated with achieving specific levels of reductions in greenhouse gas emissions.

Roadmap Scope

This roadmap addresses research needs associated with the development of California-specific GHG emission reduction supply curves for a variety of GHG types and sectors. Carbon dioxide mitigation through sequestration and direct removal approaches is not addressed.

General Supply Curve Methodological and Data Limitation Issues

Despite their usefulness, research for this roadmap indicates that there are a number of methodological problems and data limitations associated with GHG mitigation supply curve studies, including the following: inadequate incorporation of measure costs and benefits; a lack of access to proprietary industry data; a lack of measure adoption analysis and modeling; inadequate forecasting of technological innovation; use of average case measure analyses (resulting in aggregation bias); use of static versus dynamic stock modeling; and a lack of uncertainty analysis.

Goals

This roadmap's primary goal is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

The research activities in this roadmap begin with sector/gas-specific recommendations and conclude with recommendations that integrate or cut across sectors and greenhouse gases. The short-term sector/gas-specific recommendations focus on the development or synthesis of *initial* supply curve information. That is, the development, analysis, and organization of technology costs and benefits into supply curves similar to those developed in past GHG and conservation supply curve studies and described in Section 3 of this roadmap. Such basic supply curves have important limitations, particularly when they are incorporated into macroeconomic and mid- to long-term forecasting models. In addition, supply curves that focus only on technology costs and benefits do not provide policy guidance per se, though they are an important input to policy analyses.

The short-term Crosscutting/Integration recommendations address the broader needs associated with advancing the state-of-art of supply curve development and their integration with larger economic modeling efforts. One of the reasons for this organization is practicality. First-order benefits for California's climate change policy makers can be achieved fairly quickly by developing supply curves that capture incremental measure costs, measure applicability, and the potential impacts of measures on reducing GHGs in California. Further value will be obtained by expanding such analyses to explicitly include technology innovation over time, the diffusion-of-innovation framework to technology adoption, incorporation of market barriers and market failures, and integration into macroeconomic models. Although these advances are addressed primarily under the Crosscutting/Integration area, the initial supply curve work should also incorporate at least qualitative identification of market barriers and failures, as well as other co-benefits and collateral costs.

The mid-term recommendations focus on the development of *advanced* supply curves, which would build off of the initial studies to more definitively resolve current analytical and data-related weaknesses.

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.

PIER GHG Mitigation Supply Curve Research Objectives

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

Objective	Projected Cost ($000)
Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings.	50–100*
Contribute to the development of an initial California-specific CO_2 reduction supply curves for commercial buildings.	100–200*
Establish the feasibility of adapting LBNL industry-specific studies to California	50–100
Contribute to development of initial California-specific CO_2 reduction supply curves for remaining major industries	100–300**
Develop basic California-specific CO_2 reduction supply curves for the transportation sector	200–500
Address weaknesses and gaps in current transportation supply curve studies	100–300
Develop basic California-specific CO_2 reduction supply curves for the electricity generating sector	100–400*
Forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies	100–300
Develop CH_4 reduction supply curve for the landfill population in California	25–100
Develop California-specific CH_4 reduction supply curves from manure management	25–100
Develop N_2O reduction supply curve for California, reduce uncertainty in N_20 emission estimates	25–100
Develop supply curve for mitigating high global warming potential gases in California, reduce uncertainty in high GWP emission estimates	25–50
Develop/Implement a Dynamic Technology Adoption Model	100–500***
Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options	50–100
Total Short-term Cost	**1,050–3,150**

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 to complete each short-term objective.
**Range depends on number of industry-specific studies conducted ($35,000–$75,000 per industry).
***Higher range includes funding for one or more studies to empirically estimate model parameters.

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 an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

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 pertains to the issue of developing GHG mitigation supply curves. *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 the development of GHG supply curves that the proposed activities do not address. *Appendix A: Current Status of Programs* offers an overview of work being done to address climate change issues in this area.

Acronyms

ARB	California Air Resources Board
Cal/EPA	California Environmental Protection Agency
BAU	business-as-usual
CAFE	Corporate Average Fuel Economy
CALMAC	California Measurement Advisory Council
CAST	Council for Agricultural Science and Technology
CCIG	California Conservation Inventory Group
CCNG	combined-cycle natural gas
CEF	Clean Energy Futures study
CH_4	methane
CHP	combined heat and power
CIWMB	California Integrated Waste Management Board
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
CEUS	Commercial End Use Surveys
DEER	Database for Energy Efficiency Resources
DG	distributed generation
DOE	U.S. Department of Energy
DWR	California Department of Water Resources
EPA	U.S. Environmental Protection Agency
ER	Electricity Report
GHG	greenhouse gas
GWh	gigawatthour
GWP	global warming potential
HFC	hydrofluorocarbon
IWG	Interlaboratory Working Group (DOE)
kWh	kilowatthour
LBNL	Lawrence Berkeley National Laboratory
MAC	marginal abatement curve
MMTCE	million metric tons of carbon equivalent
MMBtu	million British Thermal Units
MPO	municipal planning organization
MT	metric tons
Mth	megatherm
NAS	National Academy of Sciences
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
PFC	perfluorocarbon
PG&E	Pacific Gas & Electric
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)

RASS	Residential Appliance Saturation Surveys
RD&D	Research, development, and demonstration
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SF_6	sulfur hexafluoride
SIC	standard industrial classification
TCE	metric ton of carbon equivalent
TWh	terrawatt-hour (a thousand million kilowatt hours)
USDA	U.S. Department of Agriculture
WIP	waste-in-place

1. Issue Statement

California lacks a full complement of supply curves that would enable State agencies and decision makers to develop informed decisions about the cost-effectiveness of potential greenhouse gas (GHG) mitigation measures. This lack of capability leaves the State unprepared to address potential state or national mandates for GHG reduction, or to benefit from the nascent GHG emissions trading markets.

2. Public Interest Vision

The potential magnitude of adverse ecological, agricultural, and economic impacts warrants development and implementation of technologies and policies to mitigate GHG emissions.[1] The key objective of this roadmap is to help advance the state-of-the-art of supply curve development, particularly as applied to the understanding of GHG emissions reductions opportunities in California. It also seeks to improve the applicability and functionality of such curves for policy making and macroeconomic modeling. To achieve this goal, it will also likely be necessary to develop GHG reduction supply curves for the State of California in cases where such curves are otherwise unavailable. The strengths and limitations of supply curves vary significantly by greenhouse gas type and by sector; however, virtually all supply curves developed to date can be improved with respect to their methods, data limitations, and models.

Part of the long-term vision of this roadmap is to develop the technical information necessary to ensure that California's policy makers can effectively respond to any GHG-reduction commitments made on its behalf by the United States. Even absent a national commitment to international agreements such as the Kyoto Protocol, California might decide to adopt its own GHG mitigation goals for the state. Already, the State has created a California Climate Action Registry to help companies and organizations doing business in California establish GHG emissions baselines against which future GHG emission reduction requirements could be applied. State policy makers will need robust and credible estimates of GHG mitigation costs and impacts in order to develop GHG mitigation strategies, policies, programs, and, possibly, regulations.

There are a number of target audiences for whom the information developed throughout implementation of this roadmap would likely be applicable, including the following:

- Executive and Legislative branches of State government
- State agencies, such as members of the Interagency Team on Climate Change
- Local governments that decide to develop and pursue their own GHG-reduction plans (e.g., as has occurred in Portland and Seattle)
- The California Climate Action Registry (created through SB 1771)
- Private-sector firms participating in the Climate Action Registry

[1] The potential impacts and costs of global warming on California are addressed through companion PIEREA RD&D roadmaps.

- Investor-owned and municipal utilities throughout the State
- Other national and international government and research organizations (e.g., U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA)).

3. Background

3.1 Supply Curves Basics[2]

Supply curves have been utilized in a number of disciplines for many years as a way to graphically display, in simple terms, the cost and availability of a resource or other market good. The supply curve paradigm was adopted to characterize the potential costs and benefits of energy conservation in the early 1980s. Technologies or practices that conserve energy were characterized as "liberating 'supply' for other energy demands" and could therefore be thought of as a resource and plotted on a supply curve.[3] In the early 1980s, Arthur Rosenfeld,[4] Roger Sant,[5] Amory Lovins (Lovins et al. 1986), and Alan Meier (Meier 1982) conducted much of the initial work developing and applying this framework to energy conservation. Over the last ten years, the energy conservation supply curve framework was applied in a number of studies that focused on characterizing the costs and benefits of various GHG mitigation strategies. For example, two recent EPA studies (EPA 2000 and EPA 2001) developed supply curves for mitigation of high global warming potential gases and methane, respectively.[6]

Despite some inherent weaknesses and limitations in the supply curve approach (discussed further in Section 3.4), it is likely that supply curves have been adopted in many GHG mitigation studies for at least two key reasons. First, supply curves are an effective way of presenting the combined results of individual measure analyses into a simple graphical format that is intuitively easy to understand. This is important because many of the so-called "bottom up" supply curve studies often include cost and impact data on hundreds or thousands of technologies and practices. A second reason supply curves have proved useful to GHG researchers is that the format of their results can sometimes be directly incorporated into existing energy or economic models (though more so in the former than in the latter, and rarely as effectively as researchers would like). Another appealing aspect of supply curves is that their potential savings or mitigation impacts are adjusted for the effects of overlapping options that are targeted at

[2] This section describes conservation supply curves as they have been defined and implemented in numerous studies. Readers should note that Stoft 1995 describes several technical errors in the definition and implementation of conservation supply curves in the original and subsequent conservation supply curve studies. Stoft concludes that "conservation supply curves" are not "true" supply curves in the standard economic sense but can still be useful (albeit with his recommended improvements) for their intended purpose (demonstration of cost-effective conservation opportunities).
[3] National Academy of Sciences (NAS 1991, Appendix C).
[4] Rosenfeld provides an excellent and interesting historical summary of the "early days" of developing estimates of energy-efficiency potential, beginning in the 1970s, in Rosenfeld 1999.
[5] Sant is often credited with coining the terms "least cost energy services" and "cost of conserved energy."
[6] Supply curves have also been used by government agencies, including the California Air Resources Board, to make decisions about the relative costs and benefits of reducing criteria pollutants.

the same base case technologies and segments. These points can be appreciated more easily through some generic examples.

Figure 1 presents a generic example of a supply curve. As shown in the figure, a supply curve typically consists of two axes—one that captures the cost per unit of saving a resource or mitigating an impact (e.g., $/kilowatthour (kWh) saved or $/ton of carbon avoided)[7] and the other that shows the amount of savings or mitigation that could be achieved at each level of cost. The curve is typically built up across individual measures that are applied to specific base case practices or technologies by market segment. Savings or mitigation measures are sorted on a least-cost basis and the total savings or impacts mitigated are calculated incrementally with respect to the measures that precede them. Supply curves typically (but not always) end up reflecting diminishing returns as costs increase rapidly and savings decrease significantly at the end of the curve.

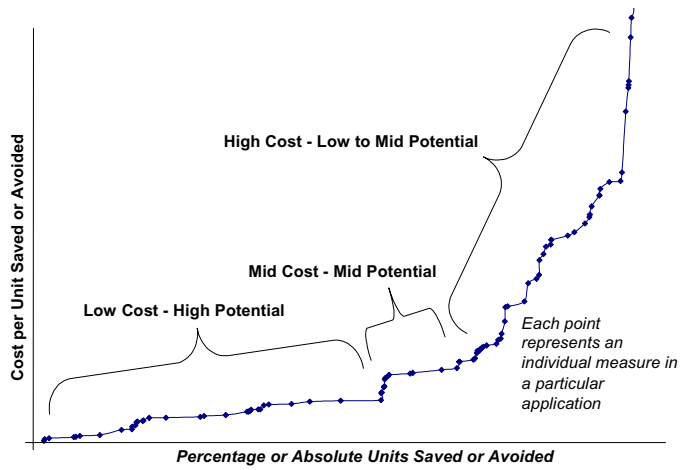

Figure 1. Generic Supply Curve

[7] Note that costs are usually annualized (sometimes referred to as "levelized") in supply curves. For example, energy conservation supply curves usually present "costs of conserved energy," which relate energy savings achieved by implementing a given efficiency measure, to that measure's "cost of conserved energy" (CCE).

$$\text{CCE} = \frac{\text{Annualized investment } (\$ / \text{yr})}{\text{Annual energy saved } (\text{kWh} / \text{yr})}$$

The initial investment in an efficient technology or program is annualized by multiplying it by the "capital recovery rate" (CRR).

$$\text{CRR} = \frac{d}{1-(1+d)^{-n}},$$

where d is the real discount rate and n is the number of years over which the investment is written off (i.e., amortized).

Table 1 presents a simplified numeric example of a supply curve calculation for several energy-efficiency measures applied to commercial lighting, for a hypothetical population of buildings. What is important to note in this example is that measures are stacked incrementally, based on least cost. When multiple measures are applicable to the same base case technology, supply curves avoid the double counting of savings. This is accomplished by applying measures sequentially and logically to the base case in question. These adjustments are typically made in energy supply curve studies by taking into account the increasing efficiency that occurs as the most cost-effective, energy-efficiency options are adopted. As the energy efficiency goes up as each measure is applied, the savings attributable to the next measure decrease, if the measures are interactive. For example, the occupancy sensor measure shown in Table 1 would save more at less cost per unit saved if it were applied to the base case consumption before the T8 lamp and electronic ballast combination. Because the T8/electronic ballast combination is more cost-effective, however, it is applied first, leaving less energy savings potential for the occupancy sensor. Thus, in a typical energy-efficiency supply curve, the sector usage of the base case end use is reduced with each unit of energy-efficiency that is acquired. Notice in Table 1 that the total end-use GWh consumption is recalculated after each measure is implemented, thus reducing the base energy available to be saved by the next measure.[8]

Table 1. Sample Technical Potential Supply Curve Calculation for Commercial Lighting (*Note: Data are illustrative only*)

Measure	Total End Use Consumption (GWh)	Applicable Square Footage (000s)	Average kWh/ft^2	Savings Percentage (%)	GWh Savings	Levelized Cost ($/kWh saved)
1. Federal Standards	500	100,000	5.0	15	75	0.01
2. T8 with Elec. Ballast	425	100,000	4.3	21	89	0.04
3. Occupancy Sensors	336	40,000	3.4	10	13	0.11
4. Perimeter Dimming	322	20,000	3.2	45	29	0.25
With all measures	293		2.9	41	207	

In the early 1990s, researchers began to apply the conservation supply curve framework to the problem of global warming. The CO_2 reduction associated with reduced power plant generation caused by implementation of energy conservation measures was added as a dimension to the conservation supply curve. Figure 2 shows an example of such work. This curve focuses on the costs of reduced CO_2 associated with implementation of conservation at different energy price points.

[8] The process of ordering measures becomes somewhat more complex when dealing with bundles or packages of multiple measures that are combined (see Stoft 1995).

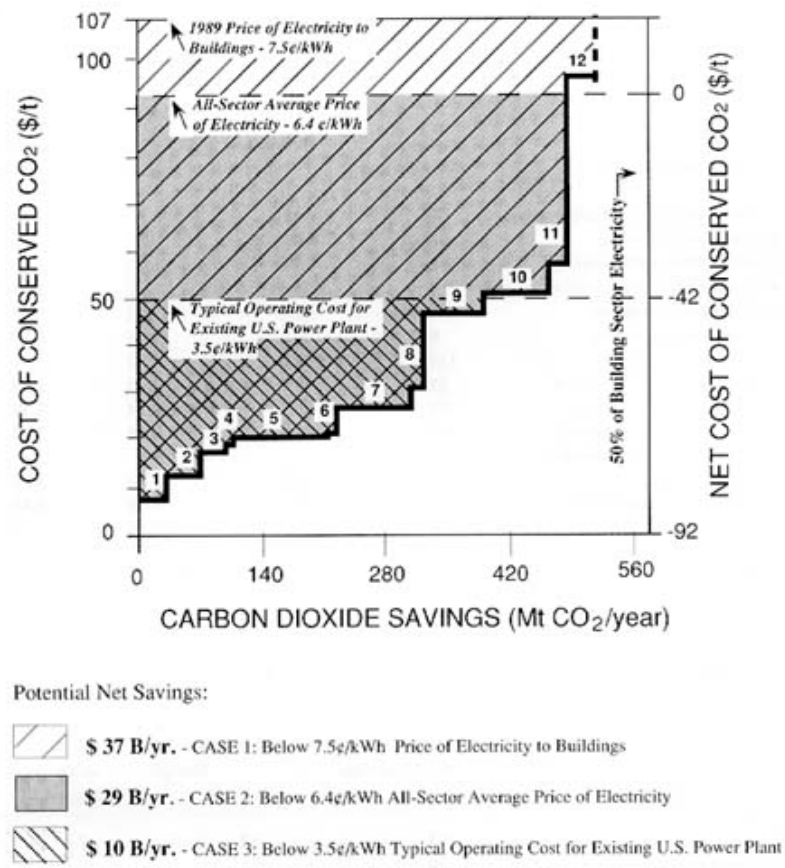

Figure 2. Net Cost of Conserved Carbon Dioxide (CC CO_2) for Electric Efficiency in the Buildings Sector

Source: NAS 1991, Appendix C.

3.2 The Many "Potentials"

Like any resource, there are a number of ways in which an energy efficiency resource can be estimated and characterized. Definitions of energy efficiency potential are in some ways analogous to definitions of potential developed for finite fossil fuel resources like coal, oil, and natural gas. For example, fossil fuel resources are typically characterized along two primary dimensions: the degree of geologic certainty with which resources may be found, and the likelihood that extraction of the resource will be economic. This relationship is shown conceptually in Figure 3. As illustrated by the lower left block in the figure, some fossil resources are known with respect to their location and size (usually from drilling samples) and are economically feasible to extract. These are usually referred to as *Proven Reserves*. Other resources are known but not economic to extract. Outside of the known resources are resources that are possible but not well known. Thus, all other quadrants of the figure are *Possible Resources*. However, both the certainty of knowledge

about existing resources and their economic viability of extraction can change quickly, for example in response to wide swings in global oil prices. Thus, the conceptual boundaries in the figure have proven to be very amorphous and dynamic over time.

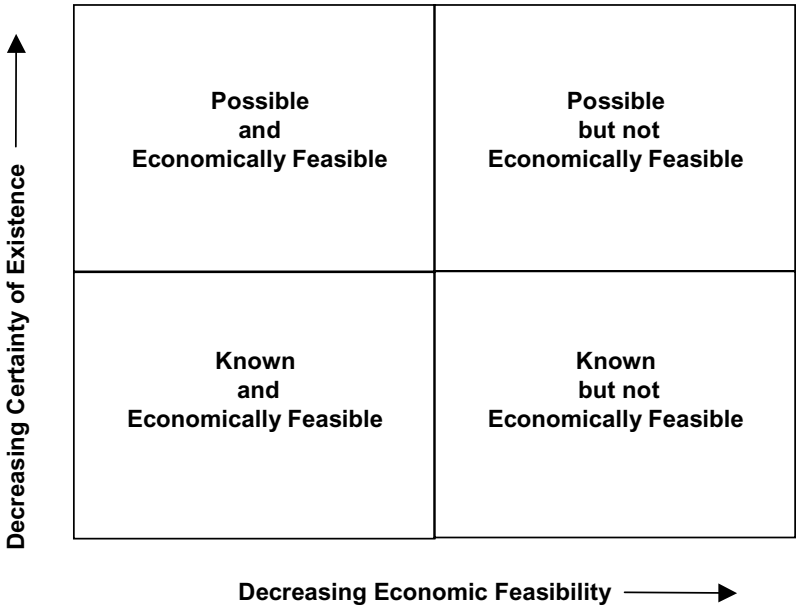

Figure 3. Conceptual Framework for Estimates of Fossil Fuel Resources
Source: Healy et al. 1983.

Somewhat analogously, previous energy-efficiency-potential studies have defined several different types of energy efficiency potential. Among the most common of these terms are *technical, economic, achievable, program,* and *naturally-occurring* potential. These potentials are shown conceptually in Figure 4 and described below.

In previous studies, a number of definitions of energy conservation and GHG mitigation *potential* have been used. The first set of energy conservation supply curve studies focused on identifying *technical potential.* **Technical Potential** was usually defined as the *complete* penetration of all measures analyzed in applications where they were deemed *technically* feasible from an *engineering* perspective. As the bottom-up methodologies began to be employed in utility integrated resource planning (IRP) processes in the late 1980s and early 1990s, many studies formally added the concept of *economic* potential (XENERGY 1992, EPRI 1990). **Economic Potential** was typically used to refer to the *technical potential* of those energy conservation measures that were cost-effective when compared to supply-side alternatives.[9]

[9] *Economic potential* has been defined differently in different studies. For example, in the traditional IRP framework, economic potential was often defined based on the marginal cost of building and running new power plants. In California, the Total Resource Cost (TRC) test was often used as part of this determination. The TRC test is a form of societal benefit cost test commonly used to compare a utility's resource alternatives. In general terms

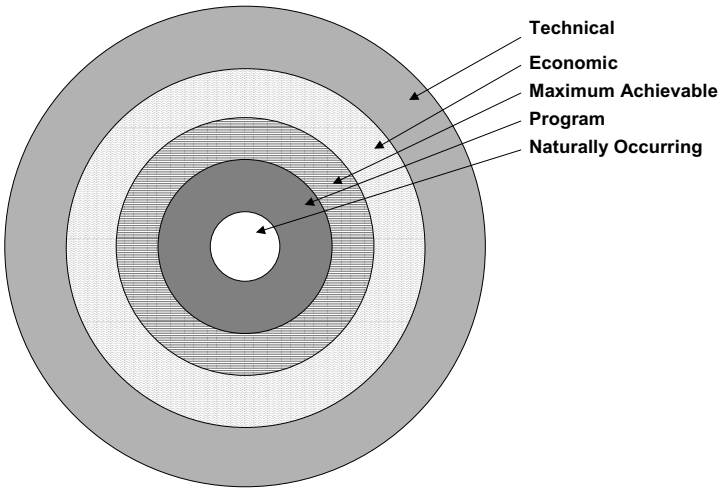

Figure 4. Relative Relationship among Common Energy Efficiency Potential Definitions

Although the concepts of technical and economic potential were important and helpful in establishing the amount of potential theoretically available in energy conservation or GHG mitigation measures, utility resource planners and government policymakers were most interested in knowing the amount of savings or resource mitigation that were likely to occur in response to a particular program or policy, rather than the maximums possible in theory. As a result, many energy studies began in the 1990s to formally estimate what is often called *achievable potential.* **Achievable Potential** usually refers to the amount of savings or resource mitigation that would occur in response to one or more specific market interventions. Because achievable potential will vary significantly as a function of the specific type and degree of intervention applied, it is often developed for multiple scenarios (e.g., "business-as-usual funding," "increased funding," and "maximum funding"). Savings associated with achievable potential are savings that are projected beyond those that would occur naturally in the absence of any market intervention.

Naturally-Occurring Potential is often used to refer to the amount of savings estimated to occur as a result of normal market forces, that is, in the absence of any utility or governmental intervention. The closely related term *business-as-usual* (BAU) is often used in GHG mitigation studies. Business-as-usual forecasts represent the energy use or GHG emissions expected to occur over some time period in the absence of market interventions. Business-as-usual forecasts are often used as a baseline against which the costs and benefits of market intervention strategies are measured. Finally, the term *frozen-efficiency*

for energy-efficiency measures, the TRC was calculated as the ratio of the present value of energy and capacity costs that would be avoided as a result of implementation of the efficiency measure, divided by the present value of utility and participant costs incurred to achieve the avoided cost savings. Other studies, including the recent *Report of Working Group III of the Intergovernmental Panel on Climate Change* (IPCC 2001), estimate economic potential from the consumer's perspective, that is, based on the direct consumer costs and benefits.

forecast deserves mention as well. In many energy forecasts, a frozen efficiency forecast is sometimes included to forecast energy use as it would be expected to occur if there were no naturally occurring efficiency improvements—that is, if efficiency levels were frozen at their current levels. In addition, frozen-efficiency analyses have been used on a "backcast" basis to demonstrate savings that have occurred from energy standards or other market interventions that were implemented in the past.[10]

The discussion above is meant to provide the reader with a brief introduction to a set of widely used terms as they evolved with respect to the energy-efficiency forecasting and planning. Many of these terms have been adopted directly or in modified form in GHG mitigation studies. For example, the U.S. DOE Interlaboratory Working Group's Scenarios for a Clean Energy Future study—also referred to hereafter as the *Clean Energy Future* or *CEF study* (USDOE/IWG 2000)—developed three future scenarios to assess the costs and benefits of mitigating GHG emission in the United States. These scenarios included a BAU forecast and "Moderate" and "Advanced" mitigation scenarios.[11] Nonetheless, it is important to emphasize that although individual study authors often use terms like those discussed above similarly, their specific definitions of the terms may vary in important ways. For example, in some studies, economic potential is calculated only based on the incremental costs of the measures and practices analyzed, while in other studies the programmatic costs of achieving those savings are included as well.[12] As shown in Figure 5, the Intergovernmental Panel on Climate Change's latest report (IPCC 2001) includes a conceptual representation of all of the potentials discussed above, plus yet another—the "socioeconomic" potential, which they define as the level of potential that could be achieved if social and cultural obstacles to the use of technologies that are otherwise economic were overcome. The socioeconomic potential incorporates the value of reducing externalities and is based on a societal rather than consumer perspective.

[10] See, for example, ECOFYS 2001.

[11] In the CEF study, the BAU forecast assumed a continuation of current energy policies and a steady pace of technological progress. In contrast, the Moderate and Advanced scenarios were defined by policies that were consistent with increasing levels of public commitment and political resolve to solving the nation's energy-related challenges. Some of the public policies and programs that define the scenarios cut across sectors; others were designed individually for each sector (buildings, industry, transportation, and electric generators) and assessed for impacts out to 2020. Numerous policies were examined, including fiscal incentives, voluntary programs, regulations, and research and development.

[12] Often, the studies that exclude programmatic costs from estimates of "economic" potential do so because the authors argue that programmatic costs vary by programmatic strategy and, thus, are best captured when estimating achievable potential.

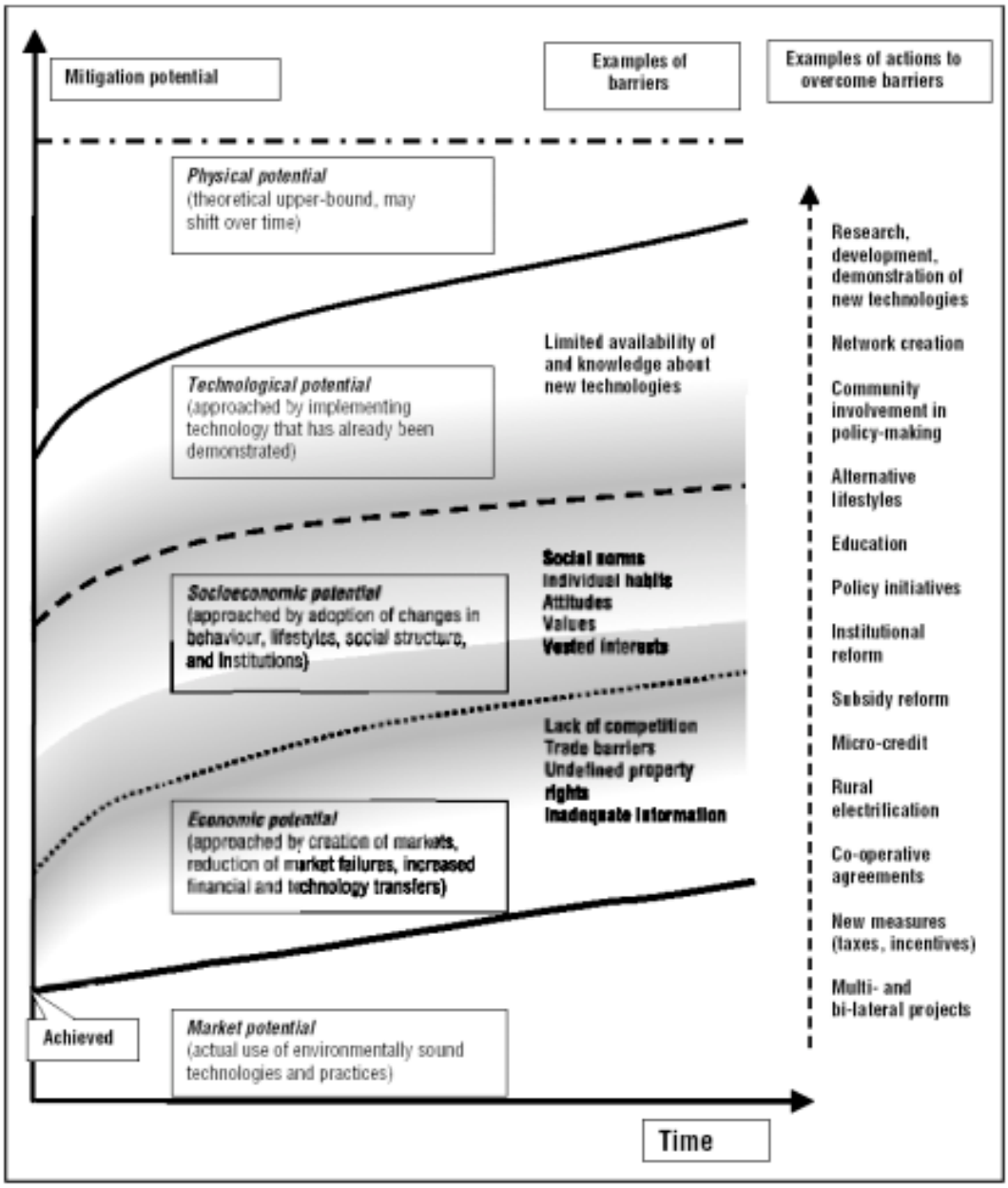

Figure 5. Penetration of Environmentally Sound Technologies: A Conceptual Framework

Source: IPCC 2001.

3.3 Scope of This Roadmap

This roadmap addresses research needs associated with development of California-specific GHG emission reduction supply curves for a variety of greenhouse gas types and sectors. Mitigation of carbon dioxide through sequestration and direct removal approaches are not addressed. Specifically, this roadmap discusses research needs with respect to the following:

Greenhouse Gas Types

- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- High global-warming-potential (GWP) gases (PFCs, HFCs, and SF_6)

Sectors

- Buildings
- Industry
- Transportation
- Electricity production and transmission
- Agriculture
- Waste

3.4 General Supply Curve Methodological and Data Limitation Issues

This section briefly enumerates several key criticisms and limitations of many of the past conservation and GHG supply curve studies. However, this discussion does not imply that all such studies suffer from these limitations, or that all of the criticisms are completely valid and relevant to the specific objectives of the individual studies.

It is important to note that the terms and concepts presented in Sections 3.1 and 3.2 are based primarily on what is often referred to as the *conservation supply curve, bottom-up, conservation paradigm,* or *engineering-economic* approach to estimating the costs associated with energy efficiency or GHG mitigation potential. This roadmap builds on this approach and, most importantly, seeks to improve it. Despite adopting this framework as a starting point, it is clear that some critics question its basic validity (e.g., Sutherland 2000) and others have important concerns about methodological and data limitations associated with many well-known applications.

Though a formal discussion of the debate between these perspectives is beyond the scope of this roadmap, this section provides some documentation of it to acknowledge awareness of these competing points of view. Wherever practical, this roadmap suggests research activities that might resolve some of the disputes between these points of view. However, the companion PIER roadmap on *The Economics of Climate Change Mitigation and*

Adaptation in California (authored by Alan Sanstad, of Lawrence Berkeley National Laboratory) addresses these issues within a broader economic modeling context.

3.4.1 Discount Rates, Market Barriers, Willingness-to-Pay, and Production-possibilities Frontiers

As alluded to in Section 3.4, there has been an ongoing debate associated with some of the high profile GHG and conservation potential studies about the use and mutability of consumer discount rates. Some studies, in which supply curves were developed as stand-alone products, have used consumer discount rates that are based on expected rates of return from competing investments. A typical discount rate used to reflect this perspective is often approximately 15%. In other studies, even lower discount rates have been used to identify economic potential from a societal perspective (i.e., discount rates of 3 to 5%). Some critics have argued that these discount rates are inappropriate, in that they do not reflect all of the costs associated with implementation of a conservation or mitigation measure. These critics argue that the appropriate discount rates to use should be based on observed consumer behavior and that these rates are often as high as 100% or more.

Discount rates estimated from actual observed consumer behavior associated with conservation investments are often referred to as "hurdle" rates. Critics and proponents of the bottom-up studies agree that observed hurdle rates are much higher than the rate of return of competing investments; the two camps disagree, however, on why this is so and whether anything can be done about it. In short, critics maintain that hurdle rates are high because supply curve studies do not adequately capture and quantify all of the costs of purchasing energy efficiency or achieving GHG reductions. Both perspectives see information, transaction, and risk costs as accounting for part of the difference between hurdle rates and traditional discount rates associated with competing alternatives. The key difference is in whether these additional costs are viewed as benign and immutable[13] or whether they are viewed as market barriers/failures that can be ameliorated through policy and program interventions. This debate has gone on for some time and has stagnated somewhat, as proponents of neither point-of-view have given much ground.

Critics like Sutherland further maintain that the benefit-cost framework used in bottom-up analyses is incorrect in its use of energy savings as a benefit and argue instead that benefits should be defined based on the value ascribed to them by consumers, usually as measured by their willingness to pay. Sutherland 2000 labels his competing point-of-view the "economics paradigm" to reflect his position that it is the accepted approach of mainstream economists. He argues that there are few inefficiencies associated with energy-related investment decisions and that the economy is operating at its optimum

[13] For example, some critics argue that a key underlying premise of the bottom-up approach, that there are extensive market barriers and failures that limit the adoption of energy-efficiency measures to levels below what is optimal for society, is false. They view many of the barriers identified in conservation supply curve studies as "benign characteristics of well-functioning markets" that do not meet the threshold definition of "market failures" (Sutherland 2000).

with respect to its use of energy resources. Under this argument, the untapped efficiency opportunities identified in bottom-up studies are not cost-effective because there are additional costs to consumers and firms of achieving the identified returns that are not included in the bottom-up analyses. These costs are often referred to as *hidden* or *transaction* costs, and are often argued to be unobservable in practice.

There are, however, many counter arguments to the position put forth by Sutherland and similar critics. Decanio (2000) and Sanstad et al. (in USDOE/IWG 2000, Appendix E-4) argue that there is a wealth of evidence that indicates that firms do not, in practice, operate along their theoretical production-possibilities frontier when it comes to trading off energy versus other production inputs. As a result, they argue that the negative tradeoff between the production of ordinary output and environmental quality, which is embedded in most economic models, is a false dichotomy. Their evidence, and the evidence from a growing body of literature on energy-efficiency-related market barriers, suggests that firms operate inside the theoretical production-possibilities frontier with respect to investments in energy efficiency and that the production-possibilities frontier itself can be (and has been) expanded through market interventions (e.g., via technological progress engendered by regulations, public R&D investments, and voluntary government and utility energy-efficiency programs). In addition, Decanio 2000 argues that conventional economic models have serious flaws with respect to their representation of the productive sectors of the economy. In particular, much of Decanio's research seeks to demonstrate that the assumption, made by some economists, that profit maximization is the firm's single objective, is contradicted by a wealth of empirical evidence and the modern theory of the firm. In addition, Decanio (1998) further maintains that the appeal to transaction costs that are argued to be, by definition, unmeasurable, is tautological.

One area of criticism that has been addressed in recent studies is the incorporation of program and policy costs associated with reducing hurdle rates. Although authors and advocates of the bottom-up studies have acknowledged the importance of program interventions and their costs, they have not always explicitly included such costs in their analyses. For example, these costs were discussed but not incorporated in the so-called "Five Lab Study" (USDOE/IWG 1997) but were included in the follow-up "Scenarios for a Clean Energy Future" study (USDOE/IWG 2000). By contrast, program costs were almost always included in utility-sponsored studies of achievable energy-efficiency potential and cost effectiveness throughout the 1990s.

3.4.2 Achievable Potential, Technological Innovation, and Static Versus Dynamic Analyses

Many energy efficiency and GHG mitigation studies have developed supply curves that are two-dimensional and static. As shown in Section 3.1, the traditional dimensions of such supply curves are cost on one axis and the amount of available savings or reduction on the other. There is a good reason for this two-dimensional simplicity: in most cases it was the authors' intent to use a supply curve representation to illustrate the potential for energy efficiency or GHG reductions as concisely as possible. In addition, a number of

macroeconomic and energy-economic models seem only to be able to capture efficiency and GHG potential through the use of such simplified two-dimensional forms. There are, nonetheless, serious limitations associated with this way of modeling energy efficiency and GHG mitigation potential.

First, a principal limitation of many two-dimensional supply curve studies is that they do not formally model adoption of efficiency or mitigation measures as a function of policy or program interventions. To be credible, estimates of potential must be based, as much as possible, on models that are calibrated to actual consumer and firm behavior. Such model calibration must be done to capture adopting behavior both with and without different types of program and policy interventions.

Second, many supply curve studies do not account for changes in technological innovation as it relates to reductions in cost and improvements in efficiency. Lack of incorporation of technology innovation ("progress ratios") is a major limitation in models that run out 20 to 100 years. How to incorporate technological innovation is a difficult question.

In shorter-term studies (e.g., 20 years or less), technological innovation is sometimes addressed through the incorporation of so-called emerging technologies (i.e., technologies that are currently well-conceptualized or demonstrated but are not yet commercially available or are not penetrating the market due to cost or other inhibiting characteristics). This approach then often requires additional, often highly uncertain, assumptions about what the cost and non-cost characteristics of the technology will be at maturity. This method's advantage is that a pool of specific options with demonstrated promise can be referenced from which it may be plausible to maintain that at least a subset of the pool will bear fruit.

Another way of approaching the problem is to incorporate technological innovation or progress ratios, on a time dependent basis, into longer-term studies. In this approach, one need not identify specific nascent technologies but rather a general rate of improvement that is empirically derived for particular segments of the economy or types of technologies (e.g., products based on computing technology would likely have different progress rates than strictly electromechanical equipment such as motors).[14] The drawback of this approach is that, without credible, empirically derived innovation rates, the use of such factors will remain open to criticism.

The two approaches to innovation can also be combined for shorter-term studies. For example, rather than assuming (as is done in some studies) that a technology will be at a certain cost once it achieves sufficient economies of scale, the cost of the technology can be modeled over time as a function of its level of penetration in the market (i.e., with costs

[14] Although as demonstrated by the evolution of variable-speed drive controls, the efficiency and cost-reduction potential of traditional industrial era equipment can also be strongly affected by information technology, almost always in ways that are difficult to predict.

falling as penetration increases; this approach also provides a way to explicitly model indirect program benefits).[15]

The general issue of time dependence is related to the two issues above (i.e., modeling program/policy interventions and technological innovation). There are a number of other important factors that affect efficiency and GHG-reduction potential that are likely to change over time. One such factor is capital stock, which is constantly decaying, turning over, and being accredited to over time. Many energy-economy models do explicitly model capital stock, and the fact that some efficiency measures can occur only when stock turns over and others may become less important as inefficient stock is decayed. However, in some macroeconomic and GCC models, it appears that two-dimensional supply curves that lack a time dimension are sometimes used.[16] Other time-related issues that are often not explicitly modeled include changes in fuel prices and feedback between supply-side and demand-side policies.

Other key issues include the following:

- Costs in supply curves tend to be single point averages and do not capture the fact that costs often vary across applications. This factor naturally leads to some aggregation bias; however, it can add significant cost, time, and complexity to incorporate the distributions around the averages.
- Non-energy costs and benefits are often not quantified. For example, in the industrial sector, non-energy benefits include minimization of waste production, increased productivity, and reductions in other emissions (Laitner et al. 2001). It is often difficult enough within the scope of many studies to quantify direct costs and benefits of measures, much less indirect ones. Nonetheless, identification and quantification of indirect costs and benefits is critical to improved modeling of adoption and would increase the credibility of many studies.
- The least-cost ordering of measures in supply curves implies that measures are adopted on a least-cost basis; whereas, actual measure adoption is generally a multi-attribute decision process. This discrepancy is a function of both the measure-specific market barriers/failures that exist and the fact that measures in supply curves do not always offer perfectly constant utility.

In summary, supply curve studies to date have suffered from a limitation that is almost, by definition, inherent to their original purpose as a policy and modeling tool: simplicity. As Florentin Krause, an interviewee for this roadmap, put it: "A supply curve framework

[15] For example, it has been argued in several studies that utility and government policies to promote electronic ballasts has resulted in a significant positive feedback loop in which production was increased, costs decreased due to production economies, and further increases in production and market penetration resulted (see, for example, XENERGY 1998b and Duke and Kammen 1999).

[16] This roadmap does not include such models in scope; however, we reference this issue to illustrate that some of the limitations of supply curve studies are tied to the limits of the larger models into which they feed. See the companion PIEREA roadmap on economic issues authored by Alan Sanstad for more issues related to macroeconomic and GCC models.

is useful mainly for a certain kind of modeling in which transparency and simplicity are more important than comprehensiveness." Most analysts agree that there are broader modeling approaches that are more appropriate for policy making than supply curves. In fact, by some definitions, addressing the weaknesses outlined above requires the adoption of a framework that goes beyond supply curves.

3.5 Why This Research Is Needed

There are a number of important reasons for PIEREA to embark on research related to GHG mitigation curves for California. First, California needs accurate GHG reduction information in order to make informed decisions on whether and to what extent it should formulate its own public policy on climate change. Second, as discussed in Sections 3.4 and 4, existing GHG reduction studies are inadequate for this purpose because they: 1) are not specific to California, 2) suffer from methodological and data limitations, and 3) are incomplete (supply curves are not available for all key GHGs). Third, no other institution in California is currently working to develop comprehensive and accurate GHG reduction supply curves for the State.

In short, PIEREA efforts are needed to advance the state-of-the-art for GHG supply curves and to develop California-specific GHG supply curves in cases where no other entity is doing so. Where methodological or data improvements are targeted that have national or international benefits, PIEREA should work jointly with other organizations to share both the costs and benefits of such work.

3.6 The PIER Focus

Existing greenhouse gas mitigation supply curves are inadequate to properly address the full selection of GHG mitigation opportunities in California. Supply curves for some sectors have been developed on a national level; however, the State needs to build upon this work to define its scope in relation to California, as well as develop supply curves for sectors that have not been addressed in other research efforts.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Developing greenhouse gas mitigation supply curves for in-state generation sources 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 roadmaps address other economic and technical aspects of GHG mitigation. Whenever possible, PIEREA will coordinate these programs and seek outside collaborators to leverage funding and avoid overlapping research.

4. Current Research and Research Needs

This roadmap's primary goal is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

At present, short-term supply curve development research needs to focus on the following areas:

1. CO_2: Buildings
2. CO_2: Industry
3. CO_2: Transportation
4. CO_2: Electricity Production
5. Methane: Waste and Agriculture
6. N_2O: Agriculture and Mobile Sources
7. High Global Warming Potential Gases: Industry and Electricity Transmission and Distribution

The following discussions outline the status of current work in the development of GHG mitigation supply curves by sector and greenhouse gas type, and identify scientific and research gaps.

4.1 CO_2: Buildings

There is a large body of recent and historic literature on the potential for energy savings and associated CO_2 reductions in the buildings sector. *Buildings sector* refers broadly here to energy use with residential and commercial buildings and includes all associated end uses (e.g., including appliances). Based on California's latest emissions inventory, the residential and commercial buildings sector account for 14% and 10% (24% combined) of the CO_2 emissions in California (CEC 2001d). Because CO_2 accounts for 84% of the State's total GHG emissions, the buildings sector represents 20% of total GHG emissions.

As noted previously, early work in the buildings sector in the US in the 1970s and 1980s created the bottom-up framework for many GHG mitigation studies in the 1990s. Within the United States, California-based studies were at the forefront of early buildings potential studies. Intensive study of energy use in California buildings has occurred over the past twenty-five years as a result of several factors, including:

- an early policy commitment to energy conservation and renewable energy and creation of the California Energy Commission (Commission) in 1974,
- the Commission's authority to promulgate State-specific energy-efficiency standards in the form of Title 20 (appliances) and Title 24 (building shell),
- the Commission's development and ongoing implementation of end-use forecasting to project energy consumption and peak demand in the commercial and residential sectors,
- the California Public Utilities Commission's (CPUC's) requirements that the State's investor-owned utilities implement energy-savings programs (from the late 1970s to the present) and practice integrated resource planning (from the late 1980s to the mid-1990s),
- the actual implementation and evaluation of energy-efficiency programs by California's investor-owned and municipal utilities and, in the case of the former, the wealth of ex-post evaluations of program impacts (several hundred studies that represent several tens of millions of dollars worth of research),
- the State's brief shift towards a market transformation program orientation, which resulted in a set of market assessment and evaluation studies that were more focused on understanding and ameliorating market barriers than were the impact evaluations that preceded them, and
- the recent California energy crisis which generated a new wave of interest and resources directed at implementing energy-efficiency measures in the State.

To provide a glimpse of the body of research born of these historic and contemporary factors, we list below just a few relatively recent examples of the studies and reports available on energy-efficiency in California's buildings sector:[17]

- *California Energy Commission End-use Demand Forecasts* (e.g., CEC 2000a and 2002). The Energy Commission periodically conducts energy demand forecasts. These forecasts include estimates of key data necessary for assessment of energy-efficiency potential, in particular, forecasts of commercial floor space, commercial square footage, residential households, end use consumption (e.g., kWh per household for air conditioning), and end use saturation levels (e.g., fraction of commercial floor space with mechanical air conditioning).
- *2001 DEER Update Study* (XENERGY 2001b). Includes updated incremental measure costs for currently available residential and commercial measures and estimates of per unit energy savings for currently available residential measures. Updates previous measure cost studies from 1992, 1994, and 1996.

[17] It is safe to say that no other state approaches California in the breadth and depth of efficiency-related buildings research.

- *CCIG Technology Energy Savings Study* (NEOS 1994). Provides per unit energy and peak demand savings estimates for a large number of residential and commercial building technologies, based on extensive building simulations by building type for five major climate regions.
- Utility Impact Evaluation and Market Transformation Studies. As mentioned above, several tens of millions of dollars were spent measuring the actual kWh and therm savings attributable to utility programs implemented in program years 1992 through 1997. From 1998 to 2000, much of the evaluation-related research required by regulators shifted toward a focus on market transformation. These studies were quite useful in broadening the available literature and associated knowledge base with respect to improved understanding of market functioning, market barriers, consumer attitudes and behavior, and the role of private sector actors in capturing efficiency opportunities. Too numerous to list here, a significant portion of this research is available on the California Measurement Advisory Council's Web site at www.calmac.org (see also XENERGY 1999). A few of these studies warrant explicit mention here, given their relevance to this roadmap:
  - XENERGY 2002. *California Statewide Commercial Sector Energy-Efficiency Potential Study: Final Report,* prepared for Pacific Gas and Electric Company. Study ID# SW039A. July.
  - Aspen 2002. *Nonresidential Market Share Tracking Study,* prepared for the California Energy Commission, in progress.
  - Regional Economic Research, Inc., 1999. *Efficiency Market Share Needs Assessment and Feasibility Scoping Study,* prepared for the California Energy Commission and Pacific Gas and Electric. May.
  - RLW 2000. *Statewide On-Site Survey of Residential Lighting and Appliances,* prepared for San Diego Gas & Electric Company.
  - Numerous utility and statewide studies of the Commercial New Construction Buildings Sector.
- Utility Program Year Application Filings. As part of their annual regulatory filings to the CPUC for approval to implement energy-efficiency programs, California's investor-owned utilities submit detailed program plans, which include inputs to cost-effectiveness calculations, often in an accompanying appendix referred to as "workpapers." These workpapers include a great deal of information on measure costs and savings.
- Commercial End Use Surveys (CEUS) and Residential Appliance Saturation Surveys (RASS). Over the past 20 years, PG&E, SCE, and SDG&E have conducted periodic residential and commercial equipment saturation surveys. Recently, the California Energy Commission began direct management of statewide residential and commercial saturation studies. The Commission is in the early stages of both projects and will likely update saturation values sometime in the 2002–2003 time frame.
- Supporting Research for Title 24 and Title 20 Standards. The Energy Commission conducts ongoing studies in support of development of new Title 24 and Title 20 standards (see www.energy.ca.gov/title24).

- Recent and Current PIER Studies. These PIER studies involve a wide variety of activities associated with the development of technologies that save energy and have other environmental benefits. PIER-related research on specific technologies provides an important source of information on emerging technologies (see www.energy.ca.gov/pier/reports.html)
- California Energy Commission. 1997. 1996 *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December. This report was to provide comprehensive data on energy consuming and producing technologies. However, the study was not completed in its entirety.

Despite the extensive and impressive ongoing research on energy-efficient technologies and practices for the building sector in California, formal integration of this information into supply curves and estimates of potential virtually ceased with the advent of electric restructuring in the State in 1996.[18] Because of the wealth of recent and ongoing research in the State, there is limited need, within this roadmap, for much new research on the key *inputs* necessary to estimate energy-efficiency potential in California's building sector. There is, however, a need for updated *integration* of the existing research into supply curves and estimates of remaining potentials in ways that clearly communicate the benefits and costs of buildings-related carbon dioxide reduction to State policy makers.

Research Needs

In the short-term, there is a need to integrate existing information on energy-efficiency opportunities in buildings into supply curves and GHG mitigation potential estimates in a way that improves upon past efforts by advancing the state-of-the-art for such studies. As part of these efforts, energy savings estimates will need to be connected to their CO_2 emission-reduction equivalents.

In addition, there is an important need to develop improved technology adoption models for energy efficiency and GHG mitigation measures. A potentially useful source of data for calibrating such models may be available from the program tracking systems and research studies developed during the last ten years of utility efficiency programs in California and other regions of the United States with extensive energy efficiency programs.

4.2 CO_2: Industry

Over the past twenty-five years, development of comprehensive energy-efficiency supply curves for the industrial sector has generally lagged behind the work conducted for the buildings sector. This lag did not reflect any lesser importance of the industrial sector or lower potential for savings, but rather, illustrated the difficulty that the sector's heterogeneity posed to researchers. Table 2 shows the importance of the industrial sector to California's electric and gas consumption.

[18] There is, however, a new study of the remaining energy-efficiency potential in existing commercial buildings in progress (XENERGY 2002).

Table 2. California Electric and Gas Use by Sector

	Electricity		Natural Gas	
Sector	**GWh**	**% of Total**	**Mth**	**% of Total**
Residential	75,388	31%	5,521	38%
Commercial	87,093	36%	2,103	15%
Industrial	**51,996**	**21%**	**6,341**	**44%**
Agricultural	14,661	6%		0%
Other	15,270	6%	379	3%
Total	244,408	100%	14,344	100%

Source: (CEC 2000a).

The industrial sector contributes 17% of the State's CO_2 emissions from fossil fuel consumption, roughly 14% of total GHG emissions (CEC 2001d).

The challenge posed by the heterogeneity of the sector can be seen in Figures 6 and 7. Even at the two-digit standard industrial classification (SIC) level, electricity use is distributed across industries with extremely different industrial processes. The 2-digit distribution of natural gas consumption is less diffuse, being concentrated in five or six major industry types.[19]

Because of the complexity of the industrial sector and concomitantly high costs of researching industry-specific energy and CO_2 reduction opportunities, relatively few comprehensive bottom-up assessments of the costs and savings potentials within the industrial sector have been conducted historically. (This is not to say that no work has been done—see for example, Geller and Neal 1994 and the work of Marc Ross at the University of Michigan.) Fortunately, the state of industrial sector research has begun to advance through a number of recent studies. Two sets of these studies complement each other well, in that one set focuses on the unique process elements of individual industry types, while the other set focuses on technologies that cut across industries. Lawrence Berkeley National Laboratory has conducted a series of recent studies for the Environmental Protection Agency that provide CO_2-reduction supply curves for specific industrial segments. Industry-specific studies have been completed to date for Pulp and Paper (Martin et al. 2000b), Cement (Martin et al. 1999), Iron and Steel (Worrell et al. 1999), and Steam (Einstein et al.).[20] The LBNL team also recently published a related study of emerging industrial technologies (Martin et al. 2000c). The DOE has also conducted several recent studies aimed at characterizing the potential to improve industrial motor (XENERGY 1998), compressed air (XENERGY 2000), and steam systems.[21]

[19] Note, however, that energy processes can vary significantly within two-digit SIC groups as well.
[20] The LBNL team has also conducted a baseline study of energy use in the chemicals sector (Martin et al. 2000a).
[21] See DOE's Office of Industrial Technologies steam studies at www.oit.doe.gov/bestpractices/steam/.

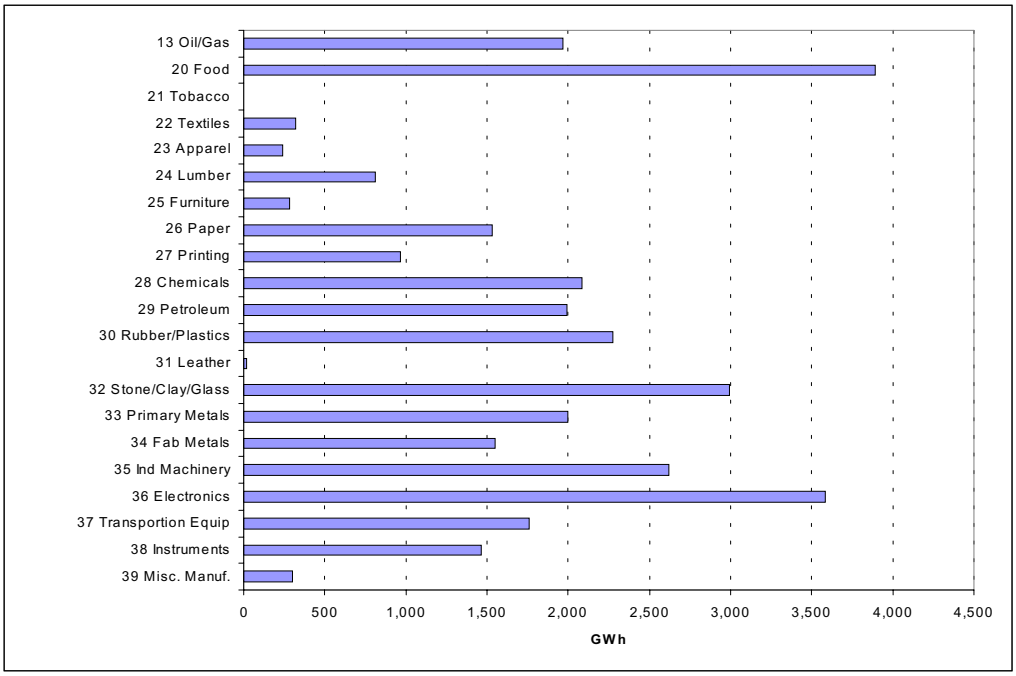

Figure 6. Breakdown of Electricity Consumption by Two-Digit Industrial SIC (PG&E/SCE/SDG&E only)

Source: XENERGY 2001c.

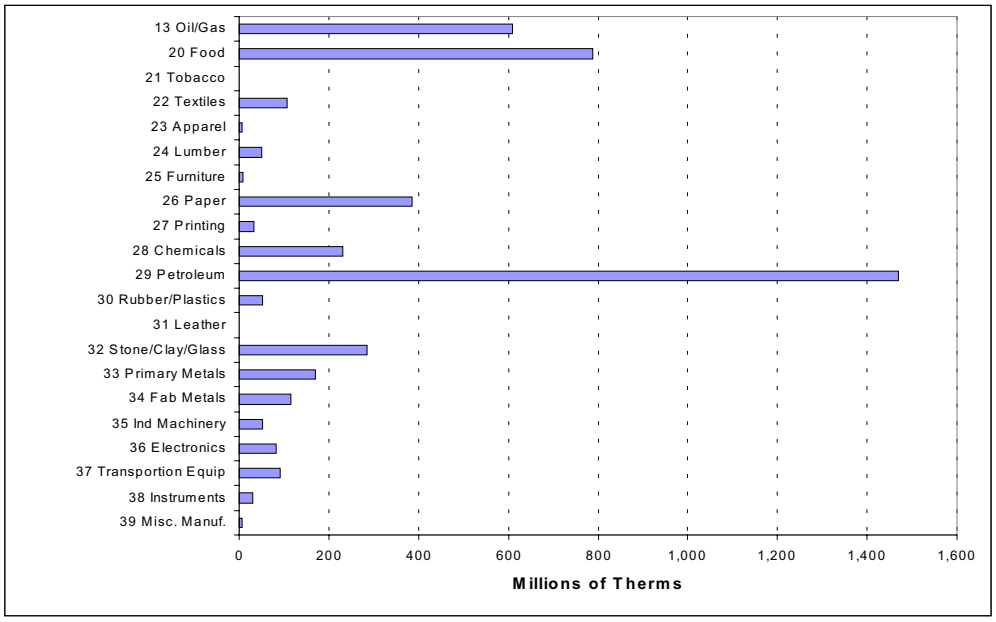

Figure 7. Breakdown of Natural Gas Consumption by Two-Digit Industrial SIC (PG&E/SCE/SDG&E only)

Source: XENERGY 2001c.

In addition to these national studies, recent California-specific industrial studies that are relevant to this roadmap include the following:

- XENERGY 2001c. *Statewide Industrial Characterization Study.*
- QC/Feldman 2001. *Large Customer Wants and Needs Study.*
- SBW 2001. *Compressed-Air Market Transformation Program Report.*
- XENERGY 1999 and 2001a. *Evaluations of the Statewide Large Customer Standard Performance Contract Programs.*
- Aspen 1999. *Southern California Edison Industrial Saturation Survey.*
- Utility Impact Evaluation Studies 1994 through 1997 (see www.calmac.org).

Part of the work conducted to prepare this roadmap was an interview of two of the key authors of the LBNL industry-specific studies (Worrell and Price 2001). The discussion focused on some of the weaknesses in the existing industrial supply curve studies and how they might be improved upon in the future. The issues raised were consistent with those identified in Section 3.5. Issues that are particularly challenging in the industrial sector included the following:

- Identifying opportunities can be time consuming and costly, because of the unique processes associated with individual industry types.
- It is difficult in practice to obtain accurate estimates of the current levels of penetration for individual strategies and technologies within specific industries. Few data sources are available that are based on statistically representative on-site surveys.
- There is limited information available on the costs and non-energy benefits of industrial strategies and technologies, and these can be difficult and costly to collect for industry-specific processes.
- Most curves do not differentiate measures that are easy to implement from those that are very difficult to implement.
- The organizational processes and criteria associated with decisions to invest in energy-efficiency and environmental mitigation projects are not well understood.
- Data on industrial sector technologies, processes, and adoptions can be difficult to obtain because industrial customers sometimes consider such information confidential or proprietary.

Given the importance of the industrial sector to GHG emissions in California, and the lack of California-specific industrial supply curves, significant further research in this topic area is needed.

Research Needs

No recent, California-specific supply curves are available for industry. However, there are a number of national studies that can be effectively leveraged and applied to the California markets. Existing studies have approached the market both by industry type and by end

use. Because of the heterogeneity of the sector, an industry-by-industry approach is appropriate for characterizing industry-specific process opportunities.

Because these studies are costly when conducted across many specific industries and because much of the basic measure cost and per-unit savings information can likely be transferred from national studies to California, the research discussed in Section 5 should both leverage the existing national studies and co-sponsor new studies for key industries not yet addressed.

In addition, there is an important need to develop improved technology adoption models for energy efficiency and GHG mitigation measures. A potentially useful source of data for calibrating such models may be available from the program tracking systems and research studies developed during the last ten years of utility efficiency programs in California and other regions of the United States with extensive energy efficiency programs.

4.3 CO_2: Transportation

The relative contribution of the transportation sector to CO_2 emissions is larger in California than it is nationally. In California, the transportation sector accounts for the largest share of CO_2 emissions from fossil fuel consumption in California by far, at roughly 59% (CEC 2001d), whereas transportation's contribution to carbon dioxide emissions nationally is on the order of 32% (USDOE/IWG 2000). Nationally, light-duty vehicles account for 56% of CO_2 emissions in the transportation sector, freight trucks 17%, and air travel 13%.

There is a large body of literature that addresses the potential to improve the fuel economy of light-duty vehicles in the United States, the largest CO_2 contributor in the transportation sector. There is much less information available, however, on the potential to reduce fuel consumption and emissions among freight trucks. (Note that air transportation is not included within the scope of this roadmap.) Key transportation-related sources reviewed for this roadmap include:

- Greene, David and John DeCicco 2000. *Engineering Economic Analyses of Automotive Fuel Economy Potential in the United States,* ORNL/TM-2000/26, January.
- U.S. DOE Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000. *Scenarios for a Clean Energy Future. Chapter 6: Transportation Sector.* U.S. Department of Energy LBNL–44029, November.
- AEA Technology Environment (AEA). 2001c. *Economic Evaluation of Emissions Reductions in the Transport Sector of the European Union (EU), Bottom-up Analysis,* European Commission, March.
- California Energy Commission. 1998. *Greenhouse Gas Emissions Reduction Strategies for California Volume 2. Chapter 6: Reducing Greenhouse Gas Emissions from Transportation.* California Energy Commission, Sacramento, January.

- National Academy of Sciences (NAS). 2001. *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards,* Prepublication – Unedited Proof, National Academy Press, Washington, D.C.
- State of California. 2001. *Strategic Plan for Research 2001 to 2010,* State of California, Cal/EPA, and California Air Resources Board, July.
- Series of studies sponsored by California Air Resources Board (ARB) and California Energy Commission (Commission) being published primarily in 2002. (ARB/CEC 2002a and 2002b). The ARB and the Commission are in the process of conducting several studies related to the fuel economy and pollution impacts of the transportation sector in response to Assembly Bill 2076,[22] which requires the Commission and ARB to develop and submit a strategy to the Legislature to reduce petroleum dependence in California.

One of the key sources listed above is the recent study by Greene and DeCicco (2000). In this work, Greene and DeCicco conducted a comprehensive literature review and comparative assessment of fuel economy supply curve methodologies and results. The result is an exhaustive and up-to-date assessment of the technical potential and associated costs of improving light vehicle fuel economy. As noted above, the National Academy of Sciences' recently released study includes assessment of technological options to improve fuel economy and their associated costs and benefits. In addition, the Clean Energy Future, European Union, and Energy Commission studies also provide useful information on the policy strategies that could be employed to induce reductions in CO_2 associated with the transport sector. Finally, to complement review of these studies, we also conducted an in-depth interview with Greene (2001).

The Greene and DeCicco study on engineering-economic analyses reviews more than 20 major studies that estimate the technological potential to improve fuel economy and associated costs. Greene and DeCicco demonstrate widely divergent results among the studies reviewed, as indicated by the multi-study results shown in Figure 8.

[22] AB 2076 (Chapter 936, Statutes of 2000).

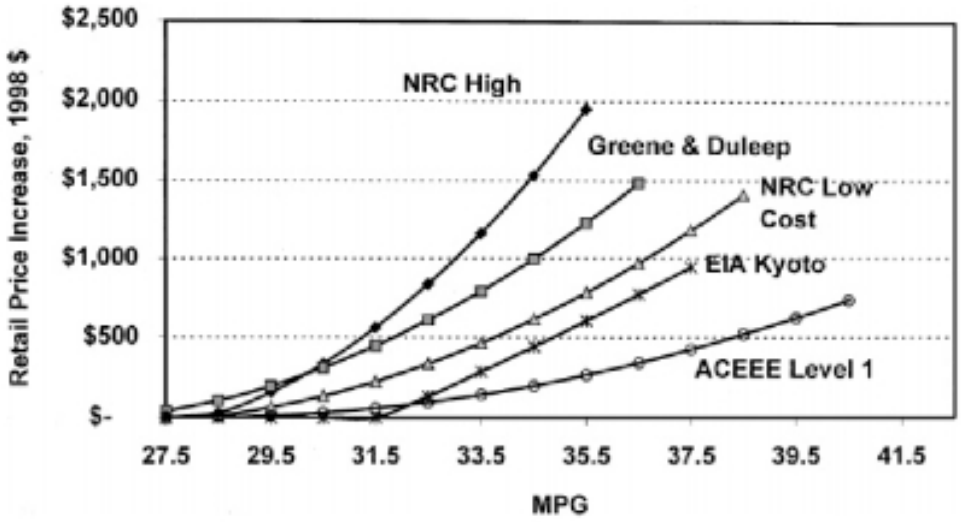

Figure 8. Passenger Car Fuel Economy Cost Curves Based on Six Studies
Source: Greene and DeCicco 2000.

Some of the relevant findings from the Greene and DeCicco cross-study analyses include the following:

- No fuel economy study they reviewed explicitly incorporated uncertainty into the estimation of technical potential. No studies have been found that evaluate the fuel economy potential of yet-to-be marketed technologies in ways that quantify uncertainties. Methods of estimating fuel economy potential rely on point estimates as inputs and produce point estimates as outputs. Sensitivity analysis has rarely been used.
- Studies diverged widely with respect to estimates of the cost of increasing fuel economy. Some of this problem arises out of inherently ambiguous situations in which fuel-efficiency improving technologies have multiple benefits. These multiple benefits make allocation of incremental costs difficult and imprecise. Also, in the highly competitive and concentrated auto industry, direct costs associated with changing automobile technologies depend on inherent production costs, timing of investments, and market risk.
- More so than is the case in buildings-related supply curves, accounting for synergistic effects among automobile efficiency improvements can be extremely complex and uncertain.
- Researchers could derive fuel economy cost curves that would show the intersection of supply and demand curves for fuel economy. These curves would indicate where the marginal consumer cost of increasing miles-per-gallon equals the marginal present value of fuel savings. Such curves would not take into account any external costs of fuel use, such as GHG.

- From a broad perspective, nearly all studies reviewed indicate that some "non-trivial" improvements are available at modest cost. Though greater consistency in assumptions and methods might narrow the range of differences in cost-economy results among future studies, the relative gains from further technology/cost analysis for light-duty vehicles may be small.
- Future research efforts may be focused more productively on better ways to represent (a) the characteristics, drivers, and effects of innovation in automotive technology; (b) the effects of regulation in shaping design decisions and expanding the technology options available; and (c) the role of capital constraints in technology deployment decisions.

Chapter 6 of *Scenarios for a Clean Energy Future* (USDOE/IWG 2000), provides estimates of impacts from new government policies on transportation energy consumption and GHG emissions. A modified version of the National Energy Modeling System (NEMS) model (USDOE/EIA 2000) was developed to forecast changes in the transportation sector scenarios that might occur in response to government policies to encourage reductions in greenhouse gases. These forecasts included BAU, moderate (low-cost), and advanced (more aggressive) GHG-reduction scenarios. The study addresses uncertainties associated with these scenarios. These uncertainties are associated with the costs and performance values of technologies under development, the outcome of an RD&D program, and consumer purchasing behavior. The technology options included in this study are cellulosic ethanol, hybrid electric drivetrains, lower weight structural materials, direct injection gasoline and diesel engines, fuel cells, and aircraft technology (e.g., reducing drag, use of composite materials, and advanced propulsion concepts). The key transportation-related policy alternatives modeled in the CEF study are:

- an increase in government/industry RD&D,
- a tax credit for high efficiency vehicles,
- acceleration of air traffic management improvements,
- the promotion of investment in cellulosic ethanol production,
- government fleet program promoting alternative fuels and efficiency,
- improving fuel economy standards (Advanced scenario only),
- telecommuting stimulation,
- carbon trading (Advanced scenario only),
- variabilization policies (Advanced scenario only), and
- intelligent traffic systems controls (Advanced scenario only).

From the CEF-NEMS models, the most influential components in reducing the energy consumption and carbon emissions in the Advanced scenario are improvements in light-duty fuel economy and freight truck efficiency gains. Policies that affect market incentives and that can increase technology development and hence technology options are found to be crucial to reducing transportation energy use and greenhouse gas emissions.

In AEA 2001c, researchers conducted a bottom-up analysis for the European Union, to provide an economic evaluation of emissions reductions potential in the transport sector. The study identified three ways to abate CO_2 emission from transport: operational, strategic (optimize vehicle use), and demand (for travel), but only addressed operational solutions. Researchers developed a supply curve for a large number of technological improvement options focused on vehicle transport. The lowest-cost options on the curve were for freight vehicles. An increased shift to diesel was also included, as were reductions in emissions associated with air-conditioning systems. The strategic and demand-based solutions generally rely on influencing behavior. The authors concluded that estimating the cost-effectiveness of strategic and demand options are not complete, and that they are difficult to extrapolate because of regional differences. Other data constraints limited the study's scope to on-road transport and aviation only. An analysis of air-conditioning (but not refrigerant leakage) and catalytic converter effects on GHGs are also important (especially because their use is expected to increase), but they are included in the report as an appendix. Appendix 1 of the report provides emission factors related to air conditioners and catalytic converters on on-road mobile sources. Nitrous oxide (N_2O) emission factors were developed from U.S. studies. The methodology that was used in that appendix may be useful for generating California values.

The California Energy Commission addressed state-specific strategies to reduce GHG emissions for the transportation sector in Chapter 6 of its *1997 Global Climate Change Report: Greenhouse Gas Emissions Reduction For California.* (CEC 1998a). The report noted that there have been dramatic decreases in criteria air pollutant emissions from the transportation sector, but not concurrent reductions for carbon dioxide. Chapter 6 of that report primarily discussed updates on the strategies related to policies set forth in the Commission's 1991 report on the same subject. These strategies include:

- developing alternative (low-emission) fuels, vehicles, and markets,
- promoting electric vehicles and hydrogen fuels,
- developing infrastructure to promote alternative fuel vehicle use,
- promoting biomass-based fuels,
- reducing vehicle miles traveled by personal vehicles through fuel/carbon taxes, user fees, or feebates,
- increasing fuel economy,
- providing incentives for alternative fuel vehicle use, and
- incorporating long-term transportation needs into land use planning.

The main emphases in the Commission's document are alternative-fuel vehicles, biomass-to-alcohol fuel, and non-technology options. The report does not make any strong policy recommendations, but mostly continues the policy drafted in the *1991 Report* and presents the current status of the options presented for reducing greenhouse gas emissions. No formal supply curve analysis is included.

The National Academy of Sciences also recently studied the effectiveness and impact of Corporate Average Fuel Economy (CAFE) Standards (NAS 2001). Chapter 4 of that study addressed the impact of a more fuel-efficient fleet with no policy recommendations. When considering the energy consumption and greenhouse gas emissions attributable to vehicles, it is important to consider not only fuel economy and vehicle miles traveled, but also the manufacture of the vehicle and fuels. The committee identified "break-even" fuel economy levels, which are combinations of technologies that would result in fuel improvements sufficient to cover the purchase price increases while holding other vehicle characteristics (size, weight, and performance) constant. Though not representative of real-world markets, this approach is useful for analytical clarity. Another key assumption pertains to how much consumers value fuel economy improvements. The study provides break-even analysis for 14-year and 3-year payback periods. These are reflections of technological possibilities, economic realities, and assumptions about parameters and consumer behavior. An analysis of automobile safety as it related to fuel economy is also included in this study.

After the principal work on this roadmap was developed (in the latter half of 2001), a series of studies sponsored by California Air Resources Board (ARB) and California Energy Commission (Commission) began to be published in 2002 (ARB/CEC 2002). The ARB and the Commission are in the process of conducting several studies related to the fuel economy and pollution impacts of the transportation sector in California in response to AB 2076, which requires the Commission and ARB to develop and submit a strategy to the Legislature to reduce petroleum dependence in California. Studies and study summaries currently available on the Commission's Web site include the following:

- ARB/CEC 2002a. *Estimating the Environmental Benefits of Petroleum Reduction Strategies – Task 1 Air Impacts*, prepared by Arthur D. Little/Acurex Environment, presentation slides, March 28, 2002.
- CEC 2002b. *Base Case Forecast of California Transportation Energy Demand*, prepared by California Energy Commission staff, P600-01-019F, March.
- ARB/CEC 2002b. *Benefits of Reducing Demand for Gasoline and Diesel – Volume 3, Task 1 Report*, prepared by Arthur D. Little/Acurex Environmental, March.
- CEC 2002c. *Analysis and Forecast of the Performance and Cost of Conventional and Electric-Hybrid Vehicles*, prepared by Energy and Environmental Analysis Inc., March.
- CEC 2001e. *Impact of Telecommuting on Vehicle Miles Traveled: A Nationwide Time-Series Analysis*, prepared by the University of California at Davis, Department of Civil and Environmental Engineering, Institute for Transportation Studies, December.
- CEC 2001f. *California Smart Growth Energy Savings MPO Survey Findings*, prepared by Parsons Brinkerhoff, P600-01-021F, September.

The effort on the studies above represents a major new effort to develop up-to-date and comprehensive data and information on the environmental and economic effects of the transportation sector in California, as well as the potential costs and benefits of reducing petroleum dependence and associated environmental impacts. These AB 2076-related

studies lay most of the groundwork needed to develop a CO_2-reduction supply curve for California.

A review of the California Air Resources Board's latest 10-year research plan (ARB 2002) identifies that ARB's research is focusing on:

- how the GHG inventory can be improved,
- assessing the true contribution of motor vehicles to nitrous oxide,
- understanding how global climate change might affect the State's air quality,
- better understanding the role of aerosols in climate change,
- analyzing the potential effects of climate change on human health,
- assessing technologies that could prevent or control GHG emissions, and
- estimating the possible effects of climate change on California's economy.

The California Air Resources Board's plan identifies a number of research organizations with which it may coordinate its GHG research efforts. They include California's local air districts, DOE, EPA, fuel cell groups, and the Energy Commission.

Research Needs

As discussed in Section 4, many supply curves have been developed at the national level for improving the efficiency of light-duty vehicles. Since the characteristics of light-duty vehicles are fairly similar across regions, there is no need to reproduce such studies on a California-specific basis. There is a need, however, to formally apply the results of these national studies to California's baseline transportation profile. Much of this work is in progress as part of the suite of AB 2076 studies discussed above. The AB 2076 studies may need to be integrated and reframed to develop a comprehensive CO_2 reduction supply curve for California. PIEREA research could also play an important role in efforts to reduce key uncertainties in the AB 2076 studies. New research also appears to be needed on analyzing options to reduce GHG emissions from freight vehicles. In addition, new research is needed to better understand the process of innovation in automotive technology, the effects of regulation on design and technological change, and the importance of capital constraints and industry competition in technology deployment. There is also a need to analyze transportation options that might reduce CO_2 by altering the mix of transportation at a macro level. Some research may be needed to determine whether off-road vehicles contribute significantly to GHG emissions and ascertaining the costs and benefits of mitigating such impacts if they are significant.

4.4 CO_2: Electricity Production

The in-state electricity generation sector in California contributes approximately 16% of the State's CO_2 emissions from fossil fuel use (CEC 2001d), which is less than half the national figure of 36% (USDOE/IWG 2000). The 16% figure does not include out-of-state sources, some of which are coal, but much of which is Northwest hydro. California's in-state generation facilities contribute a lower percentage of CO_2 than does the electricity sector nationally, because the State's generation consists primarily of natural gas,

hydroelectric, and nuclear plants; whereas, coal plays the major role nationally. Coal plants are almost non-existent in California, while nationally they account for 51% of the existing electricity generation output [in kWh] and 80% of CO_2 emissions from electricity generation (DOE and EPA 2000).

Over the last 25 years, a large body of research has been conducted on the characteristics of conventional and alternative electricity generation sources. The literature review conducted for this report focused on a few recent sources that are comprehensive in scope and relate closely to the objectives of this roadmap. These sources include the following:

- Department of Energy and Environmental Protection Agency (DOE and EPA). 2000. *Carbon Dioxide Emission from the Generation of Electric Power in the United States,* July.
- California Energy Commission (CEC). 1998b. *Greenhouse Gas Emissions Reduction Strategies for California, Appendix A: Historical and Forecasted Greenhouse Gas Emissions Inventories for California.* California Energy Commission, Sacramento, January.
- U.S. DOE and EPRI. 1997. *Renewable Energy Technology Characterizations.* Topical Report TR-109496, December.
- California Energy Commission (CEC). 1997. 1996 *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December.
- US DOE Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies 2000. *Scenarios for a Clean Energy Future.* Chapter 6: Transportation Sector. U.S. Department of Energy LBNL–44029, November.
- ECOFYS. 2001. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Greenhouse Gases in the Energy Supply Sector in the EU.* The Netherlands. March.
- California Energy Commission (CEC) 1998a. *Greenhouse Gas Emissions Reduction Strategies for California, Volume 2, Sections 4.3 to 4.5.* California Energy Commission, Sacramento, January.

Carbon dioxide emissions from the generation of electric power were inventoried at the national level in DOE and EPA (2000). This report resulted from a Presidential Directive from President Clinton in April 1999. The Directive required that DOE and EPA provide an annual report of baseline CO_2 emissions from electricity generation to the President. Emissions of CO_2 are presented on the basis of total mass (tons) and output rate (pounds per kWh). Key factors identified as contributing to changes in CO_2 emissions are: growth in demand, mix of fuels types and energy sources, and thermal efficiencies of plants. Contributing factors influencing the primary factors are: economic growth, price of electricity, weather, fuel prices, and the amount of available generation from hydro, renewable, and nuclear sources. Other factors identified as effecting current emission levels include demand-side management (DSM) programs, strategies to control air emissions to comply with the Clean Air Act of 1990, and installation of new capacity utilizing advanced technologies to increase plant efficiency, such as combined heat and power (CHP). The options identified to limit the emission of CO_2 from electricity generation are: to encourage reduction of overall electricity use through energy-efficiency

and conservation initiatives, to improve combustion efficiency at existing plants or install new units that employ more efficient technologies, and to replace fossil-fueled generation with non-fossil-fueled alternatives. Data sources and methodologies used to calculate estimates of CO_2 emissions from utility and non-utility generating plants are presented.

In 1997, the DOE Office of Utility Technologies, Energy Efficiency and Renewable Energy and EPRI jointly produced a report on the current and projected costs and characteristics of renewable energy technologies. This report updated and expanded work conducted by both organizations previously.[23] The study characterizes a wide variety of renewable energy technologies and includes current and forecasted system costs. Thirteen renewable technologies are characterized organized into the following groups: biomass, geothermal, photovoltaics, solar thermal, and wind. The report addresses criteria pollutants, including precursors such as ozone. A unique feature of this study is its attempt to forecast renewable technology costs out to 2030.

The Energy Commission published the fourth edition of its *1996 Energy Technology Status Report* in 1997. This is the last edition of which we are aware. The report provides detailed analyses of the costs and commercial availability of over 200 generation, storage, transmission and distribution, and end-use technologies. Levelized costs are developed for each technology and compared to benchmarks for commercial viability. The report characterizes over 70 generation technologies. This report, if updated, would provide much of the generation data that would be necessary to support the objectives of this roadmap.

Chapter 7 of USDOE/IWG 2000, often referred to as the "Clean Energy Future" study, provides an important example of a study that attempts to explicitly model changes in the mix of generation sources over time under several future scenarios. A modified version of the NEMS model (USDOE/EIA 2000) was developed to forecast changes in electricity generation scenarios that might occur in response to government policies to encourage reductions in greenhouse gases. These forecasts included a BAU case and moderate and advanced GHG-reduction scenarios. Technology options addressed include improvements in efficiency of conventional fossil plants, coal gasification (possibly in combination with fuel cells), cofiring coal with biomass, increased utilization of wind, biomass, geothermal, solar, and fuel cells, and extending life of existing nuclear plants. The key generation-related policy alternatives modeled in the CEF study are:

[23] For example, in 1977, EPRI first published its syndicated Technical Assessment Guide (TAG™), a series of reports developed by EPRI to provide a consistent basis for evaluating the economic feasibility of research and development alternatives for electricity production and delivery technologies. Various updates to the TAG series were conducted in the 1980s and early 1990s. The U.S. DOE and EPRI 1997 Renewables study discussed above is a related part of this series, in that previous TAGs were used as sources and the results were subsequently used to prepare EPRI's first TAG focused exclusively on renewable energy sources (EPRI 2001). EPRI 2001 is a proprietary study that was not available for review. The summary on EPRI's Web site states that the renewable TAG will be updated annually. For its part, the U.S. DOE has been conducting Renewable Energy Technology Characterizations (TCs) since 1989, the first of which was used for the 1991 National Energy Strategy.

- a renewable energy production tax credit,
- a renewable portfolio standard,
- wind deployment policies,
- enhanced R&D,
- net metering promotion,
- electric industry restructuring,
- stricter particulate matter standards, and
- a carbon trading system.

The advanced scenario embodies all of the policy options; whereas, the moderate scenario includes a subset of these. Tables 3 and 4 below show key results. Non-hydro renewables increase from 1% of generation in 1997 to 5% and 9% of generation in 2020, under the moderate and advanced scenarios, respectively. Nonetheless, the bulk of emission reductions shown in Table 4 are actually achieved by the dramatic reductions in coal generation that are made possible by the major decreases in energy consumption associated with the moderate and advanced scenarios. These results reflect the fact that the advancement of generation technology is limited to the relatively fixed amount of capacity expansion needed to meet demands over a given scenario, plus any power plant retirements.

Table 3. National Generation by Scenario and Fuel in the Electric Sector (TWh) (No cogeneration)

			2010			2020		
Fuel	**1990**	**1997**	**BAU**	**Mod.**	**Adv.**	**BAU**	**Mod.**	**Adv.**
Coal		1800	2020	1940 (-4%)	1400 (-31%)	2170	2000 (-8%)	1060 (-51%)
Petroleum		80	22	17 (-23%)	14 (-36%)	18	15 (-17%)	11 (-39%)
Natural Gas		300	890	680 (-24%)	880 (-1%)	1270	830 (-35%)	1140 (-10%)
Nuclear Power		630	580	580 (0%)	630 (9%)	520	460 (-11%)	600 (15%)
Renewables		390	410	460 (13%)	590 (45%)	440	500 (13%)	630 (42%)
Hydro		350	320	320 (0%)	320 (-0%)	320	320 (0%)	320 (0%)
Wind		3	8	37 (386%)	140 (1760%)	9	51 (495%)	160 (1770%)
Biomass		4	26	37 (43%)	47 (83%)	31	26 (-17%)	48 (55%)
- Dedicated		4	11	15 (35%)	22 (100%)	19	16 (-12%)	32 (69%)
- Cofired		0	15	22 (49%)	25 (70%)	13	10 (-24%)	17 (33%)
Geothermal		16	24	37 (55%)	50 (109%)	47	67 (41%)	67 (41%)
Other		15	28	28 (0%)	28 (0%)	31	31 (0%)	31 (0%)
Other		-3	-1	-1 (0%)	-1 (0%)	-1	-1 (0%)	-1 (0%)
Total		3190	3920	3680 (-6%)	3520 (-10%)	4420	3800 (-14%)	3440 (-22%)
Net Imports		32	30	30 (0%)	32 (7%)	27	28 (4%)	30 (0%)

Note: BAU = Business-as-Usual scenario; Mod. = Moderate scenario; Adv.= Advanced scenario. Numbers in parentheses represent the percentage change compared to the BAU scenario.

Source: USDOE/IWG 2000.

Table 4. Carbon Emissions by Scenario and Fuel in the Electric Sector (MtC) (No congeneration)

			2010			2020		
Fuel	1990	1997	BAU	Mod.	Adv.	BAU	Mod.	Adv.
Petroleum	26.8	17.6	4.6	3.4 (-26%)	2.9 (-37%)	3.7	3.0 (-19%)	2.1 (-43%)
Natural Gas	41.2	44	95	72 (-24%)	87 (-9%)	127	85 (-33%)	98 (-23%)
Coal	409	471	545	521 (-4%)	370 (-32%)	578	531 (-8%)	282 (-51%)
Total	477	532	645	597 (-7%)	460 (-29%)	709	622 (-12%)	382 (-46%)

Note: BAU = Business-as-Usual scenario; Mod. = Moderate scenario; Adv.= Advanced scenario. Numbers in parentheses represent the percentage change compared to the BAU scenario.

Source: USDOE/IWG 2000

In Europe, a comprehensive study of the potential to reduce GHG emissions from the energy supply sector also was recently completed (AEA 2001a). That study assessed options to reduce CO_2 associated with energy supply. It looked at the replacement of existing generation with combined-cycle natural gas (CCNG) units, replacement of CCNGs with renewables, replacement of CCNGs with combined heat and power (CHP) units, and removal and storage of CO_2. It also analyzed nitrous oxide reduction strategies for stationary power plant sources. That study addressed the options for CO_2 removal and N_2O reductions more comprehensively than any other in our literature review.

The Energy Commission's 1998 Global Climate Change Report (CEC 1998a) addresses a variety of state-specific strategies to reduce GHG emissions. The report primarily discusses generation-related policy options within the context of the transition from the Electricity Report (ER) process to the requirements of AB 1890. Sections 4.3 through 4.5 cover topics related to electricity generation. Section 4.3 discusses the development of environmental externality values within the ER 94 resource planning process and the fact that direct application of the values is obviated by AB 1890. Section 4.4 of the report discusses and quantifies carbon-dioxide-reduction potentials associated with new gas generation technologies. Section 4.5 of the report discusses renewable energy resources in California, again within the context of a transition to AB 1890 requirements. The report discusses its approaches, at that time, to reducing emissions from electricity generation by accounting for environmental externalities, promoting high-efficiency gas generation, and developing and integrating renewable energy resources into electricity generation. Presumably because of the uncertainty about the transition between the ER process and market-based requirements of AB 1890, the report makes no strong policy recommendations for GHG mitigation in the generation sector other than to note the Commission's commitment to "pursue the State's long-run goal to increase application broadly-based, market-oriented environmental policies as a way to improve the balancing of social costs and benefits."

Research Needs

For the most part, the current costs and GHG emissions characteristics of different types of electricity generating plants are well known (see, for example, USDOE/IWG 2000, USDOE/EPRI 1997, CEC 2000c),[24] as are the costs associated with improving the efficiency of existing plants using existing technologies.

Less well understood than basic generation costs and emission characteristics is how the mix of generation sources in California will or could change in the future and how such changes would impact overall GHG emissions. The turbulent process of restructuring and re-regulating California's electricity generation sector has contributed to increased uncertainty in the mix of California's generation sources over the next 10 to 20 years. In addition, there are a variety of new and prospective public policies that could impact GHG emissions in this sector significantly (e.g., the AB 970 DG pilot, Senator Sher's proposed renewable portfolio standard, the supply procurement decisions of the Department of Water Resources, actions taken by the California Power Authority). The Commission currently models the future mix of generation sources in the State as part of its energy forecasting process.

Future research needs to develop the supply curves based on this information and to continue to forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies.

4.5 Methane: Waste and Agriculture

According to the Energy Commission's baseline inventory study (CEC 2001d), methane emissions in California account for approximately 8% of GHG emissions in the State. Landfills in California are the largest source of methane emissions, accounting for roughly 42% (CEC 2001d), followed by agricultural sources, which make up 41%. All other sources represent less than 18% of the State's methane emissions. Landfills and agriculture represent a larger share of methane emissions in the State than they do nationally (37 and 29%, respectively, of the national methane emissions, EPA 1999). This disparity is because emissions from natural gas systems and coal mining account for a much larger share of methane emissions nationally (30%) than they for California (9%).

Only a few comprehensive studies of methane emissions and mitigation opportunities have been conducted. The literature review for this report focused on the following:

- Environmental Protection Agency (EPA). 1999. *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions*, EPA 430-R-99-013, Washington, DC: U.S. Environmental Protection Agency, September.

[24] In addition, the Energy Commission has current information it has received in the form of actual bid amounts for prospective renewable projects in California. (See www.energy.ca.gov/renewables/new_renewables_table.html. Note, however, that the amounts shown are Energy Commission incentive awards, not bid amounts).

- California Energy Commission (CEC). 1998a. *Greenhouse Gas Emissions Reduction Strategies for California Volumes 1 and 2.* California Energy Commission, Sacramento, January.
- California Energy Commission (CEC). 1997. *Energy Technology Status Report, Report Summary, 500-96-006,* California Energy Commission, Sacramento, December.
- U.S. Department of Energy and Electric Power Research Institute (USDOE/EPRI) 1997. *Renewable Energy Technology Characterizations.* Topical Report TR-109496. www.eren.doe.gov/power/pdfs/entire_document.pdf. December.
- AEA Technology Environment (AEA). 2001b. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Emissions Reductions of Nitrous Oxides and Methane in Agriculture in the EU.* UK. February.

4.5.1 Landfills

Methane emissions from landfills depend on the size and type of landfill. According to the literature reviewed, the principal means for reducing landfill methane emissions are methane recovery and use projects, as well as flaring. Another approach is to modify the waste management practices to reduce waste disposal in landfills. The most systematic assessment of the costs and reduction potential associated with domestic methane emissions is EPA 1999. This document develops a marginal abatement curve (MAC) for methane from landfills, based on methane recovery for electricity generation and direct use of methane gas by nearby end users. (Neither flaring or waste reduction are assessed because significant changes in practices are already projected to occur as a result of source reductions associated with EPA's Landfill Rule (EPA 1996) and other existing mandatory requirements.) The basic approach employed involves the estimation of project costs for landfills of different sizes. Cost-effectiveness varies as a function of landfill size expressed in tons of waste-in-place (WIP). The national population of approximately 2,500 landfills is analyzed by grouping each landfill into a size category. Cost estimates used are aggregated cost factors and a relatively simple set of landfill characteristics. Results are shown in Table 5. Uncertainties associated with the EPA analysis are shown in Table 6 and include errors associated with landfill population estimates, errors in estimates of electricity generation and direct use costs, and errors in assumptions about the amount of gas that can be feasibly recovered.

In CEC 1998a, the Commission outlined the complexities associated with GHG emissions and sinks related to municipal solid waste and forecasted emissions associated with landfills. The report also discussed several strategies for reducing methane emissions from California landfills. The strategies discussed include: working closely with the California Integrated Waste Management Board (CIWMB) to ensure that the State meets its mandatory source reduction goals, further study of the costs and benefits of specific mitigation measures, and encouragement of landfill-based electric generation. No quantitative analysis of the potential for reducing methane from increased electric generation or direct use is provided.

Table 5. Results from EPA's Landfill Gas-to-Energy Marginal Abatement Curve Analysis

Exhibit 2-10: Schedule of Emission Reductions Over and Above the Landfill Rule by Price in 2010

	Electricity Production[a]				Direct Gas Use				Total Emission Reductions		
Value of Carbon Equivalent ($/TCE)	Price ($/kWh)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Price ($/MMBtu)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Cumulative Reductions (MMTCE)	% of base-line	Label on MAC[b]
(10)	0.03	Infeasible	0	0.00	1.64	7,436,565	0	0.00	0.00	0%	N/A[c]
(6)[d]	0.03	Infeasible	0	0.00	2.05	2,330,467	114	3.48	3.48	7%	A
0	0.04	2,900,493	64	1.98	2.74	972,739	498	5.09	10.55	20%	B
10	0.05	538,232	773	11.25	3.84	920,668	106	(7.35)[e]	14.44	28%	C
20	0.06	273,860	1,919	6.96	4.94	749,467	7	(1.16)	20.23	39%	D
30	0.07	177,368	2,319	1.27	6.03	576,422	0	(0.05)	21.45	41%	E
40	0.08	129,583	2,505	0.29	7.13	468,324	0	0.00	21.75	42%	F
50	0.09	101,309	2,615	0.11	8.23	393,655	0	0.00	21.85	42%	G
75	0.12	66,064	2,685	0.05	10.98	283,477	0	0.00	21.90	42%	H
100	0.15	48,086	2,720	0.02	13.73	222,143	0	0.00	21.91	42%	I
125	0.18	Negligible	2,720	0.00	16.48	182,893	0	0.00	21.91	42%	J
150	0.20	Negligible	2,720	0.00	19.23	152,742	0	0.00	21.91	42%	K
175	0.23	Negligible	2,720	0.00	21.98	134,836	0	0.00	21.91	42%	L
200	0.26	Negligible	2,720	0.00	24.73	118,155	0	0.00	21.91	42%	M

[a] Includes emission reductions for landfills at which either a gas or an electricity project is modeled as cost-effective. By default, the analysis selects electricity projects over gas projects where both are cost-effective.

[b] Point on marginal abatement curve (see Exhibit 2-11) indicating minimum break-even WIP for electricity and direct gas use projects.

[c] Although cost-effective reductions at landfills of this size exist, they are subject to the Landfill Rule (over 2.5 MMT WIP), and thus, are not counted as emission reductions in this analysis.

[d] The potential emission reductions associated with the modeled prices of $2.05/MMBtu or -$6/TCE are "below the line" reductions in carbon equivalent terms.

[e] Negative incremental reductions indicate that emission reductions attributed to gas projects at lower prices are modeled as electricity projects at higher prices because electricity projects become cost-effective as values increase above $0/TCE.

Source: EPA 1999.

Table 6. Uncertainties Associated with EPA's Landfill Gas-to-Energy Marginal Abatement Curves

Exhibit II-14: Emission Estimate Uncertainties	
	Basis
Characterization of landfills and total WIP	A simulation characterizes the entire U.S. landfill population based on characterizations of a subset of U.S. landfills, including size, waste acceptance rate, and opening year.
Future waste disposal	Future waste disposal is assumed to remain constant at the average rate from the beginning of 1990 to the beginning of 1995. This average is based on the assumption that waste generation increases along with population, but will subsequently be offset by increases in alternative disposal methods such as recycling and composting.
Gas equation used for estimating methane emissions	Emission factors are derived from data on 85 U.S. landfills and are applied based on landfill WIP.
Recovery prior to 1997	Recovery rates (after flared methane is accounted for) are assumed to remain constant at 1990 levels for 1991 and at 1992 levels for 1993 to 1997. In addition, the gas collected but not utilized is assumed to equal 25 percent of the methane recovery.
Flare-only option	For years following 1997, the analysis lacks sufficient information about the population of landfills that flare without recovering methane for energy use.
Industrial waste landfilled	Industrial methane production is assumed to equal approximately seven percent of MSW landfill methane production.
Methane oxidation rate	Ten percent of methane generated is assumed to oxidize in soil.

Exhibit II-15: Cost Analysis Uncertainties	
	Basis
Cost estimate	Costs are estimated using aggregate cost factors and a relatively simple set of landfill characteristics. Electricity costs are estimated using representative WIP. Direct use costs are estimated using hypothetical landfills in terms of depth, area, and WIP.
Revenue	The rate at which electricity is sold from a landfill project depends on local and regional electric power market conditions and often varies by time of day and season of year. However, this analysis uses a representative figure that remains constant.
Potential for landfills to collect and use gas cost-effectively	The extent to which electricity production and direct gas use are cost-effective depends on the energy price and availability of end-users.
Methane recovery technologies	This analysis only focuses on internal combustion (IC) generators and direct gas use because they are the most cost-effective technologies for projects examined in this analysis. However, other technologies are available, e.g., electricity generation using turbine generators.
Equipment and engineering costs	Information is based on current projects and industry experts.

Source: EPA 1999.

Research Needs

The current costs of collecting and converting landfill methane to electricity are provided in EPA 1999 and were previously estimated in CEC 1997. Applying the methodology used in EPA 1999 would be fairly straightforward. The key requirement is that the population of California landfills are characterized by size, waste composition, and proximity of prospective direct-use end users. The CIWMB already maintains a database with basic characteristics on landfills in California (CIWMB 2001). Further assessment is needed to determine whether this database provides data that is comprehensive and accurate enough to develop the marginal abatement curve for California. Properly incorporating and managing a dynamic baseline forecast of landfill volumes also will be critical. The California work should seek to improve upon the work conducted by EPA, with respect to discussion and incorporation of market barriers to landfill-to-gas implementation. In

particular, issues related to distributed generation (DG) interconnection and electricity power purchase markets in California should be addressed, as should possible co-benefits such as reduced volatile organic compounds.

4.5.2 Agriculture

Methane emissions from livestock occur from both digestive processes (entermic fermentation) and manure. The EPA and others have quantified the costs of emission reductions from converting methane from manure to electricity and heat. They have also assessed methods for reducing entermic fermentation but not associated costs.

Manure emissions vary principally as a function of manure management practices and farm size. Farms use either "dry" or "liquid" manure management systems. Methane emissions are much higher for liquid systems; dry systems are fairly inconsequential. Liquid systems are more common on larger farms and the U.S. trend is toward larger farms. According to EPA 1999, "up to half of the manure on large dairy farms and virtually all of the manure on large hog farms is managed using liquid systems." Emission reduction strategies are generally limited to either increasing the use of dry systems or recovering methane and utilizing it to produce electricity, heat, or hot water. The EPA 1999 report concludes that the first option—increasing the use of dry systems—is infeasible for both "environmental impact and process design reasons." Methane for energy can be recovered by anaerobic digesters, which can also reduce foul odor and the risk of ground- and surface-water pollution. The EPA developed the average digester costs based on actual project costs from digester farm projects participating in the AgSTAR program. The EPA used FarmWare, an EPA software tool, to estimate model farm economics. The cost-effectiveness of collecting and converting the methane in liquid systems to energy varies primarily as a function of farm size, as shown in Table 7. As shown in Table 8, several uncertainties and limitations exist in the reduction estimate. These include the assumptions used to develop the model farm facility, the variability in the value of the methane recovered, importance of non-energy benefits (odor control), and the forecasting of baseline trends.

During digestion, domesticated animals produce methane by enteric fermentation. When estimating methane emission from enteric fermentation, EPA categorizes livestock populations and develops emission factors based on the diversity of feed and animal characteristics (EPA 1999). The report discusses a number of ways to reduce this form of emissions, principally through increasing production efficiency (efficiency of feed converted to product). Many of these methods involve significant changes in farm practices, from feedstock, to grazing, to breeding. Considerable uncertainty is associated with these methods. Estimating the costs associated with such changes would also be highly speculative. In addition, it is extremely difficult to forecast how price signals would be sent to farmers to change these practices (Kruger 2001).

Table 7. Results from EPA's Manure-to-Energy Marginal Abatement Curve Analysis

Exhibit 5-8: Schedule of Methane Emission Reductions for Dairy and Swine Manure Management in 2010

Manure Type	Label on MAC	Value of Carbon Equivalent ($/TCE)	Electricity Price with Additional Value of Carbon Equivalent ($/kWh)	Average Break-Even Farm Size (# of head)	Incremental Reductions (MMTCE)	Cumulative Reductions (MMTCE)	Cumulative Reductions (% of base)
DAIRY COW:	A	($30)	$0.04	1,025	0.23	0.23	4%
	B	($20)	$0.06	1,134	0.52	0.75	14%
	C	($10)	$0.07	828	0.33	1.07	20%
	D	$0	$0.09	753	0.88	1.95	36%
	E	$10	$0.10	787	0.29	2.24	41%
	F	$20	$0.12	733	0.27	2.51	46%
	G	$30	$0.14	654	0.19	2.70	49%
	H	$40	$0.15	575	0.17	2.87	52%
	I	$50	$0.17	521	0.14	3.01	55%
	J	$75	$0.21	414	0.37	3.38	62%
	K	$100	$0.25	294	0.38	3.76	68%
	L	$125	$0.29	219	0.31	4.07	74%
	M	$150	$0.34	172	0.26	4.33	79%
	N	$175	$0.38	140	0.24	4.57	83%
	O	$200	$0.42	114	0.21	4.78	87%
SWINE:	A	($30)	$0.02	> 20,000	1.23	1.23	10%
	B	($20)	$0.03	> 20,000	0.00	1.23	10%
	C	($10)	$0.05	5,112	0.00	1.23	10%
	D	$0	$0.07	5,120	0.00	1.23	10%
	E	$10	$0.08	3,906	0.00	1.23	10%
	F	$20	$0.10	4,339	0.79	2.02	16%
	G	$30	$0.12	2,990	2.25	4.28	35%
	H	$40	$0.13	1,932	1.36	5.63	46%
	I	$50	$0.15	1,390	1.10	6.74	55%
	J	$75	$0.19	821	3.52	10.26	83%
	K	$100	$0.23	602	0.51	10.77	88%
	L	$125	$0.27	510	0.25	11.03	90%
	M	$150	$0.32	500	0.01	11.04	90%
	N	$175	$0.36	500	0.00	11.04	90%
	O	$200	$0.40	500	0.00	11.04	90%

Source: EPA 1999.

Table 8. EPA's Summary of Uncertainties Associated with Manure-to-Energy Marginal Abatement Curve Analysis

Exhibit V-6: Summary of Emission Reduction Uncertainties	
Uncertainty	**Basis**
Livestock Demographics	Latest existing farm-size distribution data is for 1992. Shifts in both dairy and swine populations towards larger facilities is not reflected.
Effectiveness of Methane Recovery Technologies	These technologies have been applied on dairy and swine farms throughout the country for over two decades.
Value of Methane Recovered	
Facility Energy Costs	Energy rates vary by utility and within each state. Forecasts assume constant costs. Restructuring of utility industry may affect rates.
Non-Monetary Benefits (odor, pollution, etc.)	Value is difficult to quantify. Recent projects at swine farms have been initiated primarily to reduce odor.
Methane Recovery Costs	
Project Development/ Construction Costs	Information based on current projects and industry experts. Site-specific factors can influence costs of individual projects.

Source: EPA 1999.

Research Needs

The current costs of collecting and converting methane from liquid system manure management systems to electricity are provided in EPA 1999. The Energy Commission has also previously estimated manure biogas digester costs in CEC 1997. Applying the methodology used in EPA 1999 to the population of hog and dairy cow farms in California appears to be fairly straightforward. The key requirement is accurate characterization of the population of California farms by livestock type, size, and current manure management approach. The U.S. Department of Agriculture conducts a census of farms every five years. Results for California are published separately (USDA 1999). Several organizations have developed database search functions that work off of the census data. Further assessment is needed to determine whether this database provides all of the information needed to develop the marginal abatement curve for biogas for California. Properly incorporating and managing a dynamic baseline forecast of hog and dairy farms will also be important. As in the case of landfill generation, issues related to DG interconnection and electricity power purchase markets in California are critically important.

4.6 Nitrous Oxide and High Global-Warming-Potential Gases

Under the current GHG emission baseline (CEC 2001d), N_2O represents 6% of California's GWP emissions. High global-warming-potential gases such as perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) are believed to represent roughly 2% of the state's GHG emissions. These estimates are based on CO_2 equivalence, using the Intergovernmental Panel on Climate Change (IPCC)-approved conversion factors. Some research has been done on developing and summarizing measures to reduce N_2O and high GWP emissions; however, only recently have any studies tried to

estimate the costs and impacts of such measures. The following studies or planned studies are relevant to developing N_2O and high-GWP mitigation supply curves:

- AEA Technology Environment (AEA). 2001b. *Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change – Economic Evaluation of Emissions Reductions of Nitrous Oxides and Methane in Agriculture in the EU.* UK. February.
- Environmental Protection Agency (EPA). 2001. *U.S. High GWP Gas Emissions 1990–2010: Inventories, Projections, and Opportunities for Reductions*, EPA 000-F-97-000. Washington, DC: U.S. Environmental Protection Agency. June.
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4.6.1 Nitrous Oxide (N_2O)

According to the Energy Commission's latest research (CEC 2001d), agricultural soil management and fossil fuel combustion in mobile sources account for about two-thirds and one quarter of California's N_2O emissions, respectively (over 90% combined).

Microbial processes in soil naturally produce N_2O. Agricultural practices that increase the amount of nitrogen in soils (fertilizer application), increase the nitrogen available for nitrification and denitrification, which subsequently increases the amount of N_2O emitted from the soils. Production of nitrogen-fixing crops and application of fertilizers, livestock manure, sewage sludge, and crop residues are ways to add nitrogen to the soil. Indirect emissions of N_2O are caused from leaching, runoff, or atmospheric deposition of nitrogen to the agricultural system. These include the ammonia and NO_X released from the soil and deposited atmospherically back to the soil, and runoff of soil to water systems. Non-agricultural indirect emissions can also occur from sources of NO_X emissions that deposit onto the soil.

There are few studies of the options, costs, and potential impacts of reducing N_2O. One of the few such studies published (AEA 2001b) discusses options to reduce N_2O emissions in the European Union (EU), including N_2O emissions from the chemicals sector, combustion in both stationary and mobile sources, and agriculture. Table 9 shows the agricultural management options that could influence N_2O emissions. Other studies provide information on ways to mitigate N_2O but do not provide estimates of mitigation costs (New Zealand 2001, Canada 1999). However, EPA is currently in the process of conducting a study of the costs and potential impacts of N_2O mitigation (Kruger 2002).

Table 9. Agricultural Management Options Influencing N_2O Emissions

Type of option	Management Option
1. Crop management	**(a) change in fertiliser application rates** **(b) precision farming** **(c) crop selection (i.e. with different nitrogen requirements)** **(d) breeding nitrogen fixing crops** **(e) breeding crops to improve nitrogen use efficiency (e.g., lower requirements, more efficient uptake)** **(f) cultivation of unmanaged land (i.e. histosols)** **(g) irrigation management** **(h) soil pH management** **(i) crop residue burning** **(j) reduce soil compaction**
2. Fertiliser efficiency management	**(a) nitrification inhibitors;** **(b) release rates (e.g. slow or timed release, coatings to limit or retard water solubility);** **(c) improved fertiliser placement and timing (e.g. band placement, foliar applications).**
3. Manure management	**(a) storage times and conditions (e.g., slurry treatment to change viscosity);** **(b) application placement (e.g. slurry injection)** **(c) application timing;** **(d) application amounts (e.g. controlled rate systems);** **(e) export of manure (from the agricultural system).**
4. Reducing the amount of manure nitrogen	**(a) dietary manipulation;** **(b) breeding nitrogen efficient livestock;** **(c) livestock selection (e.g. livestock types, herd sizes).**

Source: AEA 2001b

According to AEA 2001b, there is a lack of reliable data on emissions changes in response to N_2O management decisions. Most results are site specific and include many factors that potentially influence the mechanism for N_2O emissions. Extrapolating results from these sites to a larger scale is inappropriate without more research to reduce uncertainties.

Research Needs

Whether California-specific research will be needed to estimate the costs and potential impacts of N_2O mitigation measures will depend partly on the results of EPA's current work on a national N_2O marginal abatement curve. When EPA's study is completed, it may be possible to effectively interact California's revised baseline with EPA's N_2O mitigation results to produce a California-specific N_2O mitigation supply curve. Given the nascent status of N_2O reduction studies, however, it is likely that additional research will be needed to improve N_2O mitigation cost and impact estimates. To continue the progress in estimating baseline emissions for California represented by the Energy Commission's latest study (CEC 2001b), further research may also be needed to improve the accuracy of N_2O emission estimates.

4.6.2 High GWP Gases

As noted above, high GWP gases (HFCs, PFCs, and SF_6) contribute approximately 2% of California's GHG emissions (CEC 2001d). However, these are powerful, long-lived greenhouse gases. HFCs are used primarily as substitutes for ozone-depleting substances, and PFCs and SF_6 are emitted from several industrial processes, such as aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. There is no aluminum manufacturing or magnesium casting in the state. Substitution of ozone depleting substances account for 72% of high GWP emissions in California, electric utility transmission and distribution 19%, and semiconductor manufacturing 9% (CEC 2001b).

According to EPA 2001, options for reducing emissions of high GWP gases (excluding costs and emission reductions for options already required by law or expected due to voluntary partnership programs) include:

- implementing new industrial processes that reduce emissions and improve efficiency,
- implementing better housekeeping practices to reduce leaks of high GWP gases,
- installing new, more efficient equipment with lower emission rates, and
- substituting other gases for high GWP gases in a variety of applications, where safety and performance requirements can be met.

The EPA high GWP report uses discounted cash flow analysis to estimate the cost of achieving reductions for each technology or practice (for each emission source). Costs are presented in dollars per metric ton of carbon equivalent ($/TCE). This approach is the same method EPA has used in developing MACs for methane emissions (see EPA 1999). Figure 9 shows EPA's high GWP gas MAC, using an 8% discount rate. The also develops a curve with a 4% discount rate. Table 10 shows costs and impacts of specific measures. Authors of the study concluded:

> The high GWP gas MAC illustrates three key findings. First, substantial emission reductions, 4.2 million metric tons of carbon equivalent (MMTCE), are likely to be cost-effective in the absence of a carbon value (i.e., at $0/TCE). Second, achievable reductions at carbon values of $20/TCE and $100/TCE are estimated at 28.6 MMTCE and 36.2 MMTCE, respectively. Third, above $40/TCE, the MAC becomes relatively inelastic, that is, largely non-responsive to increasing carbon values. This result is expected, given that the analysis does not incorporate new technology innovations that might arise with greater carbon values, increased research and development (R&D) expenditures, or other unexpected technology advances. In sum, the analysis suggests that over 5% of baseline emissions could be reduced through cost-neutral or possibly even cost-beneficial changes, and that viable options exist to reduce baseline emissions by nearly one half.

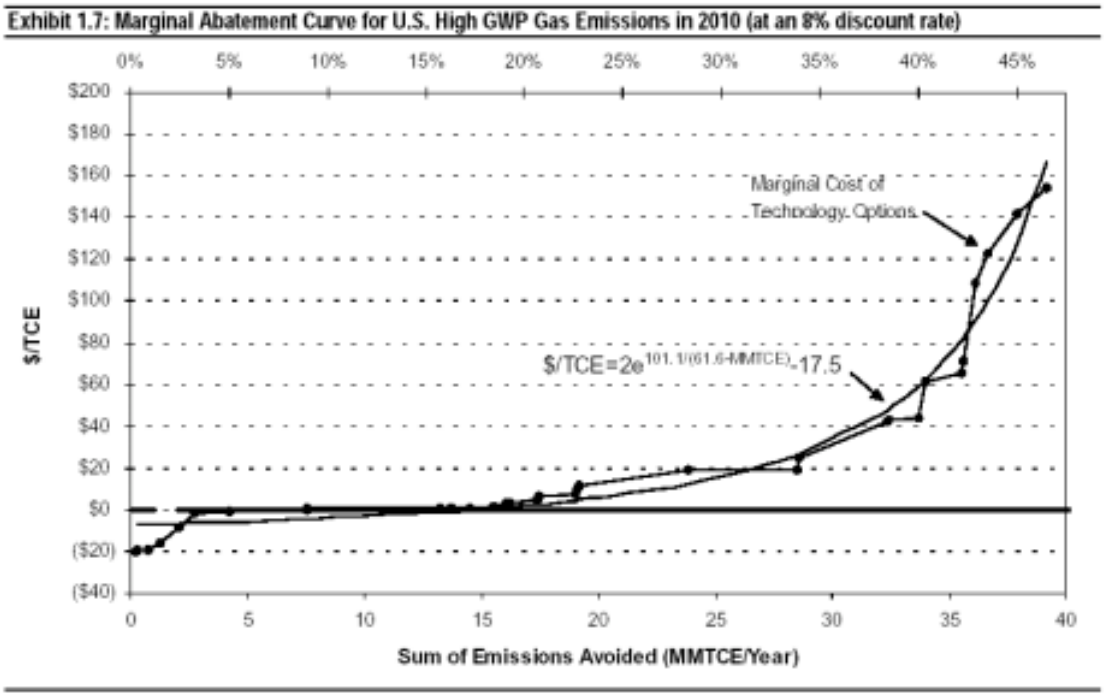

Figure 9. High GWP Marginal Abatement Curve
Source: EPA 2001.

Table 10. High GWP Marginal Abatement Curve – Measure Details

Exhibit 1.9: Composite Marginal Discount Curve Schedule of Options for 2010 (at an 8% discount rate)

#	Source	Activity	Cost ($/TCE)	Emission Reduction (MMTCE)	Sum of Reduction (MMTCE)	Percent Reduction from 2010 Baseline
1	Aerosols	Hydrocarbon Aerosol Propellants	$ (20.32)	0.2	0.2	0%
2	Fire Extinguishing	Water Mist	$ (19.42)	<0.05	0.3	0%
3	Aerosols	Not-in-kind Alternatives	$ (19.12)	0.5	0.7	1%
4	Foams	PU Spray Foams - Replace HFC-245fa/ CO_2 (water) with hydrocarbons	$ (15.64)	0.5	1.2	1%
5	Aerosols	Switching to HFC-152a	$ (8.09)	0.8	2.1	2%
6	Magnesium Smelting	Good Housekeeping	$ (1.91)	0.7	2.8	3%
7	Magnesium Smelting	SF_6 Capture/Recycling	$ (0.89)	1.5	4.2	5%
8	Magnesium Smelting	SO_2 Replacement	$ 0.24	3.3	7.5	9%
9	Aluminum Smelting	Retrofit-Minor: VSS	$ 0.54	<0.05	7.6	9%
10	HCFC-22 Production	Thermal Oxidation	$ 0.73	5.7	13.3	16%
11	Aluminum Smelting	Retrofit-Major: SWPB	$ 0.77	0.4	13.7	16%
12	Solvents	Alternative Solvents	$ 0.88	0.8	14.5	17%
13	Electric Utilities	Leak Detection and Repair	$ 1.62	1.0	15.5	18%
14	Electric Utilities	Recycling Equipment	$ 3.28	0.5	16.1	19%
15	Aluminum Smelting	Retrofit-Major: CWPB	$ 3.30	0.2	16.2	19%
16	Refrigeration/AC	Leak Reduction Options	$ 5.08	1.2	17.4	21%
17	Aluminum Smelting	Retrofit-Major: HSS	$ 6.82	0.1	17.5	21%
18	Refrigeration/AC	Replace DX with Distributed System	$ 7.21	1.5	19.1	23%
19	Aluminum Smelting	Retrofit-Major: VSS	$ 9.58	0.1	19.1	23%
20	Solvents	NIK Semi-Aqueous	$ 11.55	<0.05	19.2	23%
21	Semiconductor Manufacturing	NF_3 Drop-In	$ 18.57	4.7	23.9	28%
22	Semiconductor Manufacturing	NF_3 Remote Cleaning	$ 18.57	4.7	28.6	34%
23	Solvents	NIK Aqueous	$ 25.02	<0.05	28.6	34%
24	Semiconductor Manufacturing	Plasma Abatement	$ 41.95	3.8	32.4	38%
25	Foams	PU Appliance Foams - Replace HFC-134a with cyclopentane	$ 43.25	<0.05	32.4	38%
26	Semiconductor Manufacturing	Capture/Recycling	$ 43.99	1.3	33.7	40%
27	Fire Extinguishing	Inert Gas Systems	$ 61.44	0.3	34.0	40%
28	Refrigeration/AC	HFC Secondary Loop Systems	$ 65.30	1.5	35.6	42%
29	Solvents	Retrofit Options	$ 71.24	<0.05	35.6	42%
30	Refrigeration/AC	Ammonia Secondary Loop Systems	$ 108.67	0.6	36.2	43%
31	Foams	PU Spray Foams - Replace HFC-245fa/ CO_2 (water) with CO_2 (water)	$ 122.52	0.5	36.7	44%
32	Semiconductor Manufacturing	Catalytic Destruction	$ 141.93	1.2	37.9	45%
33	Semiconductor Manufacturing	Thermal Destruction	$ 154.54	1.3	39.2	46%

Source: EPA 2001.

The authors of the EPA high GWP mitigation study identify several sources of uncertainty underlying their results. According to the study, "The major uncertainties in the analysis stem from those inherent in data projection as well as from the lack of published information on reduction options and their costs." The authors list a number of specific areas of uncertainty, which are itemized in Table 11.

Table 11. Summary of Uncertainties Underlying High GWP Marginal Abatement Curve

The projected emission estimates are tied to factors such as growth in usage and demand for specific products or gases—difficult items to project for many sectors. This also introduces a degree of uncertainty about the emission estimates.
There is significant uncertainty in the levels of future energy prices and the indirect effects of potential emission reduction options.
Several options that were included in the MAC analysis might become more or less efficient in the future as a result of technological breakthroughs and other innovations. It is important to note that some of those options currently not considered viable may become so in the future.
Some of the emission reduction options discussed involve using chemicals (as substitutes) that can potentially impact human health and/or safety. Although some technically feasible options were omitted for this reason, some options that remain may still prove not to be feasible upon further research because of health and/or safety concerns.
The lack of specific information on reduction opportunities in many sectors can be attributed to several factors, including the following. • For some applications, minimal research has been performed on how to limit emissions of ozone-depleting substances (ODS) substitutes, including developing alternatives for them. This is particularly true for foams, aerosols, fire extinguishers, and solvents. • Data on both emissions and reduction costs may be highly proprietary for many industrial processes. This is especially true of PFC emissions from semiconductor manufacturing and aluminum smelting. • For many mitigation options, accurate measures of potential emission reductions or costs are not available. These options, although they are qualitatively discussed in the relevant chapters, are not included in the MAC analysis.

Source: EPA 2001.

Research Needs

Although complex, many of the high GWP abatement measure characteristics (principally, per-unit costs and impacts estimates) appear to be transferable from a national level to California, if appropriately matched to California baseline data. With modest resources, researchers could combine EPA's high GWP measure characteristics with California's revised baseline and likely produce a California-specific high GWP supply curve. Additional research should try to address the uncertainties summarized in Table 11. To continue the progress in estimating baseline emissions for California (CEC 2001b), further research may be needed to improve the accuracy of high GWP emission estimates.

4.7 Crosscutting

4.7.1 Technology Adoption

Supply curves are effective tools for systematically and consistently characterizing basic technology costs and benefits; however, they are limited with respect to characterizing customer adoption as a function of changes in key parameters, such as prices and technology availability, over time. A technology adoption model would be effective in incorporating these factors into an assessment.

Research Needs

A technology adoption model should be developed, or an existing model selected,[25,26] to interface directly with the technology data developed in the supply curve studies. A fairly complete specification of such a model for energy end use markets is described in RER 2000a.

The key need in this area is development of the data and analysis needed to specify the actual curves and parameters of adoption models. The initial focus should build upon the considerable body of work already available in energy end-use market modeling. Application of adoption modeling that explicitly incorporates costs and effects of market interventions should begin for non-CO_2 GHGs, such as methane, for which GHG reduction opportunities are closely related to the decision making of individual end users.

PIEREA efforts should especially focus on using technology penetration data from the past 10 years of utility efficiency programs in California and other regions of the United States to develop a set of adoption curves that are specific to energy-efficiency and GHG mitigation measures. A scoping study should be conducted to assess the availability of the necessary data, to both estimate adoptions over time and to correlate actual adoptions to measure parameters (e.g., incremental measure costs, return on investment, payback, awareness levels, program interventions) required by specific models. Researchers should develop and emphasize a practical process in which taxonomies with discrete sets of curves calibrated for specific types of measures are developed.[27]

4.7.2 Supply Curve Weaknesses

Section 3.6 of this roadmap identifies weaknesses of supply curves. If supply curves are to be used effectively, researchers need to address and correct these weaknesses.

Research Needs

Researchers need to study supply curve weaknesses, with efforts focusing on formally characterizing these weaknesses, proposing alternative bottom-up methodologies, and implementing examples of alternative methods and models. Efforts should focus on sectors for which data can be developed and utilized in quantitative analyses. In addition, efforts should focus on methods such as adoption process modeling, in which parameters that are often static or unspecified in supply curve analyses (such as awareness, interest, and availability, energy prices) are made explicit and dynamic. This work should be

[25] The Commission developed a bottom-up energy-efficiency model that includes a program penetration module, CALRAM, in the mid-1990s; however, the model has not been updated or run in several years and may not meet the requirements discussed in this roadmap.

[26] Rodgers 1995, *Diffusion of Innovations*, provides a comprehensive review and analysis of several diffusion-of-innovation models. One of the broadest attempts to specify such a model for the purpose of modeling energy-efficiency programs is provided in Chapter 7 of RER 2000a, *A Framework for Planning and Assessing Publicly Funded Energy Efficiency*.

[27] Note that the PIER Buildings area is also considering research on a Technology Impact Assessment Framework that would include specifications, and perhaps research, on adoption curves. PIER efforts in this area should be coordinated.

coordinated with the behavioral economics and energy efficiency research suggested under the Economics of Climate Change Mitigation and Adaptation portion of the PIER Climate Change Plan.

5. Goals

The primary goal of the Supply Curves portion of the PIER Climate Change Research Plan is to contribute to advancements in the science of GHG mitigation supply curve development, particularly as applied to understanding emissions reductions opportunities in California. To achieve this goal, it likely will be necessary to develop mitigation supply curves for the State of California in cases where such curves are otherwise unavailable. Improved GHG reduction supply curves will help both private and public sector decision makers to formulate the most effective and economical GHG mitigation policies.

The achievement of these goals depends on a variety of factors that vary by sector and greenhouse gas. Generally, it will be necessary to improve baseline inventory data in a variety of areas, including fuel consumption, landfills, and livestock farms. In addition, a number of methodological and macroeconomic integration issues will need to be improved upon. Finally, it will be critical that PIEREA efforts in this area are leveraged with the resources and talent available from other organizations with convergent research needs and interests.

Supply curve research activities begin with sector/gas-specific recommendations and conclude with recommendations that integrate or cut across sectors and greenhouse gases. The focus of the short-term sector/gas-specific recommendations tends to be on the development or synthesis of *initial* supply curve information (i.e., the development, analysis and organization of technology costs and benefits into supply curves that are similar to those developed in past GHG and conservation supply curve studies and described in Section 3. As discussed previously, such basic supply curves have important limitations, particularly when it comes to being effectively incorporated into macroeconomic and mid- to long-term forecasting models. In addition, supply curves that focus only on technology costs and benefits do not provide policy guidance per se, though they are an important input to policy analyses.

The short-term Crosscutting/Integration recommendations address the broader needs associated with advancing the state-of-art of supply curve development and their integration with larger economic modeling efforts. One of the reasons for this organization is practicality. First-order benefits for California's climate change policy makers can be achieved fairly quickly by developing supply curves that capture incremental measure costs, measure applicability, and the potential impacts of measures on reducing GHGs in California. Further value will be obtained by expanding such analyses to explicitly include technology innovation over time, the diffusion-of-innovation framework to technology adoption, incorporation of market barriers and market failures, and integration into integrated macroeconomic models. Although these advances are addressed primarily under the Crosscutting/Integration area, we also recommend that the initial supply curve

work incorporate at least qualitative identification of market barriers and failures, as well as other co-benefits and collateral costs.

Mid-term recommendations focus on the development of *advanced* supply curves, which would build off of the initial studies to more definitively resolve current analytical and data-related weaknesses.

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[28]

5.1.1 CO_2: Buildings

A. Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings.

Activities needed: (1) *Compile existing end use consumption and energy-efficiency measure data into residential energy-efficiency supply curves for California*. At a minimum, underlying data will need to be segmented by fuel (electric and gas), vintage (new versus existing construction) and building type (single-family, multi-family, and mobile homes). Measure penetration should be modeled for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (2) Market barriers by measure or type of measure should be identified, as well as any co-benefits. Further analysis and estimation of implicit customer discount rates is also needed.

To the extent that non-PIER divisions of the Energy Commission, other State agencies, or California utilities produce updated energy-efficiency supply curves in the near-term, PIEREA efforts should focus on estimating the associated GHG reduction and improving data sources and methodologies.

Critical Factors for Success:

- Coordination among PIEREA and other entities sponsoring supply curve, or related, research.
- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., utility program data sets).

[28] 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.

B. Contribute to the development of initial California-specific CO_2 reduction supply curves for commercial buildings.

Activities needed: (1) *Compile existing information into commercial energy-efficiency supply curves.* At a minimum, underlying data need to be segmented by fuel (electric and gas), vintage (new versus existing construction) and building type (e.g., office, retail, etc.). Customer size and ownership status should also be considered as key segmentation variables. Measure penetration should be modeled for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (2) Market barriers by measure or type of measure should be identified, as well as any co-benefits. Further analysis and estimation of implicit customer discount rates is also needed.

To the extent that non-PIER divisions of the Energy Commission, other State agencies, or California utilities produce updated energy-efficiency supply curves in the near-term, PIEREA efforts should focus on estimating the associated GHG reduction and improving data sources and methodologies.

Critical Factors for Success:

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- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., utility program data sets).

5.1.2 CO_2: Industry

A. Establish the feasibility of adapting LBNL industry-specific studies to California.

Activities needed: (1) Conduct a near-term study in which one of the recently completed industrial supply curve studies (Martin et al. and Worrell et al.) conducted at the national level for EPA is modified and appropriately applied to the California market. (2) If successful, adapt the remaining EPA industrial supply curve studies.

Critical Factors for Success:

- Coordination between PIEREA and other entities sponsoring supply curve or related research; especially LBNL and EPA.

B. Contribute to the development of initial California-specific CO_2 reduction supply curves for remaining major industries.

Activities needed: (1) For those major California industries for which national supply curve studies have not been conducted, California should develop, or co-develop, the remaining curves. Candidate industries for consideration include oil/gas extraction, food processing, petroleum and chemicals, industrial machinery, and electronics.

(2) Researchers should develop supply curves for main crosscutting technologies (e.g., steam, motor systems, compressed air), for use in the evaluation of light industries. (3) Model measure penetration for a range of market interventions to produce estimates of achievable potential; associated costs should be inclusive of any programmatic costs. (4) Identify market barriers by measure or type of measure, as well as co-benefits. Further analysis and estimation of implicit customer discount rates is also needed. Analysis of implicit discount should be incorporated into efforts to calibrate estimated to actual measure adoption both with and without program interventions.

Critical Factors for Success:

- Coordination between PIEREA and other entities sponsoring supply curve, or related, research.
- Access to data. Not all of the data necessary is readily available. Coordination among entities with unique data access is critical (e.g., industry-specific organizations).

5.1.3 CO_2: Transportation

A. Develop California-specific CO_2 reduction supply curves for the transportation sector.

Activities needed: (1) Leverage light-duty vehicle supply curves from existing sources and models. Much of the work necessary appears to have been done in studies recently completed and in progress in response to AB 2076. The AB 2076 studies may need to be integrated and reframed to develop a comprehensive CO_2 reduction supply curve for California. (2) PIEREA research could also play an important role in efforts to reduce key uncertainties in the AB 2076 studies. (3) Less work has been done to assess the costs and potential impacts of improving efficiency in motor freight transport. Consideration should be given to co-funding such a study with a national agency, since results will have national applicability.

Critical Factors for Success:

- Firsthand access to data and models employed for AB 2076 studies.
- Consistency in data and methods in AB 2076 studies, such that cross-study integration of results into a comprehensive CO_2 supply curve is feasible and cost effective.
- Coordination with state and local air quality and transportation agencies.

B. Address weaknesses and gaps in current transportation supply curve studies.

Activities needed: (1) Examine weaknesses in current light-duty fuel economy and emissions-reduction studies, to develop a better understanding of the process of innovation in automotive technology. Examine the effects of regulation in shaping

design decisions and expanding technology options; and the role of capital constraints in technology deployment decisions. (2) Conduct/enhance research to improve understanding of consumer behavior and the role of information in vehicle selection.

Critical Factors for Success:

- Coordination and leveraging of research with other R&D organizations nationally and internationally.
- Improved access to industry data.
- Clear focus on research areas where PIEREA can add value to otherwise planned ARB and Energy Commission Transportation Division research (e.g., improving methods and data and reducing uncertainties).

5.1.4 CO_2: Electricity Production

A. Develop basic California-specific CO_2 reduction supply curves for the electric generation sector.

Activities needed: (1) The Commission should compile available information on the costs and GHG emissions characteristics of California generating plants into a single, easily accessible resource (if it has not already).[29] (2) In addition to characterizing current generation costs and emissions, forecast future generation costs and emissions, particularly for renewables and DG. These forecasts should include scenario analyses that cover a wide range of possible generation mixes. Because some the benefits of such research may also be realized on a national scale, researchers should coordinate and leverage efforts with those of other organizations like NREL and EPRI, which have recently produced renewable cost estimates and forecasts. The indirect benefits (e.g., enhanced energy security) and costs (e.g., intermittent availability) of renewables and DG also should be estimated to the extent feasible.

Critical Factors for Success:

- Coordination between PIEREA and other sponsoring entities, for example, NREL and EPRI.

B. Continue to forecast the future generation mix in California, link changes in demand to emissions, and incorporate the ability to model changes in response to GHG mitigation policies.

Activities needed: (1) Establish a process for modeling the GHG emissions associated with different generation mixes in the State under alternate future scenarios (if it has not been done so already). This modeling should include electricity demand reductions and GHG reduction policies focused on the generation sector.

[29] Such information was compiled in the past in the Energy Commission's Technology Status Reports, published over several years in the 1980s and early 1990s. The fourth edition, and last to date, was published in 1997 (CEC 1997).

Critical Factors for Success:

- Adequate Energy Commission staff and resources to expand analytical responsibilities to include GHG emissions modeling. Strong linkages between supply and demand analysis groups at the Commission.

5.1.5 Methane: Waste and Agriculture

A. Develop a basic CH_4 marginal abatement curve for the landfill population in California, and reduce uncertainty in waste-in-place and methane emissions factors.

Activities needed: (1) Assess the California Integrated Waste Management Board database that characterizes the population of California landfills by size, waste composition, and proximity of prospective direct-use end users adequately to determine whether it provides all of the information needed to develop the marginal abatement curve for California. (2) If the CIWMB data are inadequate, improve estimates of waste-in-place and methane emissions factors. (3) Apply the methodology used in EPA 1999 to California landfill census data to develop a methane reduction supply curve for landfills. (4) Incorporate and maintain a dynamic baseline forecast of landfill volumes.

Critical Factors for Success:

- Coordination and co-funding with CIWMB and EPA.
- Improved data on landfill size and composition.

B. Develop basic California-specific CH_4-reduction supply curves from manure management.

Activities needed: (1) Assess the U.S. Department of Agriculture farm census data for California and other sources to determine whether this database characterizes the population of California farms by livestock type, size, and current manure management approach adequately to develop the marginal abatement curve for biogas for California. (2) Using the best available data for California, apply the methodology used in EPA 1999 to the population of hog and dairy cow farms in California to estimate manure biodigester costs and methane reduction impacts. In this assessment, address issues related to distributed generation interconnection and electricity power purchase markets in California, and any additional hassle and transaction costs associated with owning and operating biogas generators. (3) Incorporate and manage a dynamic baseline forecast of hog and dairy farms.

Note: We do not recommend attempting to develop a marginal abatement curve for entermic fermentation in California at this time.

Critical Factors for Success:

- Coordination and co-funding with EPA. Improved data on California's manure-related farm characteristics.

5.1.6 N_2O and High Global-Warming-Potential Gases

A. Develop a N_2O-reduction supply curve for California, reduce uncertainty in N_2O emission estimates.

Activities needed: (1) Develop set of N_2O-reduction options; focus primarily on agriculture and mobile combustion sources. (2) Estimate costs and potential impacts of applying options to California sources; focus primarily on agriculture and mobile combustion sources. (3) Continue improving baseline N_2O emission estimates.

Critical Factors for Success:

- Availability and development of accurate cost data and impact data.
- Understanding of agricultural economy and likelihood of farm adoption of N_2O mitigation measures.
- Coordination and co-funding with EPA and other countries conducting N_2O mitigation research that have similar agricultural practices.

B. Develop a supply curve for mitigating high global-warming-potential gases in California, reduce uncertainty in high GWP emission estimates.

Activities needed: (1) Develop a set of abatement options for high GWP gases. (2) Estimate costs and potential impacts of options as applied to California high GWP sources; principally by leveraging and appropriately combining data, sources, and methods from EPA 2001 with CEC 2001b. (3) Continue improving baseline estimates of high GWP emissions.

Critical Factors for Success:

- Improved accuracy of abatement cost and impact data.
- Coordination with EPA.
- Access to or development of alternatives to proprietary industrial data.
- Reduction in uncertainties identified in EPA 2001.

5.1.7 Crosscutting/Integrating

A. Develop/Implement a Dynamic Technology Adoption Model

Activities needed: (1) To support studies 5.1.1A and B above, develop or enhance technology adoption models and their supporting data. The technology adoption model should interface directly with the technology data developed in the supply curve studies. It should also be able to explicitly handle stock accounting; competition between technologies; multi-attribute adoption functions (e.g., economic attractiveness

and market barriers); end user awareness; dynamic changes in technology costs, availability, and energy prices; and a variety of market interventions (i.e., explicitly incorporate and model the effects of program costs by intervention type). The specification of such a model for energy end use markets is described in RER 2000a. (2) Develop the data and analysis needed to specify the actual curves and parameters of adoption models, initially focusing on the work already available in energy end-use market modeling. (3) Conduct adoption modeling that explicitly incorporates costs and effects of market interventions for non-CO_2 GHGs.

Critical Factors for Success:

- Coordination between PIEREA and other sponsoring entities, including California electric and gas utilities (via CALMAC), PIER Buildings, non-PIER Energy Commission areas, and others.
- Availability of and access to data. Unfortunately, much of the detailed, historic data that would be ideal to utilize for calibrating energy-efficiency and GHG reduction technology option curves is either unavailable or difficult to obtain. For example, the U.S. Census ceased tracking annual fluorescent ballast and other energy equipment shipment data several years ago.

B. Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options.

Activities needed: (1) Conduct a methodological study that addresses the supply curve weaknesses identified in Section 3.6, focusing on formally characterizing these weaknesses, proposing alternative bottom-up methodologies, and implementing examples of alternative methods and models. Focus on sectors for which data can be developed and utilized in quantitative analyses, and on methods such as adoption process modeling. (2) Coordinate with the behavioral economics and energy efficiency research suggested under the Economics of Climate Change Mitigation and Adaptation portion of the Climate Change roadmap.

Critical Factors for Success:

- Coordination and co-funding with other organizations interested in advancing supply curve methods.

Table 12. Short-term Budget

Objective	Projected Cost ($000)
5.1.1.A Contribute to the development of an initial California-specific CO_2 reduction supply curves for residential buildings.	50–100*
5.1.1.B Contribute to the development of an initial California-specific CO_2 reduction supply curves for commercial buildings.	100–200*
5.1.2.A Establish the feasibility of adapting LBNL industry-specific studies to California	50–100
5.1.2.B Contribute to development of initial California-specific CO_2 reduction supply curves for remaining major industries	100–300**
5.1.3.A Develop basic California-specific CO_2 reduction supply curves for the transportation sector	200–500
5.1.3.B Address weaknesses and gaps in current transportation supply curve studies	100–300
5.1.4.A Develop basic California-specific CO_2 reduction supply curves for the electricity generating sector	100–400*
5.1.4.B Forecast the future generation mix in California and incorporate the ability to model changes in response to GHG mitigation policies	100–300
5.1.5.A Develop CH_4 reduction supply curve for the landfill population in California	25–100
5.1.5.B Develop California-specific CH_4 reduction supply curves from manure management	25–100
5.1.6A Develop N_2O reduction supply curve for California, reduce uncertainty in N_20 emission estimates	25–100
5.1.6B Develop supply curve for mitigating high global warming potential gases in California, reduce uncertainty in high GWP emission estimates	25–50
5.1.7.A Develop/Implement a Dynamic Technology Adoption Model	100–500***
5.1.7.B Advance the state-of-the-art associated with bottom-up analyses of GHG reduction options	50–100
Total Short-term Cost	**1,050–3,150**

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 to complete each short-term objective.

**Range depends on number of industry-specific studies conducted ($35,000–$75,000 per industry).

***Higher range includes funding for one or more studies to empirically estimate model parameters.

5.2 Mid-term Objectives

The mid-term objectives should generally be to build off of the foundation research projects developed in the short term. Many of the short-term studies require development of initial GHG reduction supply curves for California as a first step toward PIEREA activities that focus on advancing methodologies and improving input data. Key mid-term research issues are improvement of incorporation of GHG supply curves in macroeconomic models, improving quantification of co-benefits and collateral costs, and improving input data.

A. **Develop advanced California-specific CO_2-reduction supply curves for commercial and residential buildings.**

Activities needed: (1) Improve the dynamic modeling approaches and integrate the models or results developed in the short term into larger macroeconomic climate change models. (2) Increase quantification of indirect costs and benefits of energy-efficiency and GHG reduction measures.

B. **Integrate California-specific CO_2-reduction supply curves across industries**.

Activities needed: (1) After the high-priority, near-term individual industrial studies are complete, the individual study results should be integrated into an overall industrial supply curve for the State. (2) Expand and improve adoption modeling for industrial decision makers and technologies. (3) Continue research efforts aimed at better understanding industrial customers' discount rates and quantifying the costs of technology-specific market barriers.

C. **Continue to address weaknesses and gaps in transportation supply curve studies**.

Activities needed: Continue research efforts to develop a better understanding of the process of innovation in automotive technology; the effects of regulation in shaping design decisions and expanding technology options; and the role of capital constraints in technology deployment decisions.

D. **Improve dynamic emissions modeling of California's generation system**

Activities needed: Continue to improve GHG emissions modeling associated with different generation mixes in the State under alternate future scenarios.

E. **Improve CH_4 marginal abatement curves for the landfills and manure management**

Activities needed: Continue research, as needed, to improve estimation of methane emissions associated with landfills and livestock and improve modeling of gas conversion economics, barriers, and adoption.

F. **Improve N_2O and High GWP mitigation supply curves.**

Activities needed: Continue research, as needed, to improve estimation of nitrous oxide and high GWP gases mitigation supply curves.

G. **Develop an integrated analysis of GHG reduction opportunities and associated costs and benefits.**

Activities needed: Integrate the sector-specific GHG reduction opportunities, through one or more economic-energy models, to produce a comprehensive, interactive, and dynamic assessment of alternative policy options for reducing California GHG emissions. Coordinate this work with the related recommendation in the economic portion of the PIER Global Climate Change Research Plan on large-scale computational modeling to analyze robust strategies for GHG mitigation and climate change adaptation in California.

H. **Calibrate Technology Adoption Models.**

Activities needed: Continue development of calibrated technology adoption curves.

5.3 Long-term Objectives

The long-term objective should to ensure that California has thoroughly and accurately assessed the GHG reduction opportunities and costs associated with a wide range of State, national, and international policy options. As specific GHG policies are developed and implemented, PIEREA should conduct studies that compile and use data from this experience to test, validate, and revise its GHG mitigation 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, PIEREA should consider the following:

- Co-funding existing or planned work to be carried out by:
  - the California Public Utilities Commission (CPUC), California electric and gas utilities, EPA, and DOE (buildings and industry);
  - ARB, federal Department of Transportation, and the Department of Natural Resources Canada (transportation);
  - the federal Department of Energy and EPRI (generation);
  - CIWMB (landfills); and

– EPA, the New Zealand Ministry of Agriculture and Forestry, the Research Branch of Agriculture and Agri-Food Canada, and the Council for Agricultural Science and Technology (landfills, biogas, N_2O, and high GWP gases).

Other co-funding opportunities may be available with a wide variety of countries and international agencies.

- Solicit funds from other research organizations to build upon their efforts, or to co-design new projects at the Energy Commission.

6.2 Opportunities

Co-sponsorship opportunities are likely with ARB, CIWMB, DOE, NREL, and EPA. Each of these organizations is interested in addressing climate change mitigation or closely related issues. The following specific collaborative opportunities have been identified:

- PIER could co-fund, or more likely, build upon[30] research conducted by the CPUC, California utilities, and non-PIER CEC aimed at estimating energy-efficiency potential in the states residential and commercial sectors.

- PIER could co-fund additional industrial sector supply curve studies with EPA to develop both national and California-specific results.

- PIER could co-fund efforts to compile available information on the costs and GHG emissions characteristics of California generating plants into a single, easily accessible resource, and to forecast changes in generation costs with other national and international organizations seeking the same information.

- PIER could collaborate or co-fund work with CIWMB—as well as other relevant state agencies and EPA—on developing basic CH_4 marginal abatement curves for the landfill population in California, both in terms of coordination and potential co-funding.

- PIER could collaborate or co-fund work with the California Department of Food and Agriculture—as well as other relevant state agencies, and EPA—to develop basic California-specific CH_4-reduction supply curves from manure management.

[30] Much of the research funded by California's public benefits charge has a fairly rapid turnaround time between project specification and completion (typically 6 months to 2 years). As a result, direct co-funding may be complicated by differences in timing and objectives. Nonetheless, tremendous opportunities exist for PIEREA to build upon and leverage the data and results developed in these studies for the purpose of advancing the state of supply curve-related research.

7. Areas Not Addressed by This Roadmap

This roadmap does not specifically address methane from entermic fermentation, natural gas production or coal mining; nor nitrous oxide from industrial processes and waste. These areas are not addressed because current information suggests that they are small contributors to California's GHG emissions. Note that carbon sequestration is being addressed in a companion PIEREA roadmap.

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Appendix A
Current Status of Programs

This section lists those entities and efforts that most closely address the climate change mitigation issue for California.

Current Status: California

California Public Utilities Commission and Regulated Utilities

- The CPUC's final decision for 2002 energy efficiency programs includes $10.5 million of market assessment and evaluation studies. These studies will be managed by Pacific Gas & Electric Company, Southern California Edison Company, and Sempra Energy. Among the proposed studies is a statewide energy-efficiency potential study that PIEREA may be able to leverage to achieve some of the goals outlined in this roadmap.

California Air Resources Board (ARB)

- ARB's current research activities are shown at www.arb.ca.gov/research/research.htm.
- ARB and the Energy Commission are cosponsoring a major research effort on transportation-related petroleum reduction options, costs, and impacts. (See www.energy.ca.gov/fuels/petroleum_dependence/documents/)
- ARB's *Strategic Plan for Research 2001-2010*, is their ten-year research plan that mostly focuses on health effects. There could potentially be opportunities for PIER to collaborate with ARB on some topics. (See ftp://ftp.arb.gov/carbis/research/apr/plan/ltplan/Spla0701.dpf)
- ARB actively promotes the use of alternative fuel vehicles. (See www.arb.ca.gov/msprog/ccbg/ccbg.htm)
- For this fiscal year, ARB funded a study of nitrous oxide and ammonia emissions from vehicles due to catalytic converter aging. (See www.arb.ca.gov/research/apr/plan/fy01-02/plan.pdf)

California Integrated Waste Management Board and Cal/EPA

- The goals of CIWMB and Cal/EPA include improvement of air quality and reduction of greenhouse gases. See www.cowmb.ca/gov/ and www.calepa.gov/)

Current Status: Regional and National

Environmental Protection Agency

- The EPA has been engaged in a multi-year, multi-gas supply curve research process for several years. They have published supply curve studies for methane and high GWP gases, and both can be found at, www.epa.gov/globalwarming/publications/emissions/index.html.
- The EPA is currently working on a supply curve study for N_2O.

Lawrence Berkeley National Laboratory

- Lawrence Berkeley National Laboratory (LBNL) has conducted supply curve studies for energy efficiency and carbon dioxide emission for several industrial sectors, including cement, pulp and paper, steel, and chemical. LBNL expects to conduct additional studies on industries not yet addressed. See http://eetd.lbl.gov/ea/IEUA/IEUA.html.

National Renewable Energy Laboratory (NREL)

- NREL conducts a wide variety of research and demonstration projects related to renewable energy. A summary of their latest Five-Year Research Plan is available at www.nrel.gov/publications/newpubs.html.

Current Status: International

European Union

- The European Union has developed bottom-up analyses of GHG mitigation potential for virtually all sectors and gases. These studies are provided at http://europa.eu.int/comm/environment/enveco/climate_change/sectoral_objectives.htm.

Intergovernmental Panel on Climate Change

- The IPCC's latest document on mitigation, *Climate Change 2001: Mitigation*, www.ipcc.ch/ discusses mitigation and associated costs and ancillary benefits.

Attachment VI

The Economics of Climate Change Mitigation and Adaptation in California

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PIER Environmental Area

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Executive Summary

There is a high likelihood that in the coming decades global climate change will have tangible effects on California's natural environment and economy. In the event of rapid and/or extreme shifts in the climate system, these effects could be substantial and could entail high economic costs. At the same time, California is already starting to undertake new policy initiatives to abate greenhouse gas emissions, and national and international policies for addressing climate change, while not yet fully formed, are almost certain to emerge and will themselves affect California's economic and natural resource policy process.

Economic methods are the primary tools for evaluating the socioeconomic implications of climate change and the costs and benefits of policy responses. Economics is also the primary disciplinary source of theoretical and computational tools for integrating climate science and policy. Analyzing and formulating policy responses to climate change in California is, broadly, a problem in the economics of risk and uncertainty. Applying state-of-the-art methods in decision analysis and computational modeling will allow California's policy makers to better understand the complex and uncertain nature of potential impacts, how to address the economic risks they entail, and how policy actions can be coordinated across different sectors of the economy and different regulatory areas.

Simultaneously, policies to mitigate carbon and other greenhouse gas emissions may have a major impact on California's energy system. New research on the determinants of energy demand, the nature of energy-saving technological change, and the increasing role of information technology and its relation to energy trends will help California design carbon abatement policies that are consistent with the state's continued growth and economic vitality.

The research areas and priority activities discussed in this roadmap are as follows:

Computational modeling and decision analysis: Develop new models and software for integrated economic and policy-relevant analysis capable of: (1) addressing fundamental uncertainties in climate-related costs and benefits, (2) formulating decision strategies that are robust across a variety of future climate and economic scenarios, and (3) facilitating policy responses to rapid, severe, and unanticipated climate impacts.

Climate change impacts and adaptation: Extend existing research and develop new economic models to better understand key risks, particularly from potential abrupt and extreme changes in the climate, and the costs of mitigating or adapting to them.

Economics of energy efficiency: Apply concepts and methods from the emerging field of behavioral economics to better understand the nature of consumers' energy-efficiency investment decision making and its implications for policy.

Technological change: Conduct theoretical and econometric research to determine how price-induced innovation, learning effects, and government policies have affected trends in energy efficiency in the California economy; develop a California-focused energy technology simulation model that can apply this research to project future trends and analyze policies to promote technology adoption.

Information technology and energy: Determine the past, present, and projected future relations between the diffusion of information technology and trends in energy demand in California.

Revenue recycling: Analyze the economic impacts of different schemes for returning revenues from carbon or energy taxes, or tradable permit revenues, to the state economy.

Air quality and greenhouse gas abatement: Study the benefits of "harmonized options" that simultaneously improve regional air quality and reduce greenhouse gas emissions. Coordinate with CGE modeling work to simulate constraints in criteria pollutant emissions in conjunction with consideration of greenhouse gas emissions.

Regional permit trading: Devise design criteria and implementation plans for intrastate trading regimes for carbon and other greenhouse gases.

Greenhouse abatement cost estimation: Develop improved economic models of the costs of abating non-CO_2 gases.

In the short-term (1–3 years), this roadmap recommends that research address the objectives in the table on the following page.

The 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.

Objective	Projected Cost ($000 per year)
Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.	$500
Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.	$300
Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.	$300
Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.	$300
Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.	$150
Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.	$100
Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.	$200
Assess the feasibility of intrastate markets for GHG trading and related mechanisms.	$150
Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.	$150
Total Short-term Cost per Year	**2,100**

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 per-year expenditure over the short-term period.

Roadmap Organization

This roadmap is intended to communicate to an audience that is technically acquainted with the issue. The sections build upon each other to provide a framework and justification for the proposed research and development.

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 in this area. Section 3.1 discusses existing methods for integrated economic modeling and analysis in the areas of energy and climate modeling, their limitations, and key issues in developing improved integrated modeling tools for application to California's decision making on climate change and energy and GHG-abatement policy. Section 3.2, on the economics of impacts and adaptation, briefly describes current California-focused work in this area and research priorities for extending and enhancing this work. Section 3.3 focuses on key topics relating to energy demand that bear on the central issue of how California can implement the most economically efficient policies for GHG abatement. Section 3.4 deals with two primary issues in integrated policy implementation and the goal of "synergy" between GHG abatement and other policy goals. *Section 4: Current Research and Research Needs* surveys current projects addressing the economic aspects of climate change mitigation and adaptation in California 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 done to address the economic aspects of climate change mitigation and adaptation in California.

Acronyms

CGE	computable general equilibrium
CV	contingent valuation
DOF	California Department of Finance
E/GDP ratio	Energy-to-Gross Domestic Product ratio
EPRI	Electric Power Research Institute
ETC	endogenous technological change
ETSAP	Energy Technology and Systems Analysis Programme
EVRI	Environmental Valuation Reference Inventory
GDP	Gross Domestic Product
GHG	greenhouse gas
GSP	gross state product
HFC	hydrofluorocarbons
IIASA	International Institute for Applied Systems Analysis
IT	information technology
LBNL	Lawrence Berkeley National Laboratory
LRD	Longitudinal Research Database
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NAST	National Assessment Synthesis Team
NERC	North American Electric Reliability Council
NSF	National Science Foundation
OECD	Organization for Economic Cooperation and Development
PFC	perfluorocarbon
PIEREA	Public Interest Energy Research, Environmental Area (California Energy Commission)
RFF	Resources for the Future
STAPPA/ ALAPCO	State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials
TAF	Transport and Analysis Framework
VOCs	volatile organic compounds
WSCC	Western Systems Coordinating Council

1. Issue Statement

Climate change poses a variety of risks to California's natural and economic systems. Formulating and implementing policy responses to address the impacts of climate change in California requires a carefully designed program of basic and applied economic research to assess the nature of these risks from a socioeconomic perspective, their potential costs, and the most efficient policies for either mitigating or adapting to them. At the same time, greenhouse gas (GHG) mitigation will play an increasingly important role in the state's environmental policy making in the coming decades. New economic research is required to better understand the costs and benefits of a variety of both existing and

potential policies to reduce California's emissions of greenhouse gases, and to ensure that such policies are consistent with the state's continuing economic vitality.

2. Public Interest Vision

An extensive body of existing research has studied the economic aspects of climate change mitigation and adaptation, and their implications for policy at the national and international levels. To develop economically sound policies for addressing climate change and mitigation in California, new basic and applied research is required. First, improvements in computational modeling and decision analysis are necessary to develop modeling tools that can take account of risk and uncertainty in analyzing climate impacts, response strategies, and GHG-mitigation efforts. Second, researchers need to conduct impact and adaptation studies that incorporate uncertainty and institutional constraints, for various sectors. Third, researchers need to investigate behavioral economics and energy-efficiency investment, to better understand the economic ramifications of energy-efficiency decisions and their application in public policy. Fourth, research needs to explore the role of technological change in the economics of energy production and use. Fifth, researchers should gain a better understanding of how information technology is affecting energy demand in the State, to better inform long-range energy planning. Sixth, researchers should study "revenue recycling," and its potential role in energy or carbon taxes in the State. Seventh, a coordinated research effort needs to analyze the ancillary benefits of GHG mitigation, to integrate air quality and multi-gas GHG-abatement strategies for the greatest benefit. Eighth, economic research must evaluate the concept of regional trading markets for GHG emissions, to assess those markets already in place and to visualize the development of new markets. And ninth, there is a need to improve modeling of non-CO_2 gas abatement, to improve its application in California.

This economic research and development could benefit Californians in a variety of ways: through improved air quality, the more widespread use of energy-efficient technologies, the development and/or use of regional trading markets, better quantification of the costs and benefits of GHG-mitigation options, and more. The successful completion of the work outlined in this roadmap will help all State agencies better evaluate the economics of climate change planning options.

3. Background

It is now well-established that anthropogenic emissions of GHGs are changing the global climate, and that further shifts in the climate system will occur during the twenty-first century. Although subject to considerable uncertainty, there is a high likelihood that these global changes will entail changes to California's climate resulting in both public and private costs for dealing with the accompanying impacts. At the same time, the current national policy and political impasse notwithstanding, it is plausible and perhaps likely that the United States will undertake major efforts to mitigate carbon emissions during the coming decade, possibly within a revised international framework developed from elements of the Kyoto protocol. Such an initiative could have substantial effects on the

American economy at the national, regional, and state levels. Even before the establishment of such broader policy initiatives, California has taken a significant step in enacting a requirement that carbon emissions from motor vehicles sold within the state be reduced by the end of the current decade. Overall, with respect to both GHG mitigation and adaptation to impacts, climate change is very likely to be a key—if not dominant—element of California's environmental management efforts in the coming decades.

More than a decade of increasingly active research, across a range of disciplines, has been devoted to determining the costs of large-scale GHG abatement (particularly CO_2), as well as to estimating the multi-sector impacts and attendant costs of climate change. There are now extensive—in some cases voluminous—literatures on many key aspects of the climate change issue, on both the mitigation and the adaptation sides. Moreover, work is currently under way to assess potential climate change impacts on California specifically (Wilkinson et al. 2002; EPRI 2002). Results from these initial studies indicate specific risks to certain of the state's natural and economic systems, as well as measures that could serve to anticipate and offset damages induced by climate change. These preliminary studies, as well as the large body of existing work on climate change mitigation and adaptation, indicate the need for a broader array of research aimed at understanding the potential costs and benefits of, and appropriate policy responses to, climate change in California.

This roadmap recommends and provides a rationale for research in the areas of economics and policy analysis, building upon and extending previous efforts. The overall aim of this research is to develop and apply theoretical and practical economic methods and tools for addressing the joint problems of: (1) anticipating and responding to the physical and economic impacts of climate change, and (2) designing and implementing economically sound policies for GHG mitigation in California. It is important to emphasize that the roadmap does not provide an exhaustive list of research needs related to climate change mitigation and adaptation in California. There are currently a great number of important questions to be addressed, involving different economic sectors, natural systems, and possible policy responses. This roadmap deals only with a subset of these issues, which are fundamental topics that have been judged to be of key importance and that are likely to yield particularly high benefits from PIER support.

This roadmap reflects two primary themes. First is the need to view the economics of climate change, and policy planning in response to climatic impacts, in terms of risk and uncertainty. Despite rapid scientific advances, the exact nature of the impacts of climate change on California cannot be predicted with certainty, and further research—while narrowing the uncertainty—cannot be expected to eliminate it. Thus, anticipating the possible character of climate change impacts and making the necessary investments to address them is analogous—albeit on a much broader scale—to the everyday problem of buying insurance against more prosaic risks. This point-of-view is strongly reinforced by the emerging scientific understanding of "abrupt" or "nonlinear" climate change (described in Section 3.1 below), which might entail impacts on California that are both more significant and more sudden than has been heretofore anticipated.

The second theme is the need for new and innovative research to fundamentally improve our understanding of the determinants of energy demand and the role of energy in the aggregate state economy. Such research is essential in order to improve upon existing, very imprecise estimates of the costs of GHG abatement (particularly as it relates to carbon) on a large scale. This problem also involves uncertainty, but from a somewhat different direction. That uncertainty is the hallmark of the climate problem with respect to climate *science* is widely known and figures prominently in policy and political debates. It is also a central guide to the scientific research community's ongoing efforts to improve knowledge of the climate system, potential changes therein that may be under way, and the possible impacts on biological, ecological, and other natural systems. The *economic* dimension of uncertainty related to climate change, by contrast, is much greater than is commonly understood. This uncertainty arises directly from long-standing gaps in research on the microeconomics of consumers' and firms' energy-related decision making and on the nature of energy-saving technological change.

It is important to highlight one other aspect of this roadmap. Although research on all the topics discussed would have a clear, practical benefit for California's climate change analysis, planning, and policy making, a number of points emphasize research that may appear to be more "basic" than "applied." The reason is that, in a number of critical areas, methodological advances over existing approaches (both theoretical and empirical) are required to better serve the needs of policy makers.

3.1 Computational and Decision-Analysis Tools for Integrated Risk Assessment

The central goal of PIER research and allied efforts is to develop tools that will enable state policy makers to carry out integrated analysis of potential climate impacts, response strategies, and GHG-mitigation efforts in a risk-assessment context. The need for integrated analysis of environmental, economic, and policy issues became a central theme in climate policy in the mid 1990s, and has been recently reaffirmed in the National Assessment (NAST 2001a,b).

This type of analysis at the state level would be an adaptation of what has come to be known as "integrated assessment" of global climate change when undertaken in the context of the national or global economy: fully linked quantitative analysis of the interactions among underlying economic factors, energy supply and demand, and GHG emissions and climate-related damages. In its most ambitious form, integrated assessment is global cost-benefit analysis, in which the marginal costs of GHG abatement are dynamically equated to the marginal damages from climate change over timescales of up to a century (Nordhaus 1994).

In the context of the state economy, this approach to integrated assessment is inappropriate: the costs and benefits of California GHG abatement efforts cannot be meaningfully weighed in this manner. Even short of full cost-benefit analysis, integrated economic analysis of climate change mitigation and adaptation at the state level will differ

in fundamental respects from national-level analysis in three ways. First, there is a high likelihood that state-level policies to mitigate GHGs and those to address adaptation to climate change impacts will be pursued somewhat independently. Second, state-level mitigation efforts are likely to arise both locally and in response (in the long run) to national policy mandates. Third, despite the size of California's economy, it cannot be modeled independently of either the national economy or of state-specific international trade flows.

Despite such differences, however, it is meaningful to consider forms of "integrated assessment" at the state level. The aim of such analysis would be to assess, at the level of the statewide economy, the costs and potential benefits of both climate change impacts and efforts to mitigate GHG emissions. This type of approach is essential to account for these aggregate impacts, as well as to study the complex interrelationships among sectors in adapting to climatic impacts and absorbing the costs of mitigation. The following discussion focuses on the key issues involved in the identification and development of a theoretical and computational platform that will support an appropriate integrated California analysis.

3.1.1 Key Limitations of Current Modeling Approaches

Economic analysis of climate change mitigation and adaptation has come to be carried out primarily through the construction and application of large-scale numerical simulation models (Weyant 2000). The dominant modeling approach for this purpose has been the so-called "computable general equilibrium (CGE)" paradigm. The key elements of this approach include: (1) market equilibrium of supply and demand for goods and services (including, but not limited to, energy), (2) rational behavior on the part of consumers and firms (i.e., utility maximization and cost minimization, respectively), (3) a representation of the (national or global) economy over long time horizons, and (4) perfect foresight on the part of consumers, firms, or a representative decision maker with respect to all future events and the consequences of all actions. In practice, CGE models used for integrated assessment (or for other applications) do not generally take explicit account of uncertainty; they are deterministic in that they assume perfect knowledge of the present and future values of all included variables and parameters.[1]

The use of such models for economic and policy analysis of energy issues began in the 1970s and has steadily expanded in scope and complexity. More recently, many of these originally energy-economic models have evolved to include environmental factors, with the goal of integrated assessment as described above. In fact, that capsule description understates the emerging role of the economics-based integrated assessment (IA) models. In practice, the economic concepts and methods embodied in these models have emerged as a dominant pathway through which *scientific* information on climate change is

[1] Theoretically, the general equilibrium paradigm—originated primarily by Arrow and Debreu in the 1950s—can be extended to incorporate uncertainty. Implementing this extension in practice, however, confronts substantial hurdles, some of which are noted in the succeeding discussion.

organized and transmitted to policy makers. In this respect, economics-based models play a role beyond simply estimating costs and benefits of climate-related policies and impacts.

The standard CGE approach, while usually applied to national or international economies, can (with appropriate modifications) also be applied to a state economy such as California's. Indeed, CGE modeling is currently applied to taxation and revenue analysis in California (Berck et al. 1996; see also Section 4.6, below). An extension of this existing modeling capability to energy and climate issues can provide an initial benchmark for estimating approximate, aggregate economic impacts of climate change and GHG mitigation policies. At the same time, however, it is essential to begin the study of potential integrated modeling tools for California that extend and possibly transcend the deterministic CGE approach. Key reasons for such an effort are summarized in the following discussion—very broadly, they have to do with the need to rigorously address different types of uncertainty.[2]

The creation of a single integrated economic modeling tool for California must take account of basic issues in IA modeling that are reflected by the wide range of results from existing models. As Kann and Weyant (2000) point out, this variation "has made it difficult for scientists and policy makers to know how to use the results of integrated assessment models. Thus, policy makers' high demand for reliable model results has not been fulfilled." The variation can be ascribed to different assumptions about economic and physical processes both exogenous and endogenous to a given model, different value judgements that bear on model structure and output, and different modeling simplifications that are made for computational reasons.

In the context of climate change analysis, a fundamental problem that cuts across these categories is how future events—both economic and environmental—are represented. As noted above, with few exceptions, CGE- type IA models are deterministic and are focused on determining optimal or least-cost policies over very long time horizons under conditions of certainty. Typically, a small number of "most likely" scenarios are the basis for analysis. Baseline paths for economic growth, energy demand, and other key variables are selected, often on a century-long timescale. Optimal or equilibrium solutions with these paths are then calculated, and in policy applications, the costs of hypothetical carbon taxes or similar future measures are derived.

It is sometimes emphasized that baseline paths and policy-induced alternatives are not "predictions" or "forecasts" of what will happen, but simply estimates of a plausible set of future events and their implications. In practice, however, it is clear that in diffusion from the academic to the policy arena, this type of calculation does become a de facto prediction, and is treated as such in both policy and political debate. Indeed, the most straightforward interpretation of deterministic model calculations is that they are, in fact, predictions or forecasts. As such, the weight commonly placed upon them is puzzling and, from a policy perspective, troubling. It is a truism that the track record of economic

[2] This discussion draws in part upon Kann and Weyant (2000).

forecasting in general is poor. With respect to long-run energy-economic modeling in particular, it is well known that conventional wisdom has frequently been proven wrong. Even short of the fact that forecast error is unavoidable and inevitable, standard models incorporate a wide range of more-or-less equally credible assumptions regarding parameterizations, inputs, and related features (Repetto and Austin 1997; Weyant 2000); the differences among which propagate in time as the models are applied to scenario analysis. The result is a correspondingly wide range of cost and benefit estimates for GHG abatement policies, with no rigorous means of comparison or weighting among them. Several decades of model development and supporting economic research on, for example, values of underlying parameters, have not resulted in convergence to a common knowledge base that would in turn yield convergence of model predictions and estimates. For example, in a recent structured model comparison exercise analyzing the economic impacts of the Kyoto protocol, estimates of U. S. GDP losses from compliance varied by an order of magnitude (Sanstad et al. 2001).

3.1.2 Incorporating Uncertainty

The problems described above are well known and, up to a point, uncontroversial. They all point to the need to incorporate a range of uncertainty types into an eventual integrated assessment model for California. Determining the appropriate theoretical and empirical approach for doing so is itself a major research undertaking. There are a number of examples of uncertainty analysis being undertaken with well-known models (e.g., Manne and Richels 1992; Nordhaus 1994). The computational demands of rigorous uncertainty analysis in an optimization or equilibrium framework, however, are such that drastic simplifying assumptions are generally required to maintain tractability (Kann and Weyant 2000). On an even more basic level, optimization-based uncertainty analysis does not address what has been called "Knightian" or "deep" uncertainty: situations in which values of fundamental quantities are not merely unknown but also cannot plausibly be assigned probability distributions. This description characterizes a broad range of problems in the science and economics of climate change.

The first (and paramount) example is the manifold scientific uncertainty surrounding the evolution of the regional climate. As described in the PIER roadmap on Regional Climate Modeling, projecting the future path California's climate is—and will remain—a problem of considerable technical difficulty. Because exact predictions are beyond our current scientific capability, it will continue to be necessary to evaluate many plausible scenarios for this path in order to conduct economic risk assessment and planning. This analytical requirement strongly indicates the need for a departure from standard deterministic and predictive modeling approaches.

This conclusion is reinforced in the context of potential departures from the standard assumption of gradual and "smooth" climate change. Virtually all research to date on the economics of climate change impacts has been based on this assumption—that is, steady increases in mean global temperature on decadal or century timescales. Within the atmospheric sciences community, however, attention is increasingly focused on the

possibility of anthropogenically induced "abrupt" and/or "nonlinear" climate change: dramatic shifts in the climate system on much shorter timescales, of possibly much greater severity (NRC 2002). On a global scale, examples of such phenomena include sudden sea level rise, "runaway" methane releases from the Arctic tundra or offshore clathrates, and disruptions in oceanic thermohaline circulations. In California, such abrupt and/or extreme events (and their consequences) might include prolonged drought, extensive fires, persistent El Niños (with resulting flooding and coastal damage), or the collapse of Sacramento River delta levees.

There is a body of opinion among economists that the key socioeconomic risks from climate change may arise precisely from this type of sudden shift, both on global and regional scales. The economic analysis of both impacts and adaptation under an abrupt/nonlinear scenario in principle differs both in degree and in kind from that appropriate for "smooth" climate change, involving difficult-to-quantity risks, and the need for a computationally intensive consideration of large numbers of scenarios with varying stochastic characteristics.

A second key example is *technological* uncertainty, particularly regarding the future evolution of the energy system and of energy-efficient and/or GHG-reducing technology. A consistent pair of conventional economic and IA modeling findings is that cost estimates for reducing energy use and GHG emissions depend substantially on assumptions regarding the rate and character of technological progress, but that this progress is extremely difficult to predict. Modeling that enables the exploration of a wide range of technology paths that are plausible—but cannot be predicted with certainty—would enable policy makers to better understand the future technological possibilities for GHG abatement and their economic implications.

A third example is the integrated assessment of non-market impacts of climate change. These impacts have been incorporated only to a limited extent in integrated assessment analysis, and further research on them is recognized as a priority within the modeling community. However, the quantification of non-market impacts—for example, valuation of ecosystem services—is controversial. Placing non-market phenomena on an equal footing with conventional goods and services is likely to exceed the frontiers of research for the foreseeable future. Thus, conventional economic and IA models' treatment of these aspects of climate change—particularly in the context of adaptation—should be regarded as subject to bias and likely to remain so. The reason is that these models require that all goods and services be priced in order to be considered, when determining equilibria. With conventional goods and services, observed market prices serve as the basis for calculation. With non-market goods and services, the absence of such prices poses a substantial hurdle; although there are methods for obtaining proxies, they are controversial, particularly when applied over the long timescales involved in climate impacts. These considerations indicate the desirability of modeling approaches that do not rest solely on price and equilibrium calculations. Preservation of natural systems, or biodiversity, for

example, can be much more easily analyzed when these factors can be included directly in simulations, without their value being subject to an optimization calculation.[3]

These considerations point to several conclusions. First, it is important to emphasize that, despite the types of problems just described, large-scale numerical simulation models are essential to provide applied frameworks for decision making and to integrate complex information both within economics and across other disciplines—the requirement of some form of "integrated assessment." In particular, models of this type will be essential for California's economic and policy analysis of climate change. As noted above, application of existing CGE capabilities in the near term can provide initial benchmarks to guide policy and further research. Looking ahead, however, an appropriate research emphasis should be the examination of potential modeling frameworks that address these problems, and that extend or provide specific alternatives to standard deterministic CGE modeling, or both. Following are some key considerations that such an examination should address.

The general goal of integrated assessment modeling for California should be the identification of "robust decision strategies," which are strategies that have a high (but not necessarily certain) likelihood of performing well under a range of possible futures (Lempert and Schlesinger 2000). As noted above, the "range" in question can be environmental (e.g., paths of future climate trajectories) or economic (e.g., paths of technological development) or both. Within certain limits on the scope of the modeling exercise, such strategies can be determined within an optimization and equilibrium framework that incorporates uncertainty. The scope is defined in particular by the number of economic sectors represented, the time horizon over which the analysis is conducted, and the availability (or lack) of probability distributions for modeled variables and parameters. Thus, the initial question to be addressed is the appropriate size and scope of California's ultimate integrated assessment modeling framework for climate and GHG mitigation policy analysis. It is important that the framework chosen allow for dynamic policy making with learning—that is, that decisions can be modeled dynamically over time in a manner that incorporates the emergence of new information regarding climatic impacts, technology developments, and other key factors.

Should it be determined that a modeling framework is warranted that exceeds the current computational and conceptual limits on optimization modeling under uncertainty, it will be necessary to identify, among other things, appropriate decision criteria and the appropriate method for their application. In recent years, integrated assessment and energy systems models have been developed that can analyze much higher degrees of uncertainty than is possible in any of the several standard optimization-based frameworks (e.g., Lempert and Schlesinger 2000; Gritsevskyi and Nakicenovic 2000). These models allow for the assessment of a wide range of plausible scenarios of future events pertaining

[3] A similar point applies to the treatment of intergenerational equity and distributional issues. Because of the long timescales involved in climate policy analysis, assumptions regarding the rights and interests of future generations are unavoidable and have a substantial influence on the conclusions. The representation of these issues in the standard framework has been intensively critiqued (e.g., Howarth and Norgaard 1992; Howarth 2000).

to, for example, climate change, impacts upon natural systems, and developments in energy-related technology—in contrast to the conventional approach of specifying "most likely" or "baseline" scenarios and restricting analysis to essentially marginal deviations therefrom. In these approaches, Knightian or deep uncertainties (as well as conventional, or "probability-based" uncertainties) can be addressed directly through the use of a computation-intensive search through plausible realizations of future events. These models allow for a very broad range of possible future environmental and/or technological paths; however, a trade-off is that unique optimal equilibria or policy solutions cannot be determined. Instead, they use decision criteria such as "near-optimality": policy pathways that cannot be demonstrated to be globally optimal but satisfy partial optimality criteria in decision spaces of high dimension.

In summary, there is a critical need for research to develop different theoretical and computational possibilities for an integrated modeling capability that allows for both conventional and deep uncertainty, the analysis of robust strategies, and computationally intensive scenario analysis combining market and non-market elements. In an initial phase, this effort could be focused upon economic phenomena, quantities, and trends, with the aim of establishing a view of "possible futures" for the California economy as a basis for mitigation and adaptation analysis. One important element of this work would be to devise protocols for incorporating the existing modeling capabilities for specific sectors and systems that are currently in use by state analysts. In subsequent work, this overall effort can be enhanced and expanded to include the representation of natural systems in the state that may be threatened by climate change, and the appropriate policy pathways for addressing the risks from abrupt and/or extreme climate change.

3.2 Climate Change Impact Mitigation and Adaptation

The past decade has seen the emergence of an extensive body of research on the potential physical and socioeconomic impacts of climate change, summarized most recently in the authoritative assessment of the Intergovernmental Panel on Climate Change (IPCC 2001). A comprehensive assessment of potential climate change impacts on California under the auspices of the U.S. Global Climate Change Research Program, emphasizing water and ecosystem effects, is nearing completion (Wilkinson 2002).

The literature on the detailed, sector-specific economic consequences of climate change, while expanding, is more circumscribed. Integrated assessment, as discussed in the previous section, has tended to focus on aggregate national or international damages from climate change and aggregate costs of GHG abatement. Sector-specific economic analysis of climate impacts in the United States has been pioneered in work described in Mendelsohn, Nordhaus, and Shaw (1994, 1996), Mendelsohn and Neumann (1999), and Mendelsohn (2001). The methods developed in this work are being applied to a current analysis of the economics of climate change impacts in California, focusing on a number of specific sectors and systems, including agriculture, water, ecosystems, and timber. Among other findings, preliminary results both highlight vulnerabilities and indicate potentials

for adaptation (e.g., changing the crop mix in state agriculture) and mitigating investments (e.g., to deal with coastal inundation).

These California-focused analyses suggest a wide range of both further refinements and additional research topics. The following discussion does not attempt a complete review, but instead addresses key specific research needs that are research priorities. The general aim here is to direct the analysis of California impacts research toward a focus on key risks and uncertainties, and toward developing models that provide policy makers with practical guidance for addressing them.

The economic research just described adopted scenarios of gradual climate change, localized to the California region. A next step, following the discussion in Section 3.1, is to incorporate scenarios of rapid and/or abrupt climate change, and to analyze the implications of potential extreme events. Proceeding in this direction requires in part further work in regional climatic modeling that is beyond the purview of this roadmap. However, there are several key elements to the economic component of such an effort. The first is the way in which researchers model the decision making of, and information available to, agents in the economy. An important development in recent research on the economics of climate impacts has been the incorporation of adaptive behavior on the part of economic agents (compare with the Mendelsohn et al. citations, preceding). In contrast to earlier approaches, recent work accounts for the adjustments that, for example, farmers will make to crop selection and growing practices when faced with climate change. This work assumes that economics agents exactly anticipate changes in climate that are relevant to production decisions—or in other words, have "perfect foresight" with regard to climate change.

These assumptions are less plausible, however, in the case of abrupt or strongly nonlinear climate change. Rapidly occurring climate change may overwhelm the ability of decision makers—notably in the agricultural sector—to adapt quickly enough to avoid losses. Similarly, complex nonlinear shifts in the climate regime may prove impossible to anticipate, forcing economic agents to adjust to change after the fact, and again reducing the possibility of minimizing losses. In the event that climate also shifts well outside historical experience, the magnitude of required changes in production techniques may itself be a source of super-normal economic costs. (As the National Research Council (2002) points out, the previous generation of economic research on climate impacts—eschewing adaptive and anticipatory behavior—may in fact be a more appropriate approach to modeling abrupt climate change.)

The discussion in Section 3.1 applies here also: Incorporating nonlinear or abrupt climate change into economic models will require extension and reformulation of current sectoral impact models. Minimally, it requires models to have an intrinsic stochastic structure, in order to represent the very substantial uncertainties involved. In addition to further modeling research, there is a need for further empirical work to better understand the potential magnitudes of losses in the event of abrupt and/or extreme climate change. This

work could include, for example, surveying existing records on weather-related disaster damages. A central aim should be to identify particular climate-related "thresholds" in specific systems, the crossing of which would result in discontinuous increases in damages.

A second research topic is how to explicitly incorporate the current institutional constraints on existing systems into economic models. These constraints are typically not represented in standard optimization models. They will be of considerable importance, however, in formulating policy responses to climate change. This issue is particularly important in modeling California's complex water infrastructure and how it may be affected by climate change.

A third research need is to analyze impacts on additional, economically significant sectors of the California economy, and to further study potential non-market damages from climate change. (EPRI 2002 includes an analysis of one category of potential biodiversity loss from climate change in California.) Priority sectors include recreation and tourism, both of which are important in the state economy and both of which may be vulnerable to climate impacts. The valuation of non-market damages, as noted above in Section 3.1, is a difficult problem. Conventional integrated assessments of the costs of climate change and the benefits of mitigation characteristically omit these damages, which reflect the potential effects of climate change on "services" that are provided by natural systems outside of market institutions. Examples include biodiversity and the various amenities that individuals derive from non-impacted ecosystems. It is widely recognized that this systematic omission has resulted in underestimation of the benefits of climate change mitigation. From an economic standpoint, the key feature of such impacts (and the reason for their omission) is that there are no observable price data that can be used to incorporate them into the cost-benefit calculus. Techniques for their economic evaluation have been developed in recent decades; these techniques fall under the general rubric of "contingent valuation" (CV), which is a set of methods for eliciting preferences for goods or services for which markets (and therefore prices) do not exist. An authoritative review conducted in 1993 by the National Oceanic and Atmospheric Administration concluded that, "CV studies can produce estimates reliable enough to be the starting point for a judicial or administrative determination of natural resource damages" (Arrow et al. 1993), but CV methods remain controversial. (One limitation of this method for climate change analyses is that the damages may be suffered by future generations whose preferences are impossible to elucidate now.) An appropriate research focus would be to assess the applicability of CV for evaluating specific potential non-market damages in California, combined with an assessment of other possible valuation methods. In addition, any effort in this area should be fully coordinated with biological and physical scientists, to ensure that full account is taken of the state-of-the-art in scientific understanding of the natural phenomenon or system in question (Roughgarden 1995).

3.3 The Determinants of Energy Demand and Energy-related Technological Change

California's energy system will be a focus of climate-related policy making in several ways. First, climate change will change patterns of energy use, resulting in potential shifts in supply requirements. Second, climate change will affect the nexus between the energy and water systems, with further supply implications. The third aspect, which is the focus of this section, is that the energy system will be a major focus of carbon mitigation policies.[4] Thus, estimating the costs of carbon abatement from a number of policies directed at altering energy demand patterns—including tradable carbon emissions permits, vehicle emissions limits, and end-use energy-efficiency standards—will be a central problem for California's policy makers.

The potential magnitude of these costs is possibly the single most controversial topic in energy and climate policy in the United States. The current U.S. national policy position on climate change is essentially based on the conclusion that achieving large-scale increases in energy efficiency or significant levels of carbon mitigation would entail unacceptably large economic costs. At the same time, however, both the national and many state and local governments—including California's—maintain long-standing policies and programs to promote energy efficiency under the assumption that the direct (i.e., non-environmental) benefits of these measures exceed their costs.

This contradiction is but one indicator of a much more fundamental, and long-standing, debate in energy economics and analysis, focused on the performance of markets in allocating privately and socially optimal levels of energy efficiency. A central focus of research should be to substantially improve estimates of the costs of reducing energy demand, increasing energy efficiency, and otherwise reducing carbon emissions by means of intervention in the energy system. This section focuses on three core research topics that are addressed to this goal.

3.3.1 Economics of the Energy-Efficiency "Gap"

The 1970s saw the emergence of a long-running debate between economists and energy technologists on the degree to which energy-efficient technology is optimally allocated by markets in the absence of policy intervention. The focus of this debate has been the so-called "energy efficiency gap": the putative under-adoption of such technology without government policies to encourage (or compel) it. (This is also commonly referred to as the "top-down/bottom-up" debate.) Technologists have consistently argued that the gap is both real and substantial, while economists have strongly questioned this claim on both theoretical and empirical grounds. Long a theme in energy policy, the debate over the "gap" has, with little or no amendment, been absorbed into climate policy as well.

[4] It will not be the exclusive focus of such policies, because biological carbon sequestration may also play a significant role in California.

Both technology-based and economics-based work on this issue proceeds apace. In the policy arena, however, at least at the highest levels of decision making, the views of economists have strongly prevailed: For all intents and purposes, official U.S. national policy on climate change categorically rejects the possibility of large-scale, low-or-zero cost carbon abatement through technology-focused interventions.[5] Nonetheless, the existence and magnitude of an energy-efficiency gap remains very much an open question. It is clearly a central concern for research and policy measures on mitigation. Whether or not there is indeed widespread, systematic under-investment (relative to economic criteria) in energy efficiency by consumers and firms has major implications for estimating the economic costs of intrastate carbon abatement via either the "top-down" (e.g., carbon emissions permits) or the "bottom-up" (e.g., energy-performance standards) paths.

The most striking feature of this debate is how little intellectual progress has been made toward resolving it.[6] There have been some efforts by economists to find common conceptual ground (e.g., DeCanio 1993, 1998; Howarth and Sanstad 1995; Howarth and Andersson 1993). In general, however, the analytical methods and arguments commonly brought to bear by both "camps" of antagonists differ almost not at all from those of two decades ago. Technologists continue to posit "market barriers" to energy efficiency without providing rigorous theoretical and empirical elaborations of this idea, while economists continue to apply theoretical models that rule out a priori the possibility of an energy-efficiency gap, despite a host of apparent empirical evidence to the contrary.

This debate is commonly framed as one over the merits of energy-efficient *technology.* At a fundamental level, however, it is in fact an argument over the nature of energy-related *decision making.* Fortunately, as in the field of large-scale simulation modeling, there have been advances in the economics of decision making that hold considerable promise for progress in resolving the energy-efficiency gap debate. These advances have appeared in what is called "behavioral economics," a discipline that links economics with psychology and other behavioral sciences in the study of decision making (Mullainathan and Thaler 2000). Behavioral economics has been stimulated in large part by a growing body of empirical evidence that the standard economic model of rational behavior—"expected utility maximization"—has critical empirical shortcomings as a description of individual decision making.

[5] A recent effort to integrate "top-down" and "bottom-up" findings at the national level is described in Krause et al. (2002); this work also discusses the exclusive reliance by the U. S. government on 'top-down' analysis in assessing the Kyoto Protocol.

[6] In the early to mid-1990s, there was some initial movement toward constructive engagement—at least on the terms of debate, stimulated in part by the widely cited paper by Sutherland (1991). These issues were a focal point of the Stanford University Energy Modeling Forum (EMF) study (EMF 13) on "Markets for Energy Efficiency" (REF). The October 1994 special issue of the journal *Energy Policy*, which arose from the EMF meetings, presented a variety of viewpoints on the "gap," from both economists and technologists (Huntington et al. 1994). Unfortunately, this potential opening for more productive interactions among the parties to the "top-down/bottom-up" debate has for the most part remained unexploited.

Behavioral economics provides a natural setting for a renewed and, hopefully, more productive effort to understand the nature of energy-related decision making and the character and magnitude of the energy-efficiency gap. The first step in a program of research should be a careful assessment of the empirical literature on the efficiency "gap." The goal would be to scrutinize the putative evidence of anomalies in consumers' and firms' energy-efficiency choices to determine the robustness of these anomalies when account is taken of quality and character of data, uncertainty and hedonic elements, and related factors.[7]

The second step should be to apply new models of intertemporal decision making that take account of, and seek to explain, empirical evidence against the standard discounted utility model (e.g., Loewenstein and Prelec 1992). Two phenomena are of particular interest here: "loss aversion," or the asymmetric weighting of gains and losses with respect to a neutral reference point, and "hyperbolic discounting," a widely observed pattern that stands in contrast to the conventional exponential discounting model. These and other concepts and their theoretical and empirical elaborations hold considerable promise for breaking the impasse over the energy-efficiency "gap."

3.3.2 Microeconomics of Technological Change and Energy Productivity

In the conventional representation of the economy that is embodied in most IA models, there are two mechanisms through which the economy can reduce its use of energy, whether in absolute or relative terms. First is substitution: in response to a change in relative prices, consumers and firms will tend to shift away from relatively higher to relatively lower-priced goods and services. In the case of energy, a carbon or energy tax, or a system of tradable emissions permits that raised the price of energy, will result in substitution away from energy in general, or specific carbon-intensive fuels in particular. In accord with standard behavioral and equilibrium assumptions, such substitution is costly by definition.

The other mechanism is technological improvement that, over time, reduces the relative energy-input requirements of producing goods and services. With few exceptions, such improvement is represented in the models as "autonomous" or "exogenous": it occurs over time independent of price changes or policies. More specifically, by assumption, it *cannot be affected by prices or policies.* It is well known that assumed rates of autonomous energy-saving technological change can have major effects on model estimates of the costs of carbon-abatement policies, because of the effects of these rates on baseline trajectories. Thus, for example, if the economy is becoming 1% more efficient each year "on its own," then policies to reduce energy use of carbon emissions in the future need be less stringent than if this rate is, say, 0.5%.

[7] The evidence for the "gap" has been frequently criticized for being "engineering" in character and failing to take account of economic fundamentals. However, much of this evidence was in fact the product of research by econometricians applying discrete choice methods, and is rather consistent across a range of studies.

This representation of technological change, however, while conventional and all but universal in IA modeling, would seem to omit a potentially significant additional mechanism for reducing energy use or carbon emissions. For example, suppose that a carbon tax or emissions permit system were introduced. One would speculate that the resulting new incentives for energy efficiency or carbon efficiency would also result directly in new technological improvements. That is, engineers, scientists, and entrepreneurs would recognize the newly profitable opportunities for inventing and marketing energy- or carbon-saving technology, and the resulting technical progress would serve to increase energy or carbon efficiency in addition to the substitution and autonomous effects described above.

This effect is commonly described as "induced" or "endogenous" technological change (ETC).[8] This phenomenon has been a central focus of research on economic growth since the mid-1980s, following the seminal work of Romer (1986, 1990). A closely related topic is the phenomenon of "learning-by-doing" (LBD) in production of new energy supply technologies, that is, production cost declines as experience is gained in manufacturing. The LBD phenomenon has been extensively studied and documented in a variety of cases (not restricted to energy technology) over decades of empirical study, and has recently been an active research topic in energy economics.

The significance of ETC and LBD in climate policy has been a topic of debate in recent years, particularly with respect to whether its omission in standard models creates a bias toward overestimating the costs of carbon abatement. A number of studies have shown that including either ETC or LBD in computable general equilibrium models (described in Section 3.1, preceding) can lower the costs of meeting emissions abatement targets, relative to simulations in which they are omitted (Goulder and Schneider 1999; Manne and Richels 2002; Popp 2002). Recent partial equilibrium (that is, single-market) work on the empirical measurement of ETC has also indicated that it may be a significant factor in determining the rate of energy-saving technological progress in specific technological categories (Newell et al. 1999; Popp 2000).

Understanding how ETC and LBD affect the evolution of California industries—and the potential costs and benefits of intrastate mitigation policies—should be a high research priority. Initially, emphasis should be placed upon econometric analysis of historical trends in state industries. Further work would seek to apply the results in a CGE or other integrated modeling framework.

This work should at least in part take advantage of firm-level longitudinal economic databases (primarily for manufacturing) that have become available in the past decade. (The best known of these is the U.S. Census Bureau's "Longitudinal Research Database" (LRD); see McGuckin and Pascoe (1988) for an early description.) The advent of these empirical resources has stimulated a new generation of microeconomic research and has

[8] It is important to note that this discussion pertains to technological invention by the private sector, as opposed to R&D undertaken directly by the government.

resulted in a rather dramatic expansion of the understanding of the behavior of firms, markets, and technological change—particularly in manufacturing (Bartelsman and Doms 2000). An important research frontier is to extend this work to encompass energy trends, with a particular emphasis on ETC and LBD.

3.3.3 Information Technology and Energy Trends

Despite the current cyclical downturn, an expert consensus has emerged that the development and diffusion of information technology (IT) is largely responsible for the upward shifts in aggregate labor and total factor productivity in the U. S. economy since the mid-1990s (Jorgenson and Stiroh 2000; Oliner and Sichel 2000). This conclusion has been mitigated, but not reversed, with the recent downward revisions by the U. S. Bureau of Economic Analysis of late-1990s productivity acceleration: productivity growth still remains well-above the "doldrums" of the two decades following the first oil shocks of the 1970s.

Simultaneous with this shift, there has been an acceleration in the decline of the U.S. aggregate Energy-to-GDP (E/GDP) ratio, the most aggregate index of overall energy intensity in the economy.[9] This has raised conflicting speculation regarding the direct or indirect contributions of IT to energy productivity. It has been claimed, for example, both that IT is directly improving energy efficiency on a broad scale (Romm 2000), and that the change is instead due to temporary shifts in weather patterns (Hakes 2000). A preliminary statistical study indicates that approximately one-half the acceleration in E/GDP post-1996 could be accounted for by milder-than-usual weather, indicating a possible, but not demonstrated, effect of IT on aggregate energy demand patterns (Davis et al. 2002).

Analyzing the aggregate and micro, direct and indirect, implications of the IT "revolution" for energy demand in California is an extremely important topic in the context of climate policy: large-scale impacts of IT could have a significant effect on both baseline energy trends and the costs of GHG abatement policies. At the aggregate (state economy) level, a more careful decomposition study of recent trends should be undertaken, accounting for price changes, weather patterns, structural or sectoral shifts in the composition of state economic output, and related factors. At the micro level, detailed examination of the costs and benefits to individual consumers and firms of the new generation of electronic energy-management tools should be carried out. The key challenge for the latter work will be obtaining the appropriate data. Work to date on firm-level productivity impacts of IT has relied upon specially constructed data sets in which firm output, labor use, conventional capital investments, and prices are combined with information on hardware and software investments (e.g., Brynjolfsson and Hitt 2000). This line of research, however, has not yet been extended to incorporate energy use—carrying out this extension should be a high research priority.

[9] The same pattern is observed in the California energy-to-gross state product ratio (author's calculations).

3.4 Integrated GHG Mitigation Policies and Crosscutting Issues

3.4.1 Revenue Recycling

In analyzing strategies for climate change mitigation, economists have focused primarily on the possible use of price instruments—such as carbon taxes and tradable emissions permit systems—that would reduce energy demand and/or cause a shift away from carbon-intensive fuels. Were they to be implemented, such measures could result in considerable revenue accruing to the government. This is a given in the case of carbon or other emissions taxes, and would occur in the case of tradable permit systems if the permits were auctioned or otherwise sold, rather than allocated at no cost (or "grandfathered") to emitters.

The term *revenue recycling* refers to the return of such monies back into the economy. (Early results are reported in Shackleton et al. 1992; a general review of research and findings on this topic through the mid-1990s is given in Goulder 1996.) The standard economic model of public finance is built on the premise that taxes on specific goods or services are "distortionary" in the sense that they cause consumers and firms to change their behavior—specifically, to substitute away from the taxed item. This "distortion" may in fact result in an improvement in economic efficiency, for example, in the case of taxing an environmental pollutant. In the case of taxes on labor or investment used to finance government operations, while there may also a social benefit (in the form of a government program), the taxes themselves entail some economic loss resulting from the reduction in incentives to work or invest.

The central idea of revenue recycling is to use carbon revenues *to offset other distortionary taxes.* More exactly, carbon revenues would be used to hold the government's budget constant while reducing *marginal* tax rates on labor or investment. This strategy would reduce the "distortions" caused by these taxes, and thus result in economic efficiency gains beyond the benefits of reducing carbon emissions. Put differently, carbon policy would be linked with fiscal policy.

Revenue recycling in the context of carbon abatement has been an active topic of research over the last decade. It is now well-established in the economics literature that the judicious use of carbon revenues would lower—perhaps substantially—the economic costs of carbon abatement relative to other approaches.[10,11] This topic is therefore of considerable interest in analyzing potential mitigation efforts in California. Analyzing the possibilities for carbon abatement with attendant revenue recycling within California is an

[10] *Other approaches* here refers in particular to "grandfathering" of permits, in which case there are no revenues to recycle, and to so-called "lump-sum" rebating of revenues, which has no effect on existing tax distortions.

[11] One important, indeed central, focus in the revenue recycling literature has been the so-called "strong double dividend hypothesis": whether use of emissions revenues to offset preexisting distortionary taxes would, per se, yield net economic gains *even without the accompanying environmental benefits.* In other words, would revenue recycling "pay for itself" as a fiscal, as opposed to environmental, policy? Following early optimism on this point, the expert opinion converged on a rejection of the strong double dividend hypothesis (e.g., Bovenberg and DeMooij 1994). Recent work, however, is lending new credence to the hypothesis (Parry and Bento 2000).

appropriate topic for conventional dynamic general equilibrium modeling. The key problems to be solved in such an analysis include translating existing techniques and theory for "closed" economies into an "open" economy setting. This terminology refers, in essence, to the distinction between an economy that is assumed to have active trade links with the outside (e.g., California) as opposed to being self-contained (e.g., the United States, to a first approximation for this purpose). In addition, the structure of taxation in the California economy differs critically in at least one key respect from that of the U.S. economy: state income taxes, which would be one possible "target" for revenue recycling, are fully deductible from federal taxes, so that marginal reductions in these taxes would not have the efficiency-enhancing effects found in the more general case. This difference would require a more nuanced approach to modeling the disposition of carbon revenue.

3.4.2 Multi-gas Strategies, Ancillary Benefits of CO_2 Emissions Reductions, and Regional Air Quality

Traditionally, climate policy analysis has focused on CO_2 abatement. However, several IA modeling groups have recently called attention to the importance of integrating CO_2 with other gases in devising mitigation strategies, primarily methane (CH_4) and nitrous oxide (N_2O), but also perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6) (Reilly et al. 1999; Manne and Richels 2000). Their findings include substantial cost reductions resulting from a multi-gas (as opposed to a CO_2-only) approach to implementing the Kyoto Protocol, with little difference in climate or ecosystem effects between the two.

At the same time, it is known that a number of policies to control CO_2 emissions would also have the effect of reducing emissions of other pollutants, with important implications for regional air quality. Examples include reductions of particulate matter, SO_X, NO_X, lead, and volatile organic compounds (VOCs). Moreover, these reductions would yield health and other benefits on a much shorter timescale than that applying to climate-change-mitigating effects of CO_2 reductions. As a consequence, the costs of CO_2 mitigation actions are likely to be reduced once analyses account for these "co-benefits" or "ancillary benefits." For example, recent analyses of electric power sector emission indicate that a $10/ton tax on carbon emissions would yield approximately $3 of health benefits from NO_X reduction (Burtraw et al. 1996). Similarly, a recent multi-sector, integrated analysis of energy demand in the European Union found that CO_2 abatement policies would reduce the costs of controlling acidification and ground-level ozone sufficiently to compensate up to 20% of the energy system costs related CO_2 control (Syri et al. 2001).

Such results demonstrate the importance of integrating carbon and non-carbon mitigation measures both analytically and in the formulation of California policy. Given the State's strong commitment to maintaining air quality, as well as the likelihood of broad climate-related mitigation efforts in the coming decades, there will be a clear need for a multi-gas approach that fully exploits potential synergies and reaps ancillary benefits. In the case of electric power, the analytical methods for estimating such ancillary benefits are well established and have been applied to national U.S. studies. A California-focused analysis

of this sector should be carried out using existing models localized to the California economy. The key tools in such an analysis would be an electric sector model, applied to the Western Systems Coordinating Council (WSCC) NERC region, and a model of pollutant transport. A broader, multi-sector analysis of the links among CO_2 abatement and that of other gases in a policy and economic framework is also a priority. Such an effort will require the development of new analytical tools for application to California.

3.4.3 Developing Regional Markets for GHG Trading

Emissions trading has emerged in recent years as a favored instrument for reducing GHG emissions, specifically as an alternative to direct government regulation of emissions through "command and control" measures. An emissions trading system imposes a "cap" on the total emissions of a given set of pollutants that are allowable from a sector or from an entire economy, and distributes permits to emitters that place a cap on their individual emissions. Emitters can trade these permits among themselves, however, and will do so when the costs of abatement vary among emitters. The result is that a given unit of abatement will be undertaken by whichever emitter can do so at the lowest cost, thereby minimizing the aggregate cost of meeting the overall emissions cap.

Long favored by economists, this idea has gained considerable currency as a result of its successful implementation in 1990 to reduce SO_2 emissions from electric power generators. Emissions trading has been strongly favored by the United States in international negotiations, and is currently being studied as a means of reducing non-SO_2 emissions from U. S. power generation. There is a very high likelihood that some form of emissions trading system—national, international, or both—will eventually be put into place to achieve GHG mitigation targets.

In the meantime, however, smaller-scale trading regimes are being studied and in some cases implemented. The mechanisms under consideration include both the standard "cap and trade" approach and schemes for "offset" exchanges of varying geographical scope. This work provides a starting point for considering trading regimes that would operate within California. Such programs could be implemented as stand-alone state responses to climate change or could be mounted in response to national or international agreements.

3.4.4 Estimating Costs of Abatement of Non-CO_2 gases

As noted in Section 3.4, several well-known IA models now include abatement cost estimates for non-CO_2 greenhouse gases, and the simulation results are indicating substantial potential cost reductions in GHG mitigation from a multi-gas approach. The method used in these assessments is to develop supply, or marginal cost, curves for abatement from each such gas, relating levels and costs of reduction on an economy-wide basis.

These efforts provide the starting point for an important enhancement of the standard, CO_2-focused, approach, but require further development to ensure their accuracy and

reliability. First, the theoretical foundation of the current approach assumes away the possibilities of abatement at negative net cost (Hyman 1997). That is, it is assumed that there are no inefficiencies or barriers that would allow GHG gas abatement measures whose direct benefits exceeded their costs. Although such inefficiencies or barriers may indeed be limited in practice, an improved theoretical treatment would allow for making the question one to be answered empirically. Second, current cost curves of this type do not directly account for the effects of technological improvement on lowering the costs of abatement—including the possibility of price-induced or "endogenous" technical change and the possibility of learning or experience effects that would also tend to lower costs (compare with Section 3.3). Finally, although the curves themselves are embedded in general equilibrium models, they are derived on a partial equilibrium basis, and therefore do not fully account for the linkages between abatement measures and the broader economy.

An appropriate topic for PIER is to develop and apply an enhanced methodology for the construction and measurement of these abatement cost curves. The research priorities would be to: (1) develop a theoretical model that allows for the possibility of negative cost measures and embeds cost-reducing technological change, and (2) apply this model to selected gases in the context of abatement within California.

3.5 The PIER Focus

The State needs to evaluate current methods and tools and develop new ones for evaluating the many economic aspects of GHG mitigation and adaptation. Such efforts must focus specifically on the State's unique needs.

Part of the mission of PIER is to conduct and fund research in the public interest that would otherwise not occur. Studying the economics of climate change mitigation and adaptation 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 roadmaps address other economic, ecological, and technical aspects of GHG mitigation. 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 the following areas:

1. Computational Modeling and Decision Analysis
2. Impacts and Adaptation Analysis
3. Behavioral Economics and Energy-Efficiency Investment
4. Characteristics of Energy-related Technological Change
5. Information Technology (IT) and Energy Trends
6. Revenue Recycling

7. Integrating Air Quality and Multi-gas GHG Abatement Strategies
8. Regional GHG Trading Markets
9. GHG Abatement Cost Modeling for Non-CO_2 GHGs

This section continues the discussion in Section 3, further discussing the status of current work and scientific and research gaps in these areas.

4.1 Computational Modeling and Decision Analysis

Several institutions have conducted intensive research on uncertainty, complexity, and related features in the context of climate change and energy policy over the past decade, as well as the on construction and application of models embodying these ideas and requiring computation-intensive solution techniques. Key among these are Rand, Carnegie-Mellon University, and the International Institute for Applied Systems Analysis (IIASA). The focus of this work is generally at a global scale, and no models exist that represent California per se.

Research Needs

For initial computable general equilibrium (CGE) analysis, researchers can use the E-DRAM general equilibrium model for California, developed at the University of California at Berkeley (Berck 2000). E-DRAM is an enhanced version of the DRAM model, which was developed for the California Department of Finance to conduct revenue and taxation analysis (compare with Section 4.6). The overall need is to design, construct, and apply an *integrated economic decision framework* and set of modeling tools for research and policy making related to climate change mitigation and adaptation in California. The goal of this effort would be to facilitate the formation of robust strategies within and across sectors. It would be designed to fully account for fundamental uncertainties and would leverage the State's substantial investment to date in detailed sector-specific modeling—notably for water resource and air quality management planning. Specific research elements would include: (a) reviewing and augmenting, as needed, the existing empirical resources for integrated modeling of the California economy, including state energy balances, input-output data, and estimates of technological change trends; and (b) designing an aggregate decision-analysis framework to determine robust climate mitigation and adaptation strategies at an aggregate level.

4.2 Impacts and Adaptation Analysis

The most relevant existing work was reviewed in Section 3. In addition to this work, researchers at the University of California at Berkeley have conducted a national-level study of the impacts of climate change on irrigated agriculture, and the methods used would be appropriate for application to the California agricultural/hydrological sector. Although a large number of non-market valuation studies have been carried out for a range of environmental "goods and services," there appear to be few or none focusing on climate change-related issues per se. A comprehensive list of such studies is available at

the "Environmental Valuation Reference Inventory (EVRI)" Web site constructed and maintained by Environment Canada.[12]

Research Needs

The primary research needs are to: (a) extend current theory to incorporate impacts and adaptation behavior under uncertainty and in the context of rapid and/or severe climate change; (b) develop modeling tools for specific sectors that incorporate current institutional constraints; (c) review existing methods for non-market evaluation, assess their applicability to California, and (d) apply or extend them to study amenity impacts of climate change on California, to obtain initial estimates of non-market damages.

4.3 Behavioral Economics and Energy-Efficiency Investment

There appears to be no existing systematic effort to apply behavioral economics to the problem of energy-related decision making. However, behavioral economics in general (in other applications) is a very active research area at a number of American universities, including the University of California at Berkeley, the University of Chicago, and Carnegie-Mellon University. There is multi-departmental interest in developing a significant research effort on behavioral economics at the University of California at Berkeley (Hanemann 2001). (Note that one of the world's leading researchers in this area, Matthew Rabin, is on the faculty of the Economics Department at Berkeley.) Also of particular interest to PIER is the program on Behavioral Economics at the Russell Sage Foundation, which provides funding in this area.

Research Needs

The need is for a comprehensive program of research applying behavioral economics to energy demand studies, with a focus on consumer and firm decisions regarding energy efficiency. This effort would adapt and extend the state-of-the-art behavioral economic research on intertemporal decisions. It would be aimed at fundamental advances in understanding the nature of the so-called "energy-efficiency gap" and its implications for policies designed to accelerate the diffusion of energy-efficient technology.

[12] Although this is a subscription service, an overview of the EVRI can be accessed at: http://www.evri.ec.gc.ca/evri/english/tour.htm.

4.4 Characteristics of Energy-related Technological Change

Work on ETC and LBD is being conducted by a number American researchers, including economists at Resources for the Future (RFF), Stanford University, Syracuse University, and the Electric Power Research Institute. Broadly, as noted in Section 3, work in this area is divided between the construction of prototype general equilibrium models embodying ETC, and econometric studies of LBD and technological change in specific sectors. Active research efforts are under way to incorporate learning or experience curves into energy system models at the Energy Technology and Systems Analysis Programme (ETSAP) in the Netherlands and at the U. S. Department of Energy. Such work in the context of uncertainty modeling is an active focus at the International Institute for Applied Systems Analysis (IIASA) in Austria. Overall, these various projects provide a range of technical benchmarks to initiate a California-specific research effort.

Research Needs

The primary research needs are: (a) an econometric study of historical California data to identify the impacts on energy demand of endogenous technological change, learning effects, and policies; (b) construction of a state energy system model to apply the results of (a) in forecasting and the analysis of new and potential energy-efficient and/or low-GHG technologies. As noted in Section 3, this research should make use of available micro-level data. The scope and scale of the model in (b) would depend upon resources and programmatic considerations; a possible strategy is to adapt an existing model (or reduced form thereof) such as the MESSAGE model built at IIASA.

4.5 Information Technology (IT) and Energy Trends

This area is receiving much less attention from the analytical community than might be expected. (In the past several years, a disproportionate emphasis has been placed on the putative skyrocketing electricity consumption of the Internet; this claim has been conclusively repudiated (Koomey 2000)). The initial study referred to in Section 3 was undertaken by Lawrence Berkeley National Laboratory (LBNL). There has also been some work at Argonne National Laboratory, but this work is now approximately two years old. Currently, at the micro level, work is under way (sponsored by the California Energy Commission) on installing and evaluating energy management software tools and related measures as a peak-load demand management mechanism, but this does not entail thus far a careful economic analysis of the costs and benefits of this type of measure to firms.

Research Needs

The overall need is to understand how the rapid diffusion of IT is influencing energy demand in the California economy and the implications of this diffusion for the State's long-term energy trajectory. This work should examine, using econometric methods, the relations among the composition of gross state product (GSP), aggregate energy productivity trends, and the diffusion of IT as measured both by investment and by IT-related contributions to GSP. In addition, data permitting, it should examine at the micro level the effects of IT tools for energy management.

4.6 Revenue Recycling

A summary of the main themes in economic research on revenue recycling was presented in Section 3. For PIER, the most important fact is that a dynamic general equilibrium model of the California economy was constructed in the mid-1990s by researchers at the University of California at Berkeley for use by the state's Department of Finance (DOF) (Berck et al. 1996). This model, the Dynamic Revenue Analysis Model (DRAM), remains in use at the DOF. This model was designed explicitly for intrastate fiscal policy analysis.

Research Needs

The most direct path to studying revenue recycling in the California economy would be to apply the DRAM model, adding additional details on energy supply and demand and introducing carbon and/or energy taxes and/or revenues from tradable emissions permits. Such a project could draw on the extensive, but less technically sophisticated, work on state-level revenue recycling that has been carried out by the Center for a Sustainable Economy in Washington, D.C.

4.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A reasonably large body of work has been amassed under the rubric of "ancillary benefits" of climate change; much, although not all, of this work pertains to measures that simultaneously affect air quality and GHG emissions. A useful overview, with numerous applications (as well as international geographical coverage), was provided at a conference sponsored by the Organization for Economic Cooperation and Development (OECD) in March 2000.[13] A conceptual framework for analyzing ancillary costs and benefits is provided in Krupnick et al. (2000).

The joint organization State and Territorial Air Pollution Program Administrators/ Association of Local Air Pollution Control Officials has created a comprehensive framework for joint air quality and GHG mitigation policy planning (STAPPA/ALAPCO 1999). This work includes case studies of "harmonized options" in specific locations in the United States, including Ventura County, California.

In California, joint strategies are likely to focus more on the transportation sector than on the electric power sector (which has received the most attention in analyses to date). Nevertheless, California electricity generation may remain of interest in this context as attention is turned to regional or national emissions-trading mechanisms; in addition, potential fundamental shifts in this sector attributable to an accelerated deployment of renewables and distributed generation—as well as a movement toward combined-cycle generation—would have both air quality and GHG emissions implications. In the study of ancillary benefits from power generation measures, the state-of-the-art for the United States is represented by the work at Resources for the Future, a nonprofit research

[13] "Workshop on Assessing the Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies," OECD Environment, Washington, D.C., 27–29 March 2000.

organization in Washington, D.C. This work employs the so-called "HAIKU" electric power model and the "Transport and Analysis" (TAF) framework for analyzing atmospheric transport and environmental effects. There is active work under way on regional air quality modeling in California at LBNL and elsewhere, but this has not yet been linked to or integrated with GHG mitigation analyses. A recent and possibly unique multi-sector integrated analysis, using both an energy system model and an environmental impact model, is reported in Syri et al. (2001) and was carried out by a multi-institution team in Europe.

Research Needs

The fundamental research need is to develop of a statewide menu of "harmonized" measures on a multi-sector basis, estimate their costs and benefits, and create a protocol for their implementation. This effort will involve both empirical study and the adaptation of existing air quality modeling tools. It will also be necessary to coordination this research with the State's transportation planning infrastructure.

4.8 Regional GHG Trading Markets

A number of projects are under way to establish regional or otherwise localized trading regimes or protocols for "offset" projects on various geographical scales. Of particular interest for PIER is the "Chicago Climate Exchange," a regional trading scheme for the America Midwest, currently in the design phase with financial support from the Joyce Foundation.

Research Needs

The first need is a feasibility study for an intrastate trading market. Such a study would examine the appropriate geographical and sectoral scope, which GHGs would be included, required institutional mechanisms, and related elements. Subsequent research would focus on implementation issues in the context of emerging (or by-then established) national and international policies.

4.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

The current state-of-the-art in economic modeling of non-CO_2 abatement costs was discussed in the Background section, emphasizing that: (a) the current theoretical model for non-CO_2 gas abatement rules out by assumption the possibility of "negative-cost" abatement, and (b) does not account fully for technological change.

Research Needs

The research need is to further develop the existing standard model for non-CO_2 gas abatement to include the possibility of negative-cost measures and to explicitly represent cost-reducing technological change.

5. Goals

The goal of the Economics of Mitigation and Adaptation portion of the PIER Climate Change Research Plan is to help California formulate and assess the economic implications of implementing various mitigation and adaptation strategies.

The achievement of that goal depends on the development of innovative tools and approaches that enable researchers to better account for the economic aspects of mitigation and adaptation strategies.

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[14]

5.1.1 Computational Modeling and Decision Analysis

A. Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.

Activities needed: (1) Construct new energy balances for California, and apply them to an existing CGE model (E-DRAM) to analyze selected benchmark scenarios of climate impacts and mitigation policies. (2) Develop an integrated modeling framework for studying the California economy that allows for exploratory modeling under uncertainty of key aggregate quantities, including population, economic growth, energy use, and carbon emissions—as well as their responses to possible abatement policies and climate-related impacts. (3) Apply this model to determine an initial aggregate suite of robust strategies. (4) Develop a protocol and software tools for integrated analysis, linking this model with existing models of California systems and sectors. (4) Begin work to integrate within this framework models of key intrastate natural systems and their evolution in the coming decades.

Critical Factors for Success:

- Successful development, testing, and application of new models and software; effective application to California policy making.

5.1.2 Impacts and Adaptation Studies

A. Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of

[14] 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.

natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.

Activities needed: (1) Conduct theoretical research to extend existing economic framework for sectoral impact cost estimation. (2) Conduct economic modeling of institutional elements in key systems. (3) Conduct empirical research, possibly including contingent valuation study, to value non-market impacts of climate change.

Critical Factors for Success:

- New benchmark estimates of climate change impact and mitigation costs in California.
- Successful application to policy planning in water, agriculture, and hydropower planning.
- Credible initial estimates of non-market damages in specific sectors.

5.1.3 Behavioral Economics and Energy Efficiency Investment

A. Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.

Activities needed: (1) Conduct a rigorous assessment of the empirical and theoretical literature on the energy-efficiency "gap." (2) Write a survey paper relating the "energy-efficiency gap" debate to recent advances in behavioral economics. (3) Conduct a technical research effort to construct and econometrically estimate or calibrate one or more specific models of energy-efficiency investment incorporating relevant concepts and techniques from behavioral economics.

Critical Factors for Success:

- Substantial advances in understanding the nature of energy-efficiency-related decision making by consumers and firms.
- Development and application to policy of new economic models of this type of economic decision.

5.1.4 Characteristics of Energy-related Technological Change

A. Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.

Activities needed: (1) Conduct an econometric study estimating the role of energy-related endogenous technological change and learning effects in California industries over the past three decades. (2) Based on those study results, develop forecasts of new

technology costs and penetrations, and identify promising new technologies. (3) Develop or adapt a computational energy technology model to carry out economic and technological scenario studies (incorporating uncertainty) of the future evolution of the California energy system.

Critical Factors for Success:

- Empirical estimates of role and significance of ETC and LBD in California industries; application to integrated modeling and policy studies.

5.1.5 Information Technology and Energy Trends

A. Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.

Activities needed: (1) Apply the type of analysis sketched in the text—econometric studies of historical trends—to California (with appropriate technical enhancements of methods). (2) Conduct micro-level studies of the costs and benefits of IT energy-management tools to individual consumers and firms.

Critical Factors for Success:

- Understanding of the significance of IT in the California economy and its implications for future policies to abate GHGs in the state.

5.1.6 Revenue Recycling

A. Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.

Activities needed: (1) Enhance the DRAM (or E-DRAM) model described above as needed, to conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy. (2) Conduct a general equilibrium study at the scale of the statewide economy.

Critical Factors for Success:

- Estimates of the implications of appropriately designed revenue recycling policies for lowering the costs of GHG abatement in California.

5.1.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.

Activities needed: (1) Assess the GHG implications of current California air quality planning. (2) Develop an empirical basis for multi-gas strategies in climate change-related planning. (3) Formulate "harmonized strategies" for linked AQ and GHG abatement.

Critical Factors for Success:

- Successful design of integrated policies for achieving simultaneous air quality and GHG abatement goals in California.

5.1.8 Regional GHG Trading Markets

A. Assess the feasibility of intrastate markets for GHG trading and related mechanisms.

Activities needed: (1) Conduct a feasibility study of a California GHG "cap and trade" system, as well as of offset programs for various gases, and an initial design study for such systems.

Critical Factors for Success:

- An applicable assessment of the potential for intrastate trading markets, and completion of a preliminary design for one or more such markets.

5.1.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: (1) Theoretical research to extend current economic models to incorporate possible negative-cost abatement and to improve representation of cost reductions attributable to technological change.

Critical Factors for Success:

- Development of improved methods for modeling and measuring costs and benefits of non-CO_2 gases.

Table 1. Short-term Budget

Objective	Projected Cost ($000 per year)
5.1.1.A Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.	500
5.1.2.A Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change. Identify critical "thresholds" of natural and economic systems under such change. Develop models to incorporate existing institutional constraints on key systems. Begin assessment of non-market values of intrastate climate change impacts.	300
5.1.3.A Establish a solid theoretical and empirical body of research on energy-related decision making, using a behavioral economics approach.	300
5.1.4.A Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.	300
5.1.5.A Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.	150
5.1.6.A Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.	100
5.1.7.A Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies, and incorporate these estimates into state-economy-wide integrated assessments of mitigation.	200
5.1.8.A Assess the feasibility of intrastate markets for GHG trading and related mechanisms.	150
5.1.9.A Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.	150
Total Short-term Cost per Year	**2,100**

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 per-year expenditure over the short-term period.

5.2 Mid-term Objectives

5.2.1 Computational Modeling and Decision Analysis

A. **Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.**

Activities needed: (1) Continue the model and software development indicated in the short-term. (2) Link and expand the strands developed in the short-term to include more sectors, systems, and details.

5.2.2 Impacts and Adaptation Studies

A. **Extend sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change, and to incorporate institutional constraints. Continue assessment of non-market values of intrastate climate change impacts.**

Activities needed: (1) Continue, as needed, the short-term research. (2) Apply research results to empirical studies.

5.2.3 Behavioral Economics and Energy Efficiency Investment

A. **Establish a solid theoretical and empirical body of research on energy-related decision making using a behavioral economics approach.**

Activities needed: (1) Continue the short-term theoretical and empirical research. (2) Expand the short-term work to incorporate these models in a computational equilibrium setting.

5.2.4 Characteristics of Energy-related Technological Change

A. **Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.**

Activities needed: (1) Continue the short-term theoretical and empirical research. (2) Incorporate the short-term results into computational modeling of the costs and benefits of GHG abatement within California.

5.2.5 Information Technology and Energy Trends

A. **Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.**

Activities needed: (1) Extend the line of research developed in the short-term to determine the potential role of such technologies for designing and implementing large-scale GHG abatement.

5.2.6 Revenue Recycling

A. **Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.**

Activities needed: (1) Expand the short-term work to a more geographic-and-sector detailed analysis. Study both the micro-level details and impacts of potential revenue recycling schemes, as well as the possibility of micro-level applications of the revenue recycling ideal.

5.2.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. **Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies and incorporate these estimates into state-economy-wide integrated assessments of mitigation.**

Activities needed: (1) Continue as needed the research indicated in the short-term objectives. (2) Incorporate the short-term results into policy planning.

5.2.8 Regional GHG Trading Markets

A. Assess feasibility of intrastate markets for GHG trading and related mechanisms

Activities needed: Continuation of short-term work as needed, and begin implementation as appropriate.

5.2.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: Apply short-term results to empirical studies.

5.3 Long-term Objectives

5.3.1 Computational Modeling and Decision Analysis

A. **Develop and apply modeling, software, and computational tools to analyze multi-sector robust strategies under uncertainty for GHG mitigation and climate change adaptation in California.**

Activities needed: (1) Create, apply, and develop a multi-institution effort that includes universities, state agencies, and non-governmental organizations that will focus on computationally intensive decision-modeling of climate change mitigation and adaptation.

5.3.2 Impacts and Adaptation Studies

A. **Extend current sectoral impact/adaptation models to incorporate uncertainty and the possibility of rapid and/or severe climate change, and to incorporate institutional constraints. Continue assessment of non-market values of intrastate climate change impacts**

Activities needed: (1) Incorporate research results into policy planning.

5.3.3 Behavioral Economics and Energy Efficiency Investment

A. **Establish a solid theoretical and empirical body of research on energy-related decision making using a behavioral economics approach.**

Activities needed: (1) Fully include behavioral economic principles in computational energy-economic and integrated assessment models.

5.3.4 Characteristics of Energy-related Technological Change

A. **Empirically assess the role of endogenous technological change and learning effects on energy productivity in the California economy; develop or adapt a computational energy technology model to apply these results to integrated energy and climate policy planning.**

Activities needed: (1) Incorporate the short- and mid-term results into simulation modeling of the costs and benefits of GHG abatement within California.

5.3.5 Information Technology and Energy Trends

A. **Gain an empirical understanding of the recent, current, and potential future impacts of IT on energy trends in the California economy.**

Activities needed: (1) Continue to extend the short- and mid-term research to determine the potential role of such technologies for designing and implementing large-scale GHG abatement.

5.3.6 Revenue Recycling

A. **Conduct a full dynamic assessment of options for, and costs and benefits of, recycling of carbon revenues in the California economy.**

Activities needed: (1) Continue to expand this work to a more geographic-and-sector detailed analysis. That is, continue to study both the micro-level details and impacts of potential revenue recycling schemes, and the possibility of micro-level applications of the revenue recycling ideal.

5.3.7 Integrating Air Quality and Multi-gas GHG Abatement Strategies

A. **Formulate strategies for integrated air quality and GHG abatement policies in California. Estimate costs and benefits within the California economy of integrated, multi-gas GHG control policies and incorporate these estimates into state-economy-wide integrated assessments of mitigation.**

Activities needed: (1) Incorporate research results into policy planning.

5.3.8 Regional GHG Trading Markets

A. Assess feasibility of intrastate markets for GHG trading and related mechanisms.

Activities needed: (1) Implementation of research as appropriate.

5.3.9 GHG Abatement Cost Modeling for Non-CO_2 GHGs

A. Develop improved theoretical economic basis for estimating costs of non-CO_2 GHG abatement costs.

Activities needed: (1) Application of research results to policy planning.

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.

The research direction proposed in the roadmap represents something of a departure from well-established channels. With respect to drawing significant federal support, PIER funding of the suggested research should be considered "seed money." That is, successful execution, with PIER support, of the research topics proposed here is very likely to lead to new or intensified interest and support from other agencies.

Research on the economics and integrated assessment of climate change has been and continues to be funded by a variety of federal agencies, as well as by industry. Among the key public funding sources are the "Method and Models for Integrated Assessment" special program of the National Science Foundation (NSF), the core NSF Economics and Decision Sciences programs, and the "Integrated Assessment" program Office of Biological and Environmental Research in the Department of Energy. In addition, the U.S. Environmental Protection Agency provides support for certain research in this area. The other research areas discussed above are of a fundamental nature, and as such, receive support from the National Science Foundation in particular.

6.2 Opportunities

Co-sponsorship opportunities are likely with the National Science Foundation, the Office of Biological and Environmental Research in the Department of Energy, and with other programs under the auspices of the U.S. Global Change Research Program. No specific collaborative opportunities have been identified.

7. Areas Not Addressed by This Roadmap

This roadmap does not contain a recommended research area that is specific to the transportation sector. It should be noted, however, that several of the areas recommended for research bear directly or indirectly on transportation. More generally, transportation issues will have a prominent place in climate change mitigation and adaptation in California. It is assumed that implementation of work recommended in this roadmap will be articulated with ongoing research and policy work on transportation by the Energy Commission, other state agencies, academic institutions, and non-governmental organizations.

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Appendix A
Current Status of Programs

This section outlines those efforts that most closely address the economics of climate change mitigation and adaptation in California. It should be noted that research relating to the topics presented in this roadmap is under way at literally hundreds of sites around the world. This section provides a selected list focusing on academic departments, research centers, and other organizations rather than upon individual researchers. (Many of the latter are listed in the References and their work discussed in the text of the roadmap.)

Current Status: California

Environmental Defense, Washington, D.C.
Completed study of climate change impacts on Los Angeles and Southland.

Lawrence Berkeley National Laboratory
Ongoing work on technologies and measures for demand response and load management.

National Center for Ecological Analysis and Synthesis, University of California at Santa Barbara
Completed report on climate change impacts on California.

Rand, Santa Monica, California
Ongoing work on California energy, water, and environmental issues.

Current Status: Regional, National, and International

Department of Agricultural and Resource Economics, University of California at Berkeley
Ongoing basic and applied economic research on climate change, forestry, water resources, and agriculture.

Energy Technology Systems Analysis Programme (ETSAP), Petten, The Netherlands
Ongoing work on learning effects in energy technology diffusion and energy system modeling.[15]

EPRI, Palo Alto, California
Ongoing work on energy—including electricity sector technology and evolution—and on climate change impacts.

[15] ETSAP is a permanent program of the OECD International Energy Agency (IEA).

International Institute for Applied Systems Analysis, Vienna, Austria
Ongoing work on energy systems and technology and modeling under uncertainty.

Lawrence Berkeley National Laboratory
Ongoing work on energy aspects of information technology.

Office of Renewable Energy and Energy Efficiency, U. S. Department of Energy, Washington, D.C.
Ongoing work on learning curves in energy technology.

Rand, Santa Monica, California
Ongoing work on robust strategies for climate policy, agent-based modeling, and computer-assisted decision making.

Resources for the Future, Washington, D.C.
Ongoing work on climate economics, ancillary benefits of GHG mitigation, and technological change.

State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officials, Washington, D.C.
Completed report, as well as ongoing work, on "harmonized options" for air quality and GHG mitigation.

U.S. Global Climate Change Research Program (USGCRP)
Interagency coordinating program for research on all aspects of global climate change. Sponsoring entity for the U.S. National Assessment of the Potential Consequences of Climate Variability and Change.

Attachment VII

Glossary of Terms Used in the PIEREA Climate Change Research Plan and Roadmaps

Mark Wilson
Consultant

PIER Environmental Area

February 2003

Abiotic: Not living.

Acre-foot: An amount of water that covers an acre (43,560 ft^2) to a depth of one foot. An acre-foot is equal to 325,851 gallons, which is considered to be a year's supply for two families.

Additionality: A requirement (in the Kyoto Protocol) that a carbon sequestration project must be "additional to any that would otherwise occur" for it to be counted as carbon mitigation.

Afforestation: Planting trees in areas where trees have been absent in recent times.

Agroforestry: Planting and managing trees in conjunction with agricultural crops.

Albedo: The fraction of light that is reflected by an object.

Anaerobic Digester: A technology that processes manure and traps the methane produced by its decomposition for use as a fuel to produce electricity.

Aquifer: A water-bearing stratum of permeable rock, sand, or gravel.

Autotrophic: Being able to synthesize food from inorganic substances (e.g., from light or chemical energy).

Behavioral Economics: A discipline that links economics with psychology and other behavioral sciences in the study of decision making.

Biomass: Vegetative or animal wastes that can be used for energy generation.

Biome: A major ecological community type, such as a grassland or desert.

Biopower: Energy produced from biomass.

Bioregion: A geographic area that shares common soil, watershed, climate, vegetation, and animals.

Biotic: Related to living things.

Business-as Usual (BAU): Maintaining the status quo. Analyses that employ BAU scenarios assume that the factors examined will remain as they are at the time of the assessment.

CAFE Standards: Corporate Average Fuel Economy (CAFE) standards. Originally established by the Energy Policy and Conservation Act of 1975, these standards set a target fuel efficiency for automobiles.

Cap and Trade: A type of emissions-reduction policy wherein the quantity of a pollutant's emissions allowable in a certain region from regulated sources is limited, or "capped" at a quantity that is less than the historic amount for that region, in an effort to reduce emissions. Companies responsible for those emissions are given "allowances" to emit a certain quantity of that pollutant. Entities that emit less than their allotted quantity may trade them with those that emit more than their allotted share.

Carbon-based Residuals: Carbon-based residues such as wood and paper that are sent to landfills, but could be used as a biopower fuel source.

Carbon Dioxide (CO_2): A byproduct of the burning of fossil fuels and biomass. Carbon dioxide is a greenhouse gas that contributes to global warming.

Carbon Flux: The exchange of carbon between the Earth's water and land and the atmosphere.

Carbon Inventory: The amount of carbon emissions (releases) and sinks (captures) for a given area and/or ecosystem.

Carbon Monoxide (CO): Carbon monoxide is produced when hydrocarbon-based fuels are not burned completely. It inhibits the ability of blood to carry oxygen and is regulated as a criteria pollutant.

Carbon Sequestration: A method of keeping carbon emissions from reaching the atmosphere by capturing, isolating, and diverting them to secure storage, and/or to remove CO_2 from the atmosphere by various means and store it.

Carbon Sink: A terrestrial or aquatic repository for atmospheric carbon.

Chlorofluorocarbons: Otherwise known as *CFCs*, this family of chemical compounds are mostly used as refrigerants and industrial cleansers. When they rise into the stratosphere, they can break down the ozone layer, which protects the Earth from harmful radiation.

Clathrate: A compound found deep in oceans that contains methane. Destabilization of these clathrates could release great amounts of methane (a greenhouse gas) into the atmosphere.

Combined Heat and Power: A technology for generating power (usually electricity) and heat together, which uses the heat in industrial processes or for building heating. Sometimes referred to as *cogeneration.*

Command and Control: A type of regulatory emissions policy that details specific methods for reducing emissions, sometimes including the type of technology that must be used.

Computable General Equilibrium Paradigm: A common economic model that does not take account of uncertainty. This paradigm assumes perfect knowledge of the present and future values of all included variables and parameters.

Conservation Tillage: Soil tillage practices such as minimum tillage, mulch tillage, ridge tillage, and no-till, which reduce erosion and soil loss and help retain carbon in the soil.

Contingent Valuation: A set of methods for estimating consumer preferences for goods or services in markets that do not yet exist.

Coppicing: The practice of cutting a tree or bush near the ground to promote the generation of more sprouts.

Criteria Pollutants: Air pollutants chosen for inclusion in the Clean Air Act Amendments and regulated under National Ambient Air Quality Standards (NAAQS). They include: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), Volatile Organic Compounds (VOCs), particulate matter (PM), carbon monoxide (CO), and lead (Pb).

Depth-duration-frequency Data: Data on the amount, duration, and frequency of precipitation in an area. These data are used for water planning.

Deterministic: Modeling or analysis that assumes perfect knowledge of the present and future values of all included variables and parameters.

Distributed Generation: Electricity generation at or near the place it is used. DG technologies can include such diverse technologies as microturbines, photovoltaic modules, or fuel cells.

Disturbance Regime: The dynamics of disturbances (such as fires) in an area over a long period of time.

Domain: In modeling, the area which is being modeled.

Downscaling: Applying data gathered and/or aggregated at a large scale to a smaller-scale assessment, such as to examine the effects on a single air basin.

Dynamical Model: There are two meanings of dynamical (or *dynamic*) in the context of economic modeling: (1) A *dynamic model* represents the economy over a period of years or decades. The paths of variables such as prices and quantities are represented as they change over time, in contrast to a static model that represents a market or an economy only at one point in time. (2) In another context, *dynamic model* also refers to a type of model that incorporates taxation and fiscal policy into its analysis. In this context, the term *dynamic* means that both direct and indirect effects of taxes are represented in a model. For example, the government-levied tax will result in a certain quantity of revenue being raised (the direct effect). However, it will also (in general) result in indirect changes in consumers' and firms' choices regarding consumption, employment, and investment.

Ecological Indicator: A key attribute of an ecosystem that is used to gauge the health of the whole ecosystem.

Econometric: A type of economic analysis that applies economic theory and statistical methods to develop mathematical estimates of economic relationships. Econometric analyses are used to determine the accuracy of modeled data, when compared to observed data.

Ecosystem: A group of organisms that interact with each other and their physical environment.

El Niño-Southern Oscillation: El Niño is a warming of the surface layers in the eastern and central equatorial Pacific Ocean that happens about once every three or four years. This warming is accompanied by swings in the Southern Oscillation (SO), an interannual see-saw in tropical sea level pressure between the eastern and western hemispheres. The combination of these effects can create extreme disruptions of normal weather patterns.

Emissions trading: A market-based method of reducing emissions. It allows entities that reduce emissions in one source below a specified amount to use or trade that excess amount to offset emissions from another source. Emissions trading is recognized by the Kyoto Protocol.

Endogenous Technological Change: Technological change brought about by changes in prices or policy variables.

Energy-to-GDP Ratio: A measure of energy intensity—essentially, the amount of energy needed to produce products.

ETo: Reference evapotranspiration. A measure of the amount of water evaporated and transpired by well-maintained, well-watered turf grass. This amount is measured weekly in California at various California Irrigation Management Information System (CIMIS) facilities throughout the state.

Evapotranspiration: Water loss from a combination of evaporation from the soil and transpiration from vegetation.

Expected Utility Maximization: The standard economic model of rational behavior.

Feebate: In emissions terminology, a fee levied on polluters to create a pool that will fund rebates to those that pollute less.

Fluvial: Relating to or living in a stream or river.

Frozen Efficiency Forecast: An analysis that looks at energy use over time with the assumption that energy efficiency will not change from its current status.

Gasification: The process of producing a gaseous fuel from a non-gaseous substance.

Generation Mix: A set of technologies used to generate electricity.

Geographic Information Systems (GIS): A computer system capable of assembling, storing, manipulating, and displaying geographically referenced information, i.e. data identified according to their locations. Practitioners also regard the total GIS as including operating personnel and the data that go into the system.[1]

Global Climate Model/General Circulation Model: A global, three-dimensional computer model of the climate system which can be used to simulate human-induced climate change. GCMs are highly complex and they represent the effects of such factors as reflective and absorptive properties of atmospheric water vapor, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans, and land surface.[2]

Global Positioning System: A system that can determine a precise location on the Earth, based on satellite data.

Global Warming Potential: An index that describes the radiative characteristics of greenhouse gases. It presents the combined effect of: (1) the time that these gases remain in the atmosphere, and (2) their relative effectiveness in absorbing outgoing infrared radiation (which increases global warming).[3]

Greenhouse Gases: Gases that contribute to the greenhouse effect (which causes global warming). The primary GHGs are: water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), ozone (O_3), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs)

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[1] USGS. (www.usgs.gov/research/gis/title.html).
[2] USEPA. *Inventory of GHG Emissions and Sinks 1990–1999.* Annex W. Glossary. (www.epa.gov/globalwarming/publications/emissions/us2001/annex-w.pdf).
[3] Adapted from *Climate Change 2001. Synthesis Report.* Edited by Robert Watson and the Core Writing Team. Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Annex B. Glossary of Terms. (www.ipcc.ch/pub/gloss.htm).

Gross State Product: The market value of all the goods and services produced in a state in a year, which acts as a measure of the state's economic activity.

Herbivory: Consumption of living plant material.

Hydrofluorocarbons (HFCs): Greenhouse gases produced for use as a refrigerant or in manufacturing.

Hydrograph: A graph showing the variation of water flow over time.

Hydrological: Having to do with the study of water on the Earth and its atmosphere.

Hyperbolic Discounting: Discount rates that increase as the time horizon grows shorter.

Integrated Assessment Model: IA models model the causes and effects of a specific issue and how that issue affects and is affected by other factors.

Integrated Resource Planning: A public planning process and framework within which the costs and benefits of both demand- and supply-side resources are evaluated to develop the least-total-cost mix of utility resource options. In many states, IRP includes a means for considering environmental damages caused by electricity supply/transmission and identifying cost-effective energy efficiency and renewable energy alternatives.[4]

International Terrestrial Reference Frame: An set of reference points on the Earth that are used to measure, in coordination with a Celestial Reference Frame in space, changes on the Earth's surface, such as sea level rise.

Invasive Species: Non-native species that can threaten species, ecosystems, or habitats.

Knightian Uncertainty: Also known as *deep uncertainty*. A type of uncertainty in economic analysis wherein values of fundamental quantities are not merely unknown, but also cannot plausibly be assigned probability distributions.

Leakage: In carbon sequestration scenarios, the loss of overall sequestration benefits attributable to displacement. Leakage occurs if success in protecting or increasing carbon in one location hastens the release of carbon elsewhere.

Life-cycle Assessment: An analytical method of identifying, quantifying, and assessing the environmental aspects of a product, process, or activity throughout its life.

Loss Aversion: The asymmetric weighting of gains and losses with respect to a neutral reference point.

Lysimeter: A device that measures water percolation through soil.

Macroeconomics: The study of the national economy as a whole.

[4] California Energy Commission. Energy Glossary. (http://www.energy.ca.gov/glossary/).

Marginal Abatement Curve (MAC): An MAC shows the marginal cost of reducing an emission as compared with the marginal amount of reduction obtained. The MAC is derived by rank ordering individual emission reduction opportunities by cost per emission reduction amount. The curve is usually intended to capture the full set of all available abatement options. Any point along a MAC represents the marginal cost of abating an additional amount of an emission.[5]

Methane (CH_4): A hydrocarbon and greenhouse gas that is produced from a variety of natural and human sources, most notably from the decomposition of organic matter.

Microclimate: An area that has a different environmental conditions than those within its surrounding climatic zone.

Microeconomics: The study of the components of the national economy.

Mitigation: To alleviate the harmful effects of something. In terms of climate change, to enact policies or conduct projects to reduce greenhouse gas emissions.

Monetization: To establish something as legal tender.

Net Metering: A method of tracking electricity use and generation through the same meter. Used for small distributed generation technologies such as photovoltaic modules on homes, the meter runs forwards when users are drawing electricity from the grid and backwards when the unit is contributing electricity to the grid.

Nitrogen Oxides (NO_X): Various oxides of nitrogen, most notably nitrogen dioxide (NO_2), which is produced by fossil fuel combustion and contributes to smog, acid rain, and eutrophication of water bodies.

Nitrous Oxide (N_2O): A greenhouse gas produced by certain agricultural practices and fossil fuel combustion.

Orography: The study of the physical geometry of mountains and mountain ranges.

Ozone (O_3): A form of oxygen that acts as a greenhouse gas in the troposphere (the lowest layer of the Earth's atmosphere) and as protective shield from harmful ultraviolet-B radiation in the stratosphere.

Pacific Decadal Oscillation: An El Niño-like pattern of Pacific climate variability that can persist for 20 to 30 years.

Paleoclimatic Data: Data that indicates climatic conditions in the geological past.

Paleontological Data: Data from past geological periods.

Particulate Matter (PM): Airborne particles or droplets from emissions that can be inhaled and lodged in the lungs. PM is regulated as a criteria pollutant.

Pathogen: The causative agent of a disease.

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5 Adapted from Environmental Protection Agency (EPA). 2001. *U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions.* EPA 000-F-97-000. Washington, D.C. U.S. Environmental Protection Agency.

Perfluorocarbons (PFCs): Greenhouse gases produced as refrigerants or as byproducts of industrial processes.

Permanence: For carbon sequestration, whether or not the carbon stored at the time of a trading agreement will continue to be stored in the future.

Photochemical Model: A computer model used to predict ambient air quality.

Probable Maximum Flood: The largest flood believed to be meteorologically possible in a region.

Radiative Forcing: The change in the balance between radiation coming into the atmosphere and the radiation going out.[6]

Regional Climate Model: A computer model capable of modeling potential climate changes in a small, focused region.

Renewable Energy Production Tax Credit: A tax credit given to renewable energy producers for generating power with specified renewable technologies. The RETC is used as an economic incentive for power producers to generate electricity from cleaner sources.

Renewable Portfolio Standard: A rule that establishes the percentage amount of renewable energy that a state must use by a certain date. California's RPS requires all electricity retailers to increase their use of wind, geothermal, biomass, and solar technologies by 1% per year until they reach 20% (by 2017).

Roadmap: A document that outlines a series of specific steps or activities necessary to reach a goal.

Regional Climate Model: A computer program capable of modeling potential regional climate, given a specific set of data and criteria.

Revenue Recycling: The return of revenues from programs such as carbon taxes and tradable emissions permit systems back into the economy, to offset other distortionary taxes.

Soil Organic Carbon: Also known as *humus.* Partially decomposed plant or animal matter that makes up the organic part of the soil.

Standard Industrial Classification: A four-digit code that identifies a company's type of business.

Statistical Model: A model that uses statistics obtained from observed data. Also known as an *empirical model.*

Stochastic: Something characterized by chance, probability, or randomness.

Substrate: A surface on which an organism lives.

Sulfur Hexafluoride (SF_6): A potent greenhouse gas that is used as an industrial insulator and coolant.

[6] UNEP. Introduction to Climate Change. http://www.grida.no/climate/vital/04.htm

Sulfur Oxides (SO_X): Various oxides of sulfur—most notably, sulfur dioxide (SO_2), which is produced by burning high-sulfur fossil fuels such as coal. SO_2 can cause acid rain and respiratory problems. When oxidized into sulfate aerosols, it can cause negative radiative forcing, cooling the Earth's surface.

Supply Curve: A method for graphically displaying the cost and availability of a resource or other market good.

Thermohaline Circulation: The global circulation of oceanic water temperature and salinity. A disruption of this circulation (which could occur as a result of global warming) could affect climate and oceanic ecosystems worldwide.

Tons of Carbon Equivalent (TCE): A measure for global warming potential gases. TCE indicates the potency of a greenhouse gas, when compared to that of carbon (which is used as a baseline measurement, with a value of "1").

Total Maximum Daily Load (TMDL): TMDLs are the maximum daily amount of a pollutant that can be released into a specified water body. TMDLs were established by the Clean Water Act and apply to water bodies that have been identified as needing remediation.

Transition Zone (Water): A geographic area where the characteristics of a region gradually blend into those of an adjoining region.

Trophic: Related to food relationship of organisms in a food chain.

UV-B Radiation: Ultraviolet radiation that is normally blocked from the Earth by the ozone layer. UV-B radiation contributes to skin cancer and various environmental impacts.

Variabilization Policy: A policy of charging a surcharge on a product or service based on the amount of that product or service used. For example, annual payments of a gasoline tax would cost more for the driver of an inefficient vehicle than they would for the driver of a more efficient vehicle, because the vehicle would need more gas.

Volatile Organic Compounds (VOCs): Organic compounds that evaporate readily into the atmosphere at normal temperatures. VOCs contribute significantly to photochemical smog production and certain health problems.[7] They are regulated as a criteria pollutant.

Watershed: The land area that drains to a local water body.

[7] USEPA. *Inventory of GHG Emissions and Sinks 1990–1999.* Annex W. Glossary. (www.epa.gov/globalwarming/publications/emissions/us2001/annex-w.pdf).