CALIFORNIA
ENERGY
COMMISSION

Public Interest Energy Research Program
Research Development and Demonstration Plan

Attachment IV - Carbon Sequestration in California's Terrestrial Ecosystems and Geological Formations

Contractor/Consultant Report

April 2003
P500-03-025FAIV

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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Contract No. 700-99-019

Acknowledgements

The authors and PIER would like to thank Dr. Richard R. Harris, who prepared earlier drafts on which this chapter was based, as well as those reviewers who provided information and assistance with those drafts:

- Dr. John Harte, Professor, University of California at Berkeley
- Dr. William Horwath, Associate Professor, University of California at Davis
- Dr. Connie Millar, Research Scientist, USDA-Forest Service, Pacific Southwest Experiment Station
- Gary Nakamura, Cooperative Extension Forestry Specialist, University of California, Redding
- Dr. Ye Qi, Assistant Professor, University of California at Berkeley
- Dr. Richard Standiford, Associate Dean for Forestry, University of California at Berkeley
- Dr. William Stewart, Staff Chief, California Department of Forestry and Fire Protection
- Laurie Wayburn, President, Pacific Forest Trust
- Dr. David Zilberman, Professor and Director of the Center for Sustainable Development, University of California at Berkeley

The authors would also like to thank the following individuals for their invaluable help in the preparation of this document:

- George Bluhm, California Department of Food and Agriculture
- Kate Scow, The Kearney Foundation of Soil Science
- Doug Wickizer, California Department of Forestry and Fire Protection

Contents

Tables

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

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[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 nonindustrial 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).

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[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.

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[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).

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[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

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[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.