Summary: Mechanisms Controlling Annual, Interannual, and Decadal Changes in California's Carbon Budget

We propose a large interdisciplinary study to better quantify and understand California's Carbon budget. We will focus on six issues.

How much carbon is released and taken up by California? We will collect field data (eddy covariance, biomass, ANPP, LAI, C^{14}), analyze remote-sensing images (ETM+, MODIS), assemble existing data (fire history, land and energy use), develop mechanistic models (ISOLSM, CASA), and build and run a data analysis framework that will produce carbon budgets for California. The budgets will include the sources and sinks associated with natural ecosystems, agriculture, and fossil fuel combustion. The budgets will be spatially resolved for the state, and will include the hourly, daily, seasonal, annual and interannual carbon exchanges from March 2000 to December 2007.

How much confidence should we have in our C budgets? We will estimate uncertainties for the input data by comparison with independent data. We will propagate these uncertainties by Monte Carlo simulation to determine confidence intervals for the budgets. We will also test the budgets by comparing the regional pattern of atmospheric CO_2 and CO concentration predicted from the budgets with observed CO_2 and CO concentrations.

How do our results compare with previous budgets? The Environmental Protection Agency (EPA) has created annual C budgets for the US since 1997 for reporting to the United Nations Framework Convention on Climate Change. These budgets overlap markedly with the NACP's goals. We will compare our results for California with budgets that were created by the California Energy Commission (CEC) using the EPA protocol. Our focus on mechanistic controls, and on the C exchanges at a range of time scales, goes well beyond the EPA's and CEC's scope. Nonetheless, we feel it is important to relate our results to the EPA's and CEC's parallel efforts.

How much, and why, does California's carbon balance vary from year to year? We will use our budgets to quantify the year-to-year differences in California's CO_2 exchange. We will consider the importance of interannual precipitation variability, fire emission, recovery from disturbance (fire, logging, and disease), stand thickening with fire suppression, land-use change, and agriculture. We hypothesize that variability in climate and fire cause large year-to-year differences in CO_2 exchange by California's ecosystems.

What processes control the CO_2 concentration of air leaving California? We will use our budgets and an atmospheric tracer model (MM5) to explore the effects of the various carbon sources and sinks on the atmosphere's CO_2 concentration. We will partition the enrichment or depletion of CO_2 in air leaving California into the effects of fossil fuel emission and the exchanges with short-lived and long-lived ecosystem pools. We hypothesize that the imprint of exchanges with short-lived ecosystem pools (sugars, leaves, fine roots) and fossil fuel emissions dominate the regional patterns of CO_2 concentration. As a result, inversions of regional CO_2 concentration are unlikely to provide much information about carbon uptake by long-lived pools (wood, soil).

Where do California's CO_2 emissions go? We will use the tracer model to determine how California's carbon exchanges affect the concentration of CO_2 at larger scales. We will focus on better understanding the magnitude, composition, and flow direction of the carbon-enriched (or depleted) plumes of air originating from California's cities and ecosystems. We will determine whether covariances between extreme events (e.g., fires) and circulation (e.g., strong offshore flow during Santa Ana winds) decouple some components of California's carbon budget from the North American air mass.

I. Overall Objectives

We propose a large interdisciplinary field study to better quantify and understand California's Carbon budget. Our premise is that environmental scientists spent much of the last decade collecting the key puzzle pieces required to develop regional budgets, and that interdisciplinary groups of scientists now need to work together to assemble and understand the puzzles. Our research will address six overarching issues (Box 1).

Issue 1. How much carbon is released and taken up by California?

We will work as a team to collect field data, analyze remote-sensing observations, assemble existing data sets, develop mechanistic models, and build and run a data analysis framework that will produce a series of carbon budgets for the entire state of California. Our carbon budgets will incorporate all of the sources and sinks that are considered important, including those associated with natural ecosystems, agriculture, and fossil fuel combustion. The budgets will be spatially resolved for the entire state, and will include the hourly, daily, seasonal, annual and interannual carbon exchanges from March 2000 to December 2007. The budgets will be determined using a bottom-up approach that combines land-surface modeling with information from inventories of ecosystem stocks, in-situ observations, remote sensing measures of land use and ecosystem state, fire and land use histories, fire emissions, agricultural statistics, and fossil fuels emissions and energy use statistics.

Box 1 Overarching Research Issues

Issue 1. How much carbon is released and taken up by California?	We will develop bottom-up budgets of California's CO_2 exchanges for 2000 to 2007. We will quantify, and determine the relative importance of, the important process contributing to California's Carbon balance, including fossil fuel emissions, and agriculture and natural ecosystem exchanges.
Issue 2. How much confidence should we have in our carbon budgets?	We will use two approaches to quantify the uncertainty of our budgets. We will estimate the uncertainties of the input data sets by comparison with independent data sets. We will then propagate these uncertainties by Monte Carlo simulation, and use the results to determine confidence intervals for the C budgets. We will also test the budgets by comparing the regional pattern of atmospheric CO_2 concentration predicted from the budgets with observations of actual CO_2 concentration.
Issue 3. How do our carbon budgets compare with previous budgets?	The best available carbon budget for California was produced by the California Energy Commission (CEC) for 1990 to 1999. The CEC budget was produced using the same methods that have been used since 1997 by the EPA to produce annual budgets for the US. We will compare our results with the CEC budget, and use this comparison to better understand the strengths and weakness of the two approaches.
Issue 4. How much, and why, does California's carbon balance vary from year to year?	We will use our budgets to quantify the year-to-year differences in whole-state CO_2 exchange. We expect that energy use statistics will reveal that fossil fuel emission is fairly steady, while remote sensing, and climate and fire records reveal large interannual variation in CO_2 exchange by natural and agricultural ecosystems.
Issue 5. What processes control the CO_2 concentration of air leaving California?	We will use the budgets and an atmospheric tracer model to explore the effects of the various carbon source and sinks on the atmosphere's CO_2 concentration. We will partition the enrichment or depletion of CO_2 in the air leaving California into the effects of fossil fuel emission and exchanges with short-lived and long-lived ecosystem pools.
Issue 6. Where does the CO_2 emitted by California go?	We will use an atmospheric tracer model to determine how California's carbon exchanges affect the concentration of CO_2 at larger spatial scales. We suspect that an important fraction of the CO_2 exchanged by California is transported to the south or west, bypassing North America.

Issue 2. How much confidence should we have in our carbon budgets?

We will use two approaches to quantify the uncertainty of our budgets. We will estimate the uncertainty of the various input data sets by comparison with other, independent data sets. We will then propagate these errors using Monte Carlo simulations to calculate uncertainties for our carbon budgets. We will also test the budgets by comparing the regional patterns of atmospheric CO_2 concentration that are predicted from the budgets with observations. The Monte Carlo sensitivity analysis will identify weaknesses in budget inputs, and will allow us to focus our efforts on the inputs and terms that cause the most uncertainty. The comparison of measured and predicted atmospheric concentrations will test the overall enterprise, including the temporally and spatially resolved carbon budgets and our atmospheric transport model. A finding that predicted atmospheric concentrations agree with measured concentrations will increase confidence in the budgets and model. A finding of large biases between predicted and measured concentrations will be diagnosed to indicate weaknesses in the budgets and transport model. The combination of the bottom-up Monte Carlo approach and the comparison of predicted and measured atmospheric CO_2 concentration will allow us to attach defensible confidence intervals to all budget components.

General Theme. Temporal scale is central to understanding regional carbon budgets.

The NACP calls for an improved ability to scale information across spatial and temporal scales. We believe an improved appreciation of the importance of temporal scale is critical to understanding regional carbon balance. Temporal scaling presents a major challenge because the storage of carbon in long-lived plant and soil pools is not a simple linear combination of the processes that control carbon exchange at short temporal scale. Ecosystems contain carbon pools that differ in turnover time (e.g., Century; Parton et al. 1987). Most of the CO_2 exchanged by an ecosystem cycles in and out of very short-lived (plant sugars) and short-lived (leaf and other fine structural material) pools. In contrast, a much smaller fraction of assimilated CO_2 makes its way into the long-lived pools (wood and stable soil organic material) that contribute to ecosystem carbon storage. Different processes control the input of carbon to these various pools. The input of carbon to shorter-lived pools is controlled by the interactions between weather and leaf photosynthesis and respiration. The input of carbon to long-lived pools is controlled by interactions between climate, disturbance, biotic competition, plant functional type and life history strategy, and soil carbon stabilization. Analyses that try to predict the input of carbon to a long-term pool based entirely on the processes that control the inputs of carbon to a shorter-term pool are prone to transposition of scale errors (O’Neill et al. 1986).

The observation techniques favored by different disciplines are sensitive to the exchanges of different pools. Sequential inventories, such as the Forest Inventory Analysis (FIA), are most sensitive to the exchange of carbon in and out of long-lived pools. Measurements of land-surface CO_2 exchange are most sensitive to fluxes in and out of shorter-lived pools. Long-term gas exchange integrals may provide some information about the flux into long-lived pools, but these measures are very uncertain since they are the small residuals of much larger fluxes. Care needs to be taken when comparing the results of techniques that probe the exchange of carbon into and out of shorter-lived pools with the results of techniques that probe the exchanges of carbon into and out of long-lived pools; in many cases the techniques are measuring different things.

We will explicitly incorporate the concept of temporal scale into our experimental design. We will use a suite of models and measurement techniques that probe processes and storage pools across a range of time scales. We will use ISOLSM, a land surface model that predicts photosynthesis and respiration and is useful for determining the exchanges with faster-turnover pools, and CASA, a biogeochemical model that predicts NPP and decomposition and is useful for determining the exchanges with slower-turnover pools. We will combine the two model's results to produce pool-resolved carbon exchange budgets for California. These budgets will be spatially and temporally resolved, and will include separate information on the exchanges of carbon with very fast-, fast-, and slow-turnover pools. We expect to find significant differences in the carbon budgets at different time scales, and will put considerable effort into understanding the role of temporal scale.

Issue 3. How do our carbon budgets compare with previous budgets?

The EPA (EPA-GHG 2004), along with various state agencies (California Energy Commission (CEC) 2002), have already created a series of detailed carbon budgets for reporting to the United Nations Framework Convention on Climate Change. These budgets overlap markedly with the NACP's goals, and, at a minimum, should be used as a starting point for NACP research. The EPA budgets emphasize changes in long-lived carbon pools. Carbon storage by natural land is calculated largely from the FIA sequential inventories (Birdsey and Lewis 2003), which are done at 5- to 15-year intervals and focus on long-lived carbon stocks. The EPA and FIA budgets are appropriate for quantifying the long-term changes in carbon stocks (decadal) emphasized by the Framework, but less appropriate for issues related to shorter term exchanges (daily to interannual). We will construct budgets at a range of time scales, and will use the ISOLSM and CASA models to partition the whole-ecosystem exchanges of CO_2 into the component exchanges with very fast-, fast- and slow-turnover pools. We hypothesize that the CEC and EPA budgets provide reliable measures of the carbon exchanges with long-term pools (decadal and longer). Such a finding would confirm that these existing budgets provide good measures of the long-term sinks emphasized by the Framework. Our focus on mechanistic controls, and on the C exchanges at a range of time scales (daily to decadal), goes well beyond the EPA's and CEC's scope. Nonetheless, it is important to relate our results to the EPA's and CEC's parallel efforts.

Issue 4. How much, and why, does California's carbon balance vary from year to year?

The EPA approach ignores the exchanges of carbon with faster turnover pools, and we predict that the interannual patterns of CO_2 exchange reported by the CEC will differ markedly from the interannual patterns in our budgets. We hypothesize that California's natural and agricultural ecosystems drive large seasonal and interannual variation in California's carbon budgets via processes that are not considered in the EPA approach. We will use our budgets, models, and observations to quantify the relative importance of the following processes.

Interannual precipitation. California experiences large year-to-year shifts in precipitation associated with the El Nino Southern Oscillation. How does precipitation variation affect carbon exchange by California's natural ecosystems? How does variation in the Western US snowpack and area of irrigated cropland affect California's carbon budget?

Fire emissions. Many of California's ecosystems burn frequently. The annual area burned fluctuates markedly from year to year. How does year-to-year variation in area burned and fire emission affect California's carbon budget?

Disturbance recovery. Ecosystems accumulate carbon as they recover from past disturbance. Large regions of shrubland may act as strong carbon sinks as they recover from past fire. How much carbon is accumulating in recovering ecosystems?

Forest mortality. Many forests in California are experiencing significant mortality from insects and other emerging threats such as Sudden Oak Death. The mountains in Southern California have been particularly hard hit, with 20 to 50% mortality among old growth Ponderosa Pine stands. How do pests affect California's carbon budget?

Stand thickening. Stand thickening with fire suppression is one of the largest hypothesized carbon sinks in North America (Hurtt et al 2002, Houghton et al. 2000). Fire suppression has shifted the structure of California's forests, decreasing the number of large trees and markedly increasing the number of small trees (Minnich et al. 1995, Barbour and Billings 2000). Has stand thickening caused long-term changes in carbon storage in California? Does a forest with many small trees really contain more carbon than a forest with a few large trees?

Issue 5. What processes control the CO_2 concentration of air leaving California?

One of the NACP's goals is to use a top-down approach to quantify North America's carbon balance (Fan et al. 1998, Sarmiento and Wofsy 1999, Wofsy and Harriss 2002, Gerbig et al. 2003, Lin et al. 2003). The largest-scale top-down approach relies on observations of the atmosphere's composition entering and leaving North America, while other approaches will use aircraft measurements to characterize regional exchange. It is important to realize that the top-down approach, like all other approaches, is most sensitive to the exchanges of CO_2 at certain time scales and comparatively insensitive to the exchanges of CO_2 at other time scales. In particular, we hypothesize that the imprint of exchanges with shorter-lived pools (metabolic pools and fine tissues) dominates the CO_2 gradients across California and North America, and that analyses of longitudinal CO_2 gradients are much less useful for quantifying the exchange of carbon with long-lived pools.

The timescale of atmospheric mixing helps determine which carbon exchange processes exert the greatest influence on concentration gradients. The atmosphere mixes rapidly within latitudinal zones and slowly across latitudinal zones. Latitudinal gradients therefore contain a great deal of information about the seasonal and annual patterns of CO_2 exchange (Fung et al. 1987, Tans et al. 1990). In contrast, the atmosphere's transit time across California or North America is short, and the associated CO_2 concentration variations will be determined primarily by exchanges with faster-turnover pools. We will use our budgets and the tracer model to partition the predicted CO_2 gradient across California into exchanges with pools of different lifetimes. We predict that the gradient across California is determined mainly by fossil fuel emissions and the day-to-day patterns of agriculture and natural ecosystem exchange. We will make additional tracer runs assuming progressively larger sinks in long-term carbon pools to determine the minimum long-term sink that could be resolved by analyses of longitudinal gradients.

Fig. 1 Smoke from Southern CA fires, 2003/10/26. Extreme fires covary with unusual atmospheric circulation (Santa Ana winds from the east), sweeping the combusted CO_2 away from North America. Terra MODIS image from Goddard Space Flight Center Scientific Visualization Studio.

Issue 6. Where does the CO_2 emitted by California go?

A weakness in the large-scale top-down approach is uncertainty over the trajectory of CO_2 out of North America. In particular, covariances between carbon exchange and atmospheric transport may confound the strategy (Denning et al 1995). We hypothesize that covariances partially decouple California's carbon sources from the broader atmospheric circulation, and that a significant fraction of the CO_2 emitted by California bypasses the US. We will use an atmospheric tracer model to track the CO_2 enriched and depleted plumes of air leaving California, with an emphasis on determined the importance of the following phenomena.

Fire weather. Most California fires occur during brief periods with unusual meteorological conditions (Fig. 1). Santa Ana winds originate from the east, resulting in the transport of combusted CO_2 to the west. To what extent does this covariance decouple the carbon emitted by fires in California from the North American air mass?

Seasonal and diel. Atmospheric circulation in California varies seasonally and diurnally, with increased offshore flow at night and in the winter (CARB 1984). To what extent does this covariance decouple California's respiratory carbon losses from North America's air mass?

Spatial patterns. California's carbon sources are concentrated in Southern California and near the coast; California's carbon sinks are concentrated in Northern California and inland (Fig. 3, 5). California's mean circulation is from north to south along the coast and from west to east inland (CARB 1984). Much of the air that passes over California's coastal cities probably exits to Mexico; much of the air that passes over inland forest and agriculture probably exits to Arizona and Nevada. To what extent does this covariance decouple California's carbon sources from the North American air mass?

II. Rationale

The need to better quantify North America's carbon budget has been discussed in a series of planning documents and is the focus of the NACP and the *Carbon Cycle Science Research Announcement* (Moore et al. 1999, Sarmiento and Wofsy 1999, Mahoney et al. 2003, Wofsy and Harriss 2002, NRA-040OES-01). We will concentrate in this section on establishing the motivation for a regional field study in California.

The need for regional field studies.

A key rationale for the NACP is to provide decision-makers and stake holders with information on the state of the US carbon cycle (Wofsy and Harriss 2002, Mahoney et al. 2003, SOCCR Terms of Reference). The NACP will be judged by the reliability, consistency and relevance of the *State of the Carbon Cycle Reports (SOCCRs)*, underlining the need for the NACP to deliver on its stated objectives.

We believe regional field studies are critical to meeting these objectives. Regional studies will allow researchers to focus initially on smaller, better-constrained, and more tractable areas as they build the understanding, methodology, and tools required to determine North America's carbon budget. Regional studies will allow researchers to begin assembling the geographic pieces of a continental carbon budget. Regional studies will provide significant information on individual regions for use in early SOCCRs. Regional studies will also provide information that can be combined with information from other regions to calculate continental budgets for use in later SOCCRs. Regional studies will allow researchers to simultaneously apply multiple independent techniques to selected aspects of the carbon cycle. Comparisons between independent measures will allow researchers to test their understanding, and to establish the reliability and uncertainty of their carbon budgets.

Why focus on California?

Both California and the United States are complex and spatially heterogeneous, with a number of processes that contribute significantly to carbon exchange, a wide range of land cover types, and a wide range of natural ecosystems (Fig. 1, 3, 5). California’s carbon budget includes a mix of combustion sources and ecosystem sinks that broadly parallels the mix for the entire US (CEC 2002, EPA-GHG 2004). California includes a mix of developed land, forestland, rangeland, cropland, shrubland, and grassland that broadly parallels the mix for the entire US (USDA NRI statistics for 2001, NLCD summary statistics). Achieving our goal of quantifying California’s Carbon budget will force us to deal with this complexity and heterogeneity. Likewise, achieving the NACP’s overall goal of quantifying North America’s Carbon budget will force the NACP to deal with this complexity and heterogeneity. Many of the initial NACP projects will likely focus on areas that are comparatively homogenous and where the CO_2 fluxes are dominated by just one process (for example, the fixation of carbon into shorter-lived pools by agriculture in the upper Midwest). This is a reasonable starting point, provided that parallel efforts target complex and spatially heterogeneous areas that are more representative of the United States as a whole.

Our goal of quantifying California’s carbon budget would be unrealistic if not for the availability of a large number of existing data sets characterizing California’s environment. The State of California, the Federal Government, and individual researchers have done an excellent job monitoring California’s environment, producing many high quality spatially-resolved data sets. For example, extensive information on the state of California’s wildlands is available since the 1930s (Weislander 1935, Weislander and Jensen 1946, Bolsinger 1988, 1989, Colwell 1995). Existing data sets will play a key role in our analysis, even though most were developed originally to address environmental issues that are not directly related to carbon cycle science (e.g., air pollution, water resources, land management). Of critical importance is the California Energy Commission’s carbon budget (CEC 2002). California is one of only 10 states that have completed their budgets using the EPA protocols (see the EPA website; national inventories are available back to 1997, but just a handful of states have finished their recent budgets). These state and federal budgets overlap markedly with the NACP’s objectives, and the CEC budget serves as the starting point for our research. We believe the need to begin grappling with complex and spatially heterogeneous regions, combined with the ready availability of a number of essential data sets, makes California a natural choice for a regional field study.

III. Methods: Bottom-up determination of California's carbon budgets

Our bottom-up budgets will consider the three main sources and sinks of carbon: (a) natural lands, (b) agriculture, and (c) fossil fuel combustion. Our overall approach is summarized in Figure 2.

A. Natural lands

Objectives, Rationale, and State of the art

Our goal is to develop spatially-gridded, temporally-resolved information on the net exchanges of CO_2 by California's natural ecosystems from 2000 to 2007. Both California and the United States have large areas of natural vegetation that may act as

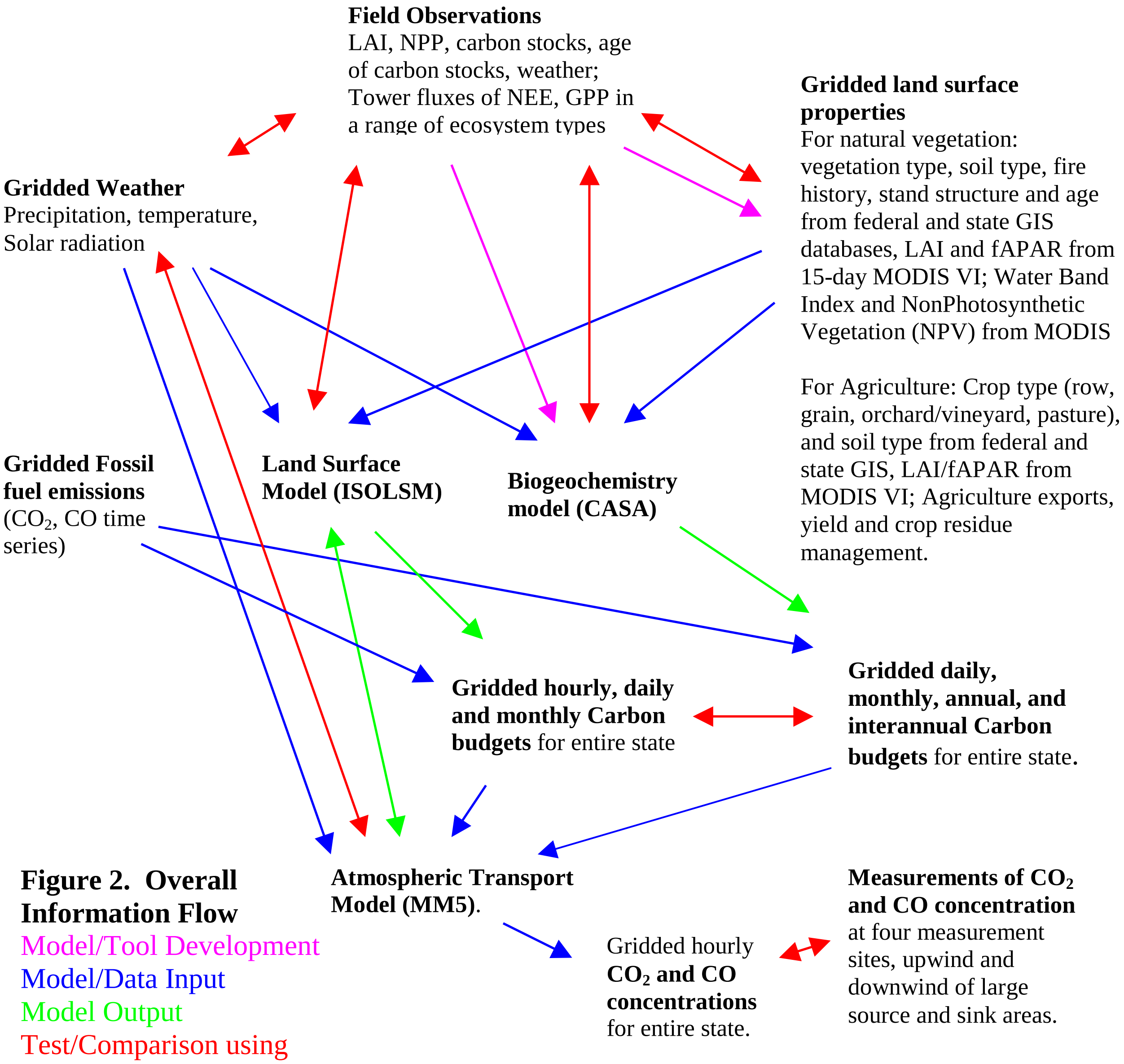

Figure 2. Overall Information Flow

Model/Tool Development

Model/Data Input

Model Output

Test/Comparison using reserved Data

sources or sinks of carbon dioxide; 28% of California and 29% of the United States is currently forest; 35% of California and 18% of the United States is currently shrubland (NLCD summary statistics, Fig 3, 5). We hypothesize that natural ecosystems are particularly important controllers of the diel, seasonal, and interannual patterns of net CO_2 exchange.

Carbon budgets for natural lands can be derived from field observations, gridded input data, and process-based models. Some budgets have been developed almost entirely from observations of carbon stocks. The USDA's Forest Inventory Analysis (FIA, Birdsey and Lewis 2003), which is used in the EPA and CEC budgets (CEC 2002, EPA-GHG 2004), relies on periodic measurements of forest stocks. Other budgets have been developed largely from biogeochemical models (Schimel et al. 2000, Hurtt et al. 2002). All approaches have significant advantages and disadvantages. Inventories provide direct measures of carbon change, but are expensive and may not include all land-types and carbon pools; models can account for all land-types and carbon pools, but may not be properly calibrated and tested for each system. The current trend is toward hybrid approaches that employ several different types of information (Pacala et al. 2001, Janssens et al. 2003, Sarmiento and Wofsy 1999, Wofsy and Harriss 2002). We will adopt the hybrid approach, relying on a combination of field measurements, remote sensing, existing spatial databases, and biogeochemical modeling (Fig. 2).

Field Site Selection (Goulden and Trumbore will take responsibility)

We plan field measurements that will be used to develop and test models and improve understanding of the mechanistic controls on carbon storage (Tab. 1). Our fieldwork will employ many of the techniques used in FIFE (Sellers et al. 1992), HAPEX, BOREAS (Sellers et al. 1997), and LBA. Our experimental design is similar to that used during OTTER (Peterson and Waring 1994). Most of the variation in California's natural vegetation is caused by topographically-induced climate gradients. Southern, Central, and Northern California have regular vegetation gradients (Fig. 3; grassland and shrubland at low elevation; forest at moderate elevation; subalpine and alpine at high elevation; xeric shrublands on eastern slopes; Barbour and Major 1995, Schoenherr 1995). The Southern California representatives of some of these vegetation types may differ from those found in Northern California, but this variation is small relative to the variation between ecosystem types (Barbour and Billings 2000).

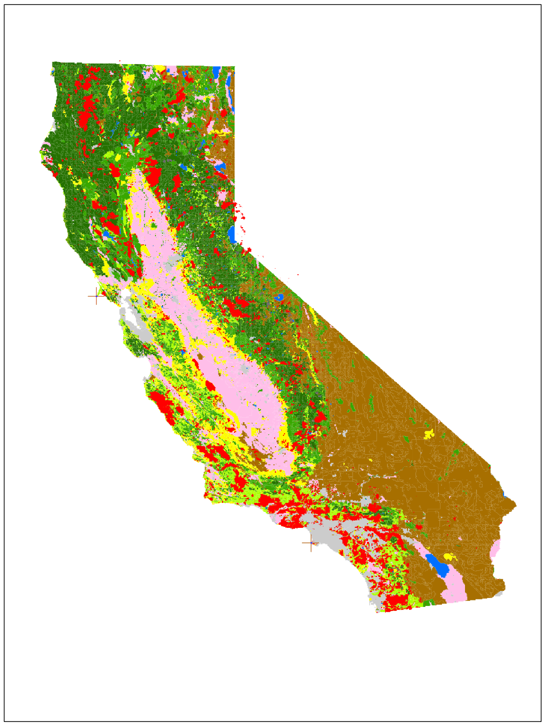

Fig. 3 California vegetation type and recent fire history. Areas that have burned since 1966 are shown in red. Brown area is desert; yellow is grassland; green shades are shrub, woodland and forest; gray is urban; pink is agriculture.

We will focus our measurements on a 150 km climate transect that traverses the Santa Ana, San Jacinto, and San Bernardino

Mountains as it moves from the Pacific Ocean to the Mojave desert. Our transect will include 10 ecosystem types: Grassland, Coastal Sage Scrub, Chaparral, Oak Woodland, Mixed Evergreen Forest, Pine and Mixed Conifer Forest, Subalpine Forest, Juniper Woodland, Pinion Woodland and Creosote Bush Desert. This transect will allow us to include field sites that are broadly representatives of ~80% of California's natural vegetation (Barbour and Major 1995). We will select 10 study sites in each of the 10 ecosystem-types, for a total of 100 inventory sites. Several of these ecosystems are subject to frequent fire, and in these cases we will stratify our sites by disturbance history. Fires exert long-term effects on species composition, biomass, leaf areas, and detrital stocks. We will incorporate a chronosequence approach (Litvak et al 2003, Fig 4) for ecosystems that burn regularly, including Grassland, Coastal Sage Scrub, Chaparral, Oak Woodland, Mixed Evergreen Forest, Pine and Mixed Conifer Forest.

Candidate sites will be selected from GIS and remote sensing analyses that consider vegetation type, topography, edaphic conditions (soils), climate, and land ownership. The final sites will be selected randomly after screening for areas where we can obtain permission and where there is a sufficiently large area of similar vegetation to include four 500-m MODIS pixels. We will focus on areas within the Irvine Ranch Land Reserve (~50,000 acre), the Audubon's Starr Ranch (~4000 acre), the Santa Ana Mountains within the Cleveland National Forest (~135,000 acre), the San Bernardino and San Jacinto Mountains within the San Bernardino National Forest (~590,000 acre), the San Bernardino and San Jacinto Mountains administered by the Bureau of Land Management's Palm Springs office (~125,000 acres), and the University of California Natural Reserve System (3 relevant reserves for a total of ~17,200 acres). We will avoid areas that are formally designated as wilderness, since obtaining research permission is extremely difficult. We have informally contacted individuals responsible for administering research on these lands, and will prepare formal applications for research access once the site locations are finalized.

Field Measurements (Goulden and Trumbore)

We will measure the Leaf Area Index (LAI), Aboveground Net Primary Production (ANPP), carbon stocks, mean residence time of carbon stocks and weather at all 100 inventory sites. The area sampled at each inventory site will vary with vegetation type. Each grassland site will have 10 randomly-located 1-m^2 plots; each shrub site will have 5 randomly-located 25-m^2 plots; each forest site will have 5 randomly-located 25 x 25-m plots. The proposed measurements and techniques are summarized in Table 1.

We will install and operate 7 eddy covariance towers in middle-aged stands along the transect. These sites will be selected for micrometeological suitability, ease of obtaining permits, and adequate size to include four 500-m MODIS pixels. The sites will reuse equipment we are currently using at 8 sites in Canada and 2 sites

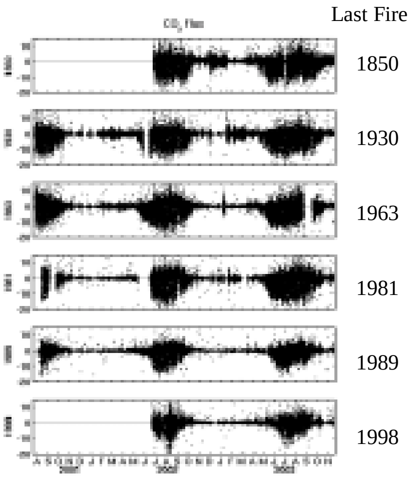

Fig. 4 Year-round net CO$_2$ exchange measured by eddy covariance at 6 sites in Canada differing in time since last burn (a "chronosequence"). We will redeploy this tower equipment to a climate transect in Southern California.

Table 1 Field Measurements

Measurement	*Why needed*	*How measured*
Aboveground biomass at 100 sites along climate gradient	Develop and test CASA's treatment of plant allocation and tissue lifetime	One-time measurement of woody vegetation using allometric equations (BIOPAK) and herb and grass clipping
Aboveground detritus at 100 sites	Develop and test of litter decomposition submodule and fuel loads in CASA	Determine decay class and density of CWD along 100-m transect. Sample fine detritus in 5 1-m^2 quadrates.
Soil carbon at 100 sites	Develop and test CASA's soil carbon submodel, parameterize ISOLSM	C analyses on samples from 5 pits per site.
Age/turnover of carbon pools	Develop and test CASA	Turnover times determined with AMS measurements of C^{14} in density and chemically fractionated soil pools (Trumbore et al. 1996).
LAI and fAPAR at 100 sites	Develop and test relationships between of Vegetation Indices and LAI and fAPAR.	Semi-monthly measurements at 25 locations per site using LiCor LAI-2000 with correction for leaf clumping (Gower et al. 1999)
Aboveground Net Primary Production at 100 sites	Develop and test CASA light use efficiency model. Test ISOLSM.	Semi-monthly measurement at 5 plots per site using dendrometers for woody vegetation and herb and grass clipping.
Litterfall at 100 sites	A component of ANPP. A check on LAI.	Litter collection in 5 baskets per site.
Weather at 100 sites	Test CASA and ISOLSM. Test gridded precip, irradiance and temperature data.	Air and soil T, irradiance with HOBO data loggers. Precip with manual gauges.
Whole-ecosystem CO_2, energy, and water vapor exchange and microclimate at 7 sites along climate gradient.	Develop and test CASA and ISOLSM. Develop and test remote-sensing indicators of drought.	Eddy covariance and micrometeorological instrumentation.

Table 2 Remote Sensing

Inputs	*Why needed*	*How*
Statewide MODIS scenes, 500-m resolution, 10-day composites, Bands 1-7	Calculate Vegetation Indices, Input to spectral mixing model	MOD09GHK (v.4)
Statewide fire occurrence and perimeters	Determine fire disturbance, Calculate carbon emissions from combustion.	MOD14, MOD40
Outputs	*Why needed*	*How*
Statewide 10-day composites of LAI and fAPAR	Input to CASA and ISOLSM for calculation of canopy gas exchange and primary production	Calculated from MODIS Vegetation Indices using ecosystem-specific regressions developed from field work (Tab. 1)
Statewide 10-day composites of NDWI and NPV	Possible indicators of plant drought stress for input to CASA and ISOLSM	NPV by end member mixture analysis. NDWI from MODIS Bands 2 and 5.
Stand structure and time since disturbance	Input to CASA	End member mixture analysis on ETM+ images. Empirical relationship between structure/age and shadow, soil, NPV and green material (e.g., Roberts et al. in press).
Forest mortality	Input to CASA	Increased NPV indicated by end member mixture analysis on ETM+ and MODIS images.
Crop type	Input to CASA and ISOLSM	Temporal pattern of NDVI or NDWI compared to crop phenology. Validated against crop statistics.

in Brazil with support from NSF, DOE, and NASA (Fig. 4). Most of these sites use solar power, aluminum towers, and satellite telemetry. The California transect will use the equipment from the 6 tower sites in Canada that are scheduled for decommission in Fall 2004, and the 1 or 2 sites in Brazil that are scheduled for decommission in Spring 2005. At a minimum, we will install and operate towers in Grassland, Coastal Sage, Chaparral, Mixed Evergreen Forest, Ponderosa Pine, Pinyon Juniper, and Creosote Bush. We will install the equipment as soon as it is returned to the US, allowing us to avoid the cost and time for storage. We are not requesting support in this proposal for either equipment or maintenance for the towers. Rather, the towers will be equipped entirely with existing equipment, and we will support the operation of the towers from alternative funding sources.

We will supplement our field data from Southern California with field data from other groups working in Northern California, including Dennis Baldocchi's group, which is working near Ione, and Allen Goldstein's group, which is working at Blodgett Forest. Additionally, Bev Law's group has submitted a proposal to this RFP, which includes fieldwork in Northern California and Oregon. Law's proposal is complementary to ours, and we have agreed to share data and protocols, and to intercompare model inputs and outputs, if both proposals are funded. Similarly, our eddy covariance towers will join the AmeriFlux network. All of the field data that we collect (Tab. 1) will be available to other researchers, initially through our project's website. These data are one of our main deliverables.

Remote sensing (Roberts and Dennison)

Our biogeochemical (CASA) and biogeophysical (ISOLSM) models require 10-day inputs of LAI and fAPAR (Tab. 2). Questions have been raised (c.f., Cohen et al. 2003) about the suitability of the existing MODIS LAI product (MOD15) for some vegetation types, and we will develop our own LAI/fAPAR data fields for California. We will develop a set of ecosystem-specific relationships between MODIS Vegetation Indices and LAI, and use these relationships to calculate 10-day LAI fields. Our approach will be largely empirical. We will search for the most robust (especially with respect to solar angle and topography) relationships between semimonthly Vegetation Indices such as EVI, NDWI and NDVI and the LAIs measured at the 100 inventory plots (Tab. 1). We will then combine the relationships with a series of 10-day median reflectance mosaics that include 4 MODIS tiles over the Western United States. Mosaics based on the MODIS surface reflectance product with 500 meter resolution (MOD09GHK version 4) have already been completed for 2000 to 2002, and will be extended as the study progresses (Tab. 2; Dennison et al. submitted).

Seasonally-droughted, evergreen ecosystems present a particular challenge to remote sensing. Evergreen shrubs and trees may cease gas exchange during the drought without significantly reducing LAI (Goulden 1996, Goldstein et al. 2000, Irvine et al. 2002). NDVI-based techniques for modeling NPP, such as those used for the MODIS NPP product (MOD17) and many biogeochemical models, are largely insensitive to this shutdown (Gamon et al. 1995). In fact, the only approach currently available for assessing evergreen shutdown is direct measurement of gas exchange using chambers, micrometeorology, or sap flow sensors. The Normalized Difference Water Index (NDWI; Gao, 1996), and the fraction of light absorbed by Non-Photosynthetic Vegetation (NPV; Roberts et al. 1993), may provide information on the seasonal shutdown. NDWI, which is

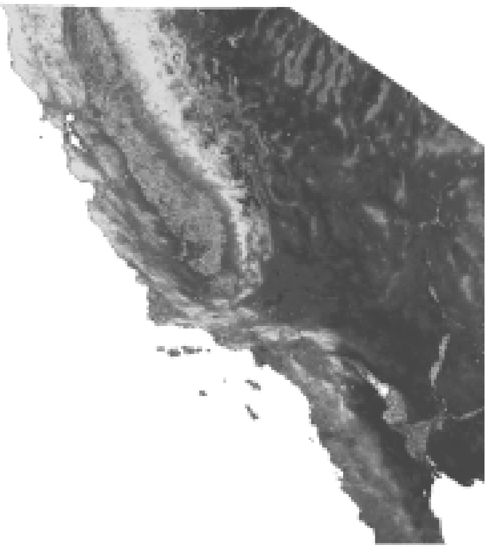

Fig. 5 MOD13 EVI tile h08v05 15 day composite DOY 273 2003. Light areas have higher EVI; dark areas have low plant cover.

calculated with the 1241 and 857 nm MODIS bands, is correlated with plant water content (Penueles et al. 1997, Sims and Gamon 2003, Dennison et al. 2003). NDWI may be sensitive to seasonal declines in canopy water status and canopy gas exchange. The fraction of light reflected by NPV, as determined by spectral mixture analysis, provides an alternative approach for detecting canopy drought stress (Dennison and Roberts 2003, Roberts et al. 2003). Spectral measures of chaparral NPV indicate an increase with leaf senescence during the California drought. NPV provides a much more sensitive measure of canopy senescence than the converse approach of looking for a decline in NDVI. We will compare the seasonal courses of whole-ecosystem gas exchange measured by eddy covariance (Tab. 1) with the simultaneous NDWI and NPV calculated from MODIS (Tab. 2). We will then incorporate the best remote-sensing-based predictor of canopy drought stress into ISOLSM and CASA (Tab. 3).

CASA requires information on forest structure, disturbance history and inferred forest age. The fire history data for California are excellent (Fig. 3, Tab. 3), providing key information on stand age for ecosystems that burn regularly. Data on logging history is more difficult to obtain, especially for Northern California where much of the land is private. We will determine the extent of recent logging using the LCMMP statewide change detection analyses (Tab. 3). Two five-year cycles of change detection have been completed, providing a measure of the areas logged since approximately 1990. We will assess the patterns of logging before 1990 using spectral mixture analysis to define temporal trajectories that map changes in forest age as changes in the balance of Green Vegetation, Shade, Soil and NPV (Sabol et al. 2002, Roberts et al. in press). This approach will be applied to Landsat ETM+ data from 2000 to early 2003 to derive several broad age classes, including recently logged (< 10 years old); early regeneration (11-30 years); intermediate (31-50 years); advanced regeneration (51-100) and old-growth (> 100 years). Based on previous work at several sites (Roberts et al. in press), these broad classes should be readily separated in Landsat ETM+ data. Maps of recent logging activity will be tested against the LCMMP data. We will then combine these three pieces of information (historical fire perimeters; change detection since ~1990; stand structure and inferred age from ETM+) to produce a single statewide data set of time since last disturbance and mode of last disturbance.

The data on NPV should also prove useful for developing gridded information on forest mortality caused by insect outbreaks. Trees killed by bark beetles remain standing with brown needles for several years. Insect outbreaks should show up as large semipermanent increases in NPV. We will use ETM+ data from before May 2003, and

MODIS data throughout the record, to quantify the extent of forest mortality (Tab. 2). We will test these data sets by comparison with GIS data on tree mortality from the USFS Pacific Southwest Region Insect and Disease Aerial Detection Surveys (Tab. 5, IDADS).

All remote-sensing products we produce will be available to other researchers. These data, along with improved remote-sensing tools for drought-stressed evergreen ecosystems, are among our main deliverables.

Assembling existing gridded data (the entire science team will share responsibility)

We will make heavy use of existing data (Tab. 3). ISOLSM and CASA require gridded information on topography, land cover, vegetation type, and soil type. CASA requires information on disturbance history. ISOLSM and CASA require gridded information on daily weather, including irradiance, precipitation, and temperature. Table 3 lists the likely data sources for each of these inputs. In most cases several alternative sources of broadly similar data are available, which will allow us to assess uncertainty by cross comparing data sets (Tab. 5). Additional data, such as weather records from the RAWS, SNOTEL, and METAR networks, and forest biomass records from the FIA, will allow further cross checks and model tests (Tab. 5).

Biogeophysical modeling (*ISOLSM; Riley*)

We will use two different models to produce gridded predictions of the net and gross CO_2 exchanges by California's natural ecosystems. The first model, ISOLSM (Riley et al. 2003, Riley *et al.* 2002, Riley 2004), which is based on LSM1 (Bonan 1996), fits into the class of biogeophysical models that includes BATS, SiB2, and CLM (Dickinson et al. 1986, Sellers et al. 1996, Dai et al. 2003). ISOLSM emphasizes fast physiological and biophysical processes, such as leaf photosynthesis and radiation transport. These fluxes are dominated by the movement of carbon into and out of shorter-lived pools, and ISOLSM is most suitable for predicting CO_2 exchange on time scales from hours to seasons. ISOLSM divides the canopy into sunlit and shaded fractions, and includes biophysically-based modules that simulate the aboveground fluxes of radiation, momentum, sensible heat, and latent heat; the belowground fluxes of energy and water; and the CO_2 and H_2O fluxes between plants and the atmosphere. The model is well suited for regional-scale simulations driven by meteorological measurements or predictions and remote sensing. LSM1 has been tested in many ecosystem types (e.g., Bonan et al. 1997, Bonan 1994, Riley et al. 2003). We will further test ISOLSM by comparison with our tower-flux observations (Tab. 1, 5)

We will drive ISOLSM with irradiance fields derived from GOES images (Tab. 3; Diak et al. 2004) and temperature and precipitation fields derived from ground-based observations (Tab. 3). We will confirm the reliability of these input data by comparison with individual stations in the RAWS, SNOTEL, and METAR networks (Tab. 5). If the GOES and NCEP weather inputs prove unsuitable, we will use MTCLIM v4.3 (Thornton et al. 1997) to construct input meteorological fields from weather station data. We will also run ISOLSM in coupled mode with MM5.

The end result of the ISOLSM runs will be gridded predictions of the CO_2 exchange by California's ecosystems (Tab. 3). These budgets will be one of our core deliverables, and will help to address Issue 1 (*How much carbon does California release and take up?*). Moreover, we will use the ISOLSM-derived budgets to address Issue 4 (*How much, and why, does California's carbon balance vary from year to year?*). We predict ISOLSM will show large year-to-year variation in the carbon exchange by natural

Table 3 Spatial data sets Inputs and outputs to ISOLSM and CASA

Input	*Why needed*	*Source*
Land cover	Models parameterized differently for urban vs agriculture vs natural land	NLCD
Ecosystem type	Models parameterized differently for different vegetation types	GAP, NLCD; crop type from MODIS (Tab. 2)
Soil type	Models need soil depth, physical and biogeochemical properties	STATSGO, SSURGO
LAI and fAPAR	Models need seasonal patterns of LAI	Analysis of field data and MODIS Vegetation Indices (Tab. 2)
Historical fire perimeters	CASA needs information on disturbance history. Needed to calculate direct fire emissions	1900-2002 from FRAP. Updated annually. Recent data checked against MOD14, 43
Change detection analyses	A component of comprehensive time since disturbance data layer for CASA	Two 5-year intervals from LCMMP
County crop area	Develop and test of MODIS gridded crop type. (Tab. 2)	County crop statistics from USDA-NASS and California Statistical Abstract
County crop production	Develop, input, and test CASA.	County crop statistics from USDA-NASS and California Statistical Abstract
Gridded, daily observations of irradiance (for model runs from 2000 forward)	Meteorological input for ISOLSM and CASA. Testing MM5.	GOES-derived daily integrated irradiance at 0.2^{o} spatial resolution from University of Wisconsin Diak et al. 2004
Gridded observations of Temperature (for model runs from 2000 forward)	Meteorological input to ISOLSM and CASA. Testing MM5.	Observation-derived air temperature at 0.5^{o} spatial resolution from NCEP.
Gridded observations of Precipitation (for model runs from 2000 forward)	Meteorological input to ISOLSM and CASA. Testing MM5.	Observation-derived daily precipitation at 10-km spatial resolution from River Forecast Center and National Precipitation Verification Unit at NCEP.
Gridded observations of temperature, precipitation, and solar radiation from 1895 to 1994	Meteorological inputs for longer CASA runs.	VEMAP Phase II historical (1895-1994) gridded climate dataset (VEMAP2; Kittel et al. 2004).
Output	*Why needed*	*How*
ISOLSM Gridded hourly, daily, monthly, annual, and interannual CO_2 exchange by California's natural and agricultural lands	A key deliverable. An input to transport model.	Model prediction
CASA Gridded daily, monthly, annual, and interannual CO_2 exchange by California's natural and agricultural lands	A key deliverable. An input to transport model.	Model prediction

Table 4 Fossil Fuel emissions

Inputs	*Why needed*	*From where*
Annual whole-state CO_2 Fossil Fuel emissions for 1990-1999	The best information available on CA Fossil Fuel C emissions. Our subsequent work will extrapolate these budgets forward and allocate them to finer scales.	California Energy Commission (CEC) Report using EPA protocols. Scheduled for update at 5-year intervals.
Monthly and annual natural gas and petroleum use from 1990 to present	Needed to extrapolate C inventories from the 1990s to current.	Annual (1990-2000) and monthly (1998-current) energy use statistics from DOE-EIA.
EPA temporal profiles	To estimate carbon emission at finer temporal scales. Information on relative emissions by hour of day and day of week.	EPA Clearinghouse for inventories and emission factors.
EPA MIMS Spatial Allocator	Needed to spatially distribute state's C emissions. Uses ~ 65 surrogates at 4 km resolution, including distribution of population, transportation corridors, land use and heavy industry.	EPA Clearinghouse for inventories and emission factors.
Whole-state CO budget	The tracer model will predict both CO and CO_2 concentrations. The ratio of CO to CO_2 can be used to separate fossil fuel and ecosystem effects.	EPA and California Air Resources databases. The CO emission will be spatially and temporally distributed following the approach used for CO_2.
Output		
Gridded CO and CO_2 emissions for California	A key deliverable. The largest component of the State (and Country) C budgets. An input to the transport model.	Spreadsheet and GIS analysis of data described above.

ecosystems. We will then investigate the cause of these variations, with emphases on the processes described in Issue 4. Additionally, we will use the flux information in conjunction with the atmospheric tracer model to address Issue 6 *(Where does the* CO_2 *emitted by California go?)*

Biogeochemical modeling (CASA; Randerson)

The second model, CASA, emphasizes processes that control carbon storage within ecosystems over timescales of months to centuries (Potter et al. 1993). NPP is calculated using a light use efficiency model that requires the amount of light absorbed by plant canopies and functions that represent local soil moisture and temperature conditions (Field et al. 1995, Field et al. 1998). The accumulation of carbon in leaves, stems, and roots depends on a simple NPP allocation scheme and plant tissue turnover times that are assigned separately for different plant functional types (Thompson et al. 1996, Van der Werf et al. 2003). Loss pathways include decomposition, fires, herbivory, and harvest by humans (Van der Werf et al. 2003). The CASA ecosystem model has been primarily used to test hypotheses concerning changes in ecosystem carbon and carbon isotope fluxes at the scale of biomes and continents (Thompson et al. 1996, Fung et al. 1997, Randerson et al. 1999a, Randerson et al. 1999b, Behrenfeld et al. 2001, Hicke et al. 2003, Van der Werf et al. 2004).

Our goal of developing reliable flux estimates for California will lead us to optimize several of CASA's parameters (Tab. 1, 3). We will calibrate the light use efficiency model using the aboveground NPP and fAPAR observations collected at the field sites (Tab. 1). We will adjust allocation and plant tissue turnover times using the aboveground biomass, radiocarbon (C^{14}) measurements, and stand age information. We will constrain the decomposition rates of leaves and twigs based on the detritus observations. Soil carbon data will provide a strong constraint on soil carbon pools with decadal and century turnover times. The radiocarbon-derived ages of roots, soil carbon, and soil respiration will provide a constraint on the more rapidly cycling components of soil organic matter (Gaudinski et al. 2000, Trumbore, 2000). Model inputs for the CASA runs are listed in Table 3 and model tests are listed in Table 5.

The CASA runs will span a range of time scales. We will run CASA for the period from 2000 to 2007 using the weather data and Vegetation Indices that are collected during this period (Tab. 2, 3). We will also run CASA for longer time periods, using historical weather data (Tab. 3), the fire and disturbance history, and assuming modern fAPAR, to investigate the carbon exchanges by longer-lived ecosystem pools. We will use CASA to produce spatially and temporally-resolved predictions of the CO_2 exchange into and out of California's natural ecosystems (Tab. 3). Additionally, we will combine the results from the 2000 to 2007 CASA and ISOLSM runs to produce separate spatially and temporally-resolved budgets for the exchanges of CO_2 with very fast-, fast-, and slow-turnover pools. This will allow us to keep track of how much of a pixel's net CO_2 exchange is being cycled through faster-turnover pools and how much is being cycled through slow-turnover pools.

The budgets produced by CASA are one of our core deliverables, and will help address Issue 1 (*How much carbon does California release and take up?*). We will use the CASA-derived budgets to help address Issue 3 (*How do our carbon budgets compare with previous budgets*?). We expect that CASA's predictions of carbon storage in the long-lived pools in California's ecosystems will be similar to that in the CEC budget. We will also use the CASA-derived budgets to help address Issue 4 (*How much, and why, does California's carbon balance vary from year to year?*). We predict that CASA will show large year-to-year variation in the carbon exchange by natural ecosystems. We will investigate the cause of this carbon flux variation, with an emphasis on the processes described in Issue 4. We will use the atmospheric tracer model in conjunction with the pool-resolved flux information produced by ISOLSM and CASA to address Issue 5 *(What processes control the CO_2 concentration of the air leaving California?*). Finally, we will use the flux information in conjunction with the atmospheric tracer model to address Issue 6 *(Where does the CO_2 emitted by California go?).*

B. Agriculture

Objectives, Rationale, and State of the Art

Our goal is to develop spatially-gridded, temporally-resolved information on the net CO_2 exchange by California agriculture from 2000 to 2007. Both California and the United States have large areas of intensive agriculture; 10% of California and 19% of the United States is classified as cropland (USDA NRI statistics). We hypothesize that agriculture is an important controller of the diel, seasonal, and, possibly, interannual variations in statewide net CO_2 exchange. Agriculture sequesters large amounts of carbon during the growing season. Most of this carbon is subsequently released during the dormant season and during the consumption of the agricultural products. Agriculture export results in a horizontal transfer of carbon, with the CO_2 release occurring at a different location from the CO_2 fixation. Interannual variation in the Western snowpack, and the availability of water for irrigation, may cause significant year-to-year differences in cropland area.

The development of carbon budgets for agriculture parallels that for natural ecosystems. Some budgets have made heavy use of agricultural statistics (Prince et al. 2001); other budgets have relied mainly on biogeochemical modeling. The current trend is toward hybrid approaches that incorporate information from both crop statistics and process-based models (Lobell et al. 2002). We will adopt the hybrid approach, relying on combination of crop statistics, remote sensing, existing spatial databases, and biogeochemical modeling (Fig. 2, Tab. 2, 3).

Strategy (Roberts, Dennison, Riley, and Randerson)

Our treatment of the short-term carbon fluxes (diel to seasonal) by agriculture will parallel our treatment of the fluxes by natural lands. CASA and ISOLSM will be parameterized for four different crop types (Grains (which cover ~1-2% of CA's total land), Row crops (~2-3% of CA), Vineyard/Orchard (~3% of CA), and Pasture (~2-4% of CA); NLCD 92, USDA-NASS 1997), and used to predict the hourly (ISOLSM) to annual (ISOLSM, CASA) exchanges of CO_2. Gridded inputs for crop type will be determined from the MODIS time series mosaics (Dennison et al. submitted) using temporal NDVI or NDWI as an input into a classifier (Tab. 2). We anticipate phenological differences between row crops, orchards, grains and pasture will enable accurate mapping of these four cover types using MODIS 500 m data. These inputs will be checked against existing crop classifications from the GAP, NLCD 92 and NLCD 2001 databases (Tab. 5, Davis et al. 1998, Vogelman 2001), and also against countywide crop area statistics (Prince et al. 2001, Lobell et al. 2002, USDA-NASS, California Statistical Abstract). The modeled ANPP for each crop type will be allocated into exportable produce and crop residue based on harvest indices from the agricultural literature (Tab. 3, Lobell et al. 2002, Prince et al. 2001). The exports will then be compared with the countywide crop production statistics (USDA-NASS, California Statistical Abstract), and subtracted from the local carbon pools.

The resulting budgets for the carbon fluxes by California agriculture will be one of our core deliverables, and will help us address Issue 1 (*How much carbon does California release and take up?*). We will use these budgets to further address Issue 4 (*How much, and why, does California's carbon balance vary from year to year?*). We predict that the models will show large year-to-year variation in the carbon exchange by agricultural ecosystems, which will correlate with variation in the availability of water for irrigation. We will also use the agriculture flux information in conjunction with the atmospheric tracer model to help address Issue 5 *(What processes control the CO_2 concentration of the air leaving California?*) and Issue 6 *(Where does the CO_2 emitted by California go?).*

C. Fossil Fuel

Objectives, Rationale, and State of the Art

Our goal is to develop spatially-gridded, temporally-resolved CO_2 and CO emission data for California from 2000 to 2007. Fossil fuel emissions are easily the largest terms in both the US and California carbon budgets (EPA-GHG 2004, CEC 2002). Any comprehensive attempt to better understand the US or California carbon budget needs to pay particular attention to fossil fuel emissions.

Regional and national carbon budgets are calculated by summing the carbon released from the various fuels after accounting for each fuel's carbon content and combustion efficiency (Marland and Rotty 1984, EPA-GHG 2004, CEC 2002). The large-scale emissions are then distributed spatially using readily available energy-use proxies such as population density (Brenkert 1998, Andres at al. 1997). The alternative approach of calculating high-spatial-resolution carbon emission from high-spatial-resolution energy use statistics has not found wide use, presumably because of the difficulty of collecting the necessary data. Unfortunately, the existing gridded data sets for carbon emissions are inadequate for our research since they have insufficient spatial (1^o x 1^o) and temporal (annual) resolution, and are only infrequently updated with the most current energy statistics (the most recent gridded data available at CDIAC are for 1995). Moreover, the spatial distribution of fossil fuel emissions in these data sets is done using population density, which may underestimate emissions in rural and power-producing areas and overestimate emissions in suburban areas.

Strategy (Goulden and Randerson)

We will constrain the fossil fuel CO_2 emissions for the entire state of California using the inventories published by the California Energy Commission (CEC) for 1990 to 1999 (CEC 2002). This inventory follows the protocols used by the EPA for the annual greenhouse gas inventories (EPA-GHG 2004). We will then extrapolate the 1999 emission inventories forward using energy statistics for natural gas and petroleum (mainly gasoline and distillate fuel) combustion, which account for 96% of California's fossil fuel emissions (CEC 2002). We will combine the combustion factors (e.g., metric tons C per thousand ft^3 of natural gas, etc) used in CEC 2002 with updated monthly and annual energy use statistics from DOE's Energy Information Administration (DOE-EIA). We will force our approach to equal the total emissions for 1999, and will check it against the budgets that the CEC prepares for its next scheduled report (for years 2000-

2004). Next, we will interpolate the emissions as a function of day of week and time of day using EPA's temporal allocation profile and weighting factor files (EPA-Temporal Factors). EPA's temporal allocation profile provides information on the relative emissions as a function of time of day and day of week. Finally, we will distribute the emissions spatially using the EPA's MIMS Spatial Allocator (EPA-Spatial Allocator). The MIMS Spatial allocator distributes the emissions as a function of approximately 65 surrogates available at 4 km resolution, including spatial information on population, transportation corridors, land use and heavy industry. We will use a similar approach to produce gridded CO budgets based on inventories available from the EPA and the California Air Resources Board (EPA-NEI).

These budgets will be one of our core deliverables, and will help to address Issues 1 (*How much carbon does California release and take up?*), 4 (*How much, and why, does California's carbon balance vary from year to year?*), 5 *(What processes control the CO_2 concentration of the air leaving California?*), and 6 *(Where does the CO_2 emitted by California go?).* Our fossil fuel budgets will be based on the CEC's approach, and they will not be useful for addressing Issue 3.

IV. Methods: Investigating the Impact of California's Carbon Budget on the Atmosphere (Riley)

California's position on the leading edge of the continent makes it especially appropriate for understanding atmospheric CO_2 transport. The air that enters the West Coast from the Pacific Ocean is probably as homogenous as can be expected for any location in the coterminous United States. California has a strong south to north gradient in the relative importance of anthropogenic and natural carbon sources and sinks (Fig. 3, 5). Air passing over Southern California is impacted most strongly by combustion; air passing over Central California is impacted by a mix of anthropogenic sources and agriculture; air passing over Northern California is impacted most strongly by ecosystem gas exchange (Fig. 3, 5). Much of the air that enters California probably exits to the east, though an important fraction exits to the south or west (CARB 1984; Fig. 1). The CO_2 released by Southern California's urban areas, and by large fires, may be preferentially transported to the south or west, partially decoupling California's Carbon exchange from North America's air mass (Issue 6).

We will use a coupled land-surface, atmosphere, and atmospheric tracer model to investigate the impact of California's CO_2 and CO exchanges on atmospheric CO_2 and CO concentration (Cooley et al. 2003, Cooley et al. 2004). The integrated modeling framework includes the mesoscale meteorological model MM5, the land-surface model ISOLSM, and an atmospheric tracer model. The coupled model is currently running on both desktop machines and the National Energy Research Super Computer (NERSC) SMP machine. This powerful computer allows us to efficiently perform sensitivity tests of model structure and parameters. We have invested considerable time in developing and testing the coupled model (Fig. 6). We have favorably compared the coupled model to continental-scale precipitation records and data from the three-year FIFE dataset of soil moisture, temperature, surface energy and water fluxes, and near-surface air temperatures (Betts and Ball 1998). The coupled model simulates energy exchange, precipitation, near-surface air temperatures, and soil moisture and temperatures at least as well as the land-surface model currently in MM5 (OSULSM), and, importantly, provides consistent estimates of CO_2 exchange with the atmosphere.

We will feed the bottom up natural land, agriculture, and fossil fuel CO_2 budgets (Tab. 3) into the coupled model to produce temporally and spatially resolved predictions of atmospheric CO_2 concentration (Fig. 2). We will also feed the bottom up fossil fuel and fire budgets for CO (Tab. 3) into the coupled model to produce temporally and spatially resolved predictions of atmospheric CO concentration after accounting for the destruction of CO using climatological mean OH (Fig. 2). The resulting CO_2 and CO concentration fields are one of our main deliverables. We will analyze these fields to address Issue 6 (*Where does the CO_2 emitted by California go?*). We predict that a substantial fraction of California's CO_2 emissions are advected south or west, bypassing North America (Fig. 1). Additionally, we will feed the fossil fuel inventories and pool-resolved flux data from CASA and ISOLSM into MM5 to address Issue 5 (*What processes control the CO_2 concentration of the air leaving California?*). We predict that the gradients in atmospheric CO_2 are determined almost entirely by fossil fuel emissions and the exchanges with short-lived ecosystem pools, and that exchanges with long-lived ecosystem pools exert a small influence. We will further address Issue 5 by sequentially increasing the magnitude of the long-term ecosystem sink to further quantify the sensitivity of atmospheric CO_2 concentration to long-term carbon storage.

V. Methods: Testing, Validation, and Uncertainty

Researchers have recently increased efforts to reconcile the carbon budgets produced by different disciplines (Pacala et al. 2001, Janssens et al. 2003, Sarmiento and Wofsy 1999, Wofsy and Harriss 2002). This hybrid approach, which combines data from many independent experimental approaches, is critical for increasing confidence in large-scale carbon budgets. We will use this general approach to quantify the uncertainty of our budgets. We will estimate the uncertainty of the various input data sets (Tab. 1, 2, 3, 4) by comparison with other, independent data sets (Tab. 5). Our goal will be to check everything we use and produce with an independent measure. Table 5 summarizes some of the cross checks we plan. We will use the cross-checks to establish confidence intervals for our model inputs. We will propagate these errors using Monte Carlo simulations to calculate uncertainties for our carbon budgets.

We will also test the budgets by comparing the regional patterns of atmospheric CO_2 concentration predicted from the budgets with observations of CO_2 concentration. The regional patterns of atmospheric CO_2 concentration will be predicted by feeding the carbon budgets into the MM5 tracer model. These predictions will be compared with measurements of CO_2 and CO concentration at four measurement sites located upwind and downwind of large source and sink areas. Records of atmospheric composition are being made by several groups on the northern California coast at Trinidad Head (see "Trinidad Head" in references). We will use these data in conjunction with three additional sites that we install to measure the longitudinal gradient in CO_2 concentration across California. We will locate one of our stations on an island off the Southern California coast, a second station in the Southeastern California desert, and a third station in Northeastern California. We will locate the southeastern station in a region that is strongly influenced by upwind urban and suburbanized areas, and the northeastern station in a region that is strongly influenced by upwind exchanges with forest and cropland. We have identified candidate sites from UC's Natural Reserve system, including the Santa

Table 5 Cross checks, validation, and uncertainty

Comparisons to check field data for consistency	
LAI measured using Licor LAI2000 (Tab. 1)	Integrated litterfall
Measured aboveground biomass and detritus along transect (Tab. 1)	Calculated biomass and detritus from time since disturbance, ANPP, litterfall, and C^{14} turnover
Comparisons to check remote-sensing products	
MODIS LAI/fAPAR predictions for sites (Tab. 2)	Reserved subset of LAI/fAPAR measurements along transect
MODIS LAI/fAPAR predictions for state (Tab. 2)	MOD15
Crop-type predicted from MODIS time series (Tab. 2)	Crop type from GAP Analysis and NLCD
Crop-type predicted from MODIS time series (Tab. 2)	Reserved county crop statistics from USDA-NASS
MODIS WBI or NPV measure of canopy drought shutdown (Tab. 2)	Reserved subset of tower data
Stand age inferred from MODIS (Tab. 2)	LCMMP Change detection, FRAP Fire perimeters
Insect-caused forest mortality from NPV (Tab. 2)	USFS-PSW Insect and Disease Aerial Detection Surveys (IDADS)
Comparisons to check existing gridded data sets	
STATSGO and SSURGO predictions for site (Tab. 3)	Observed soil C along transect
Updated fire perimeters from CDFFP (Tab. 3)	MODIS fire products (MOD14, MOD40)
Solar radiation, temperate, and precipitation for individual sites pulled out from gridded data sets (Tab. 3)	Observations of radiation, temperate, and precipitation from individual RAWS, SNOTEL, and METAR sites
Gridded solar radiation, temperate, and precipitation (Tab. 3)	Gridded predictions using MTCLIM v4.3/ DAYMET run with RAWS, SNOTEL, and METAR station data.
Gridded solar radiation, temperate, and precipitation (Tab. 3)	Check against gridded climate data from NCEP, DAO, and our MM5 output.
Comparisons to check model predictions	
Diel patterns of CO_2 and energy exchange predicted for site by ISOLSM (Tab. 3)	Reserved subset of tower-flux measurements along transect
Seasonal patterns of exchange predicted for site and year by CASA and ISOLSM (Tab. 3)	Reserved subset of tower-flux measurements along transect
ANPP predicted for site and year by CASA and ISOLSM (Tab. 3)	Reserved subset of ANPP measurements along transect
Detritus stocks predicted for site by CASA (Tab. 3)	Reserved subset of detritus C measurements along transect
Steady state soil C predicted for site by CASA (Tab. 3)	Reserved subset of soil C measurements along transect
Biomass predicted for site by CASA (Tab. 3)	Reserved subset of biomass C measurements along transect
Crop-production predicted by CASA (Tab. 3)	Reserved county crop statistics
Daily, Monthly, and Annual carbon fluxes predicted by ISOLSM across entire state (Tab. 3)	Daily, Monthly, and Annual carbon fluxes predicted by CASA across entire state
ANPP predicted by CASA and ISOLSM across state (Tab. 3)	MOD17
ANPP predicted by CASA and ISOLSM across state (Tab. 3)	ORNL DAAC NPP Dataset
Biomass predicted by CASA across areas of private forest (Tab. 3)	Biomass measured by FIA in comparable areas
Weather predicted by MM5	Gridded solar radiation, temperate, and precipitation
Comparisons to check carbon budgets and tracer model	
Predicted statewide C emissions for 2000 to 2004 (Tab. 4)	Updated CEC emission inventories (expect release in ~2006)
Spatial gradient in CO and CO_2 across California predicted by MM5 using the Carbon Budgets	Measured gradients in atmospheric CO and CO_2 across California

Cruz Island Reserve, which is located on an island off the coast, the Sweeney Granite Mountains Desert Research Center, which is located in the Mojave Desert in Southeastern California, and the Eagle Lake Field Station, which is located on the Modoc Plateau in Northeastern California. We will select final locations for these sites following runs of the tracer model to maximize the predicted gradients in CO_2 and CO.

The measurement stations will use the types of instruments we have been using for our measurements in Canada (Fig. 4). We will measure CO_2 concentration with a LI7000 gas analyzer. We will measure CO concentration with a Thermo Electron Corporation 48C Trace Level CO Analyzer modified for increased stability and sensitivity following the approach used by Bill Munger. We will use solar power, and will return the data at hourly intervals by GOES telemetry. Both gas analyzers will be calibrated every 4 hours with working standards and weekly with a second, long-term standard to maintain precision. All standards will be tied to the World Meteorological Organization standards for CO and CO_2 maintained by NOAA-CMDL. This last point will ensure that the data we collect are useful to other NACP researchers, and that we will be able to compare our observations with those made at Trinidad Head.

The data intercomparisons and Monte Carlo analyses, and the comparison of predicted and observed atmospheric CO_2 concentration, will be used to identify weaknesses in our carbon budgets. This approach will allow us to focus subsequent efforts on the inputs and terms that are most uncertain. The results of the intercomparisons and Monte Carlo analyses will form one of our core deliverables, and will allow us to address Issue 2 (*How much confidence should we have in our carbon budgets?*). Moreover, an increased appreciation of the underlying uncertainties will be critical for addressing Issues 1, 3, 4, 5, and 6.

VI. References

Andres et al. 1997 Geographic Patterns of Carbon Dioxide Emissions from Fossil-Fuel Burning, Hydraulic Cement Production, and Gas Flaring on a One Degree by One Degree Grid Cell Basis: 1950 to 1990 http://cdiac.esd.ornl.gov/epubs/ndp/ndp058/ndp058.html

Barbour, Michael G. and William Dwight Billings eds. 2000 North American terrestrial vegetation 2nd ed. Cambridge University Press Cambridge, U.K. ; New York :

Barbour, M. G. and J. Major eds. 1995 printing Terrestrial vegetation of California California Native Plant Society, Davis, Calif.

Behrenfeld, M.J., J.T. Randerson, C.R. McClain, G.C. Feldman, S.O. Los, C.J. Tucker, P.G. Falkowski, C.B. Field, R. Frouin, W.E. Esaias, D.D. Kolber, and N.H. Pollack, Biospheric primary production during an ENSO transition, Science, 291 (5513), 2594-2597, 2001.

Betts AK, Ball JH (1998) Fife Surface Climate and Site-Average Dataset 1987-89. Journal of the Atmospheric Sciences, 55, 1091-1108.

Birdsey, R.A.; Lewis, G.M. 2003. Carbon in U.S. forests and wood products, 1987-1997: state-by-state estimates Gen. Tech. Rep. NE-310. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 42 p.

Bolsinger, C. L. 1988. The Hardwoods of California's Timberlands, Woodlands, and Savannas. USDA FS, Resource Bulletin PNW-RB-148.

Bolsinger, C. L. 1989. Shrubs of California's chaparral, timberland, and woodland: area, ownership, and stand characteristics. USDA FS, Resource Bulletin PNW-RB-160.

Bonan GB (1994) Comparison of two land surface process models using prescribed forcings. Journal of Geophysical Research (Atmospheres), 99, 25803-25818.

Bonan GB (1996) A land surface model (LSM version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide. TN-417+STR, NCAR, Boulder, CO.

Bonan GB, Davis KJ, Baldocchi D, Fitzgerald D, Neumann H (1997) Comparison of the NCAR LSM I land surface model with BOREAS aspen and jack pine tower fluxes. Journal of Geophysical Research, 102, 29,065-029,076.

Brenkart 1998 Carbon Dioxide Emission Estimates from Fossil-Fuel Burning, Hydraulic Cement Production, and Gas Flaring for 1995 on a One Degree Grid Cell Basis http://cdiac.esd.ornl.gov/epubs/ndp/ndp058a/ndp058a.html

California Statistical Abstract. California Department of Finance. http://www.dof.ca.gov/html/fs_data/stat-abs/toc.htm

CARB 1984 California surface wind climatology Prepared by Thomas P. Hayes, John J.R. Kinney, Neil J.M. Wheeler California Air Resources Board, Aerometric Data Division, Aerometric Projects and Laboratory Branch, Meteorology Section.

Cohen WB, Maiersperger TK, Yang ZQ, Gower ST, Turner DP, Ritts WD, Berterretche M, Running SW 2003 Comparisons of land cover and LAI estimates derived from ETM plus and MODIS for four sites in North America: a quality assessment of 2000/2001 provisional MODIS products Remote Sensing of Environment 88 (3): 233-255 DEC 15 2003

CEC California Energy Commission Inventory of California Greenhouse Gas Emissions and Sinks 1990-1999 http://www.energy.ca.gov/reports/600-02-001F/index.html

Colwell, W.L. 1995. The status of vegeation mapping in California today. Pages 195-222 in Barbour, M. G. and J. Major eds. 1995.

Cooley HS, Riley WJ, Torn MS. 2003. Interactions between land cover change and climate in a coupled regional climate model. in 88th Ecological Society of America Annual Meeting, Savannah, GA.

Cooley HS, Riley WJ, Torn MS, He Y (2004) Impact of agricultural practice on regional climate in a coupled land surface mesoscale model. to be submitted to J. Geophys. Res.

Dai, Y., X. Zeng, R.E. Dickinson, I. Baker, G.B. Bonan, M.G. Bosilovich, A.S. Denning, P.A. Dirmeyer, P.R. Houser, G. Niu, K.W. Oleson, C.A. Schlosser, and Z.-L. Yang, 2003: The Common Land Model (CLM), Bull. Amer. Meteor. Soc., 84, doi:10.1175/BAMS-84-8-1013.

Davis, F. W., D. M. Stoms, A. D. Hollander, K. A. Thomas, P. A. Stine, D. Odion, M. I. Borchert, J. H. Thorne, M. V. Gray, R. E. Walker, K. Warner, and J. Graae. 1998. The California Gap Analysis Project--Final Report. University of California, Santa Barbara, CA.

DOE-EIA. Department of Energy – Energy Information Administration http://www.eia.doe.gov/emeu/states

Denning, A.S., I.Y. Fung and D.A. Randall, 1995: Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota. Nature, 376, 240-243.

Dennison, P.E., Roberts, D.A., Thorgusen, S.R., Regelbrugge, J.C., Weise, D., And Lee, C, 2003, Modeling seasonal changes in live fuel moisture and equivalent water thickness using a cumulative water balance index. Remote Sensing of Environment, 88, 442-452.

Dennison, P.E., Roberts, D.A., Peterson, S.H., and Rechel, J., Use of Normalized Difference Water Index for Monitoring Live Fuel Moisture, International Journal of Remote Sensing Letters, submitted.

Diak, George R., John R. Mecikalski, Martha C. Anderson, John M. Norman, William P. Kustas, Ryan D. Torn, and Rebecca L. DeWolf, 2004 Estimating Land Surface Energy Budgets From Space: Review and Current Efforts at the University of Wisconsin—Madison and USDA–ARS. pages 65–78. BAMS 85:1 January 2004

Dickinson, R. E., A. Henderson-Sellers, P. J. Kennedy, and M. F. Wilson, 1986: Biosphere Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model. NCAR Technical Note, NCAR, TN275+STR, 69 pp.

EPA-NEI US Environmental Protection Agency National Emissions Inventory http://www.epa.gov/ttn/chief/net/index.html

EPA-Spatial Allocator http://www.epa.gov/asmdnerl/mims/software/spatial_allocator.html

EPA- Temporal Factors http://www.epa.gov/ttn/chief/emch/temporal/

EPA-GHG 2004 US Environmental Protection Agency Inventory of U.S. Greenhouse Gas Emissions and Sinks http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2004.html

Fan S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans 1998 A Large Terrestrial Carbon Sink in North America Implied by Atmospheric and Oceanic Carbon Dioxide Data and Models Science; 282: 442-446

FIA US Forest Service Forest Inventory and Analysis http://www.fia.fs.fed.us/

Field, C.B., M.J. Berenfeld, J.T. Randerson, and P. Falkowski, Primary production of the biosphere: Integrating terrestrial and oceanic components, Science, 281, 237-240, 1998.

Field, C.B., J.T. Randerson, and C.M. Malmström, Ecosystem net primary production: Combining ecology and remote sensing, Remote Sensing of Environment, 51 (1), 74-88, 1995

FRAP Fire Perimeters California Department of Forestry and Fire Protection. http://frap.cdf.ca.gov/data/frapgisdata/select.asp

Fung IY, Tucker CJ, Prentice KC 1987. Application Of Advanced Very High-Resolution Radiometer Vegetation Index To Study Atmosphere-Biosphere Exchange Of CO2. Journal Of Geophysical Research-Atmospheres. 92 (D3): 2999-3015.

Fung, I.Y., J.A. Berry, C.B. Field, M.V. Thompson, J.T. Randerson, C.M. Malmstrom, P.M. Vitousek, G.J. Collatz, P. Sellers, D. Randall, F. Badeck, and J. John, Carbon 13 exchanges between the atmosphere and biosphere, Global Biogeochemical Cycles, 11, 507-533, 1997.

Gamon JA, Field CB, Goulden ML, Griffin KL, Hartley AE, Joel G, Penuelas J, Valentini R 1995 Relationships Between NDVI, Canopy Structure, And Photosynthesis In 3 Californian Vegetation Types Ecological Applications 5 (1): 28-41

Gao, B.C., 1996, NDWI - a Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water from Space. Remote Sensing of Environment, 58, 257-266.

GAP Analysis. California Gap Analysis http://www.biogeog.ucsb.edu/projects/gap/gap_rep.html

Gaudinski, J.B., S.E. Trumbore, E.A. Davidson, and S.H. Zheng, Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes, Biogeochemistry, 51 (1), 33-69, 2000.

Gerbig C, Lin JC, Wofsy SC, Daube BC, Andrews AE, Stephens BB, Bakwin PS, Grainger CA (2003b) Toward constraining regional-scale fluxes of CO2 with atmospheric observations over a continent: 2. Analysis of COBRA data using a receptor-oriented framework - art. no. 4757. Journal of Geophysical Research-Atmospheres, 108, 4757.

Goldstein AH, Hultman NE, Fracheboud JM, Bauer MR, Panek JA, Xu M, Qi Y, Guenther AB, Baugh W 2000 Effects of climate variability on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). Agricultural and Forest Meteorology 101 (2-3): 113-129

Goulden ML 1996 Carbon assimilation and water-use efficiency by neighboring Mediterranean-climate oaks that differ in water access
Tree Physiol 16 (4): 417-424.

Hicke, J.A., G.P. Asner, E.S. Kasischke, N.H.F. French, J.T. Randerson, G.J. Collatz, B.J. Stocks, C.J. Tucker, S.O. Los, and C.B. Field, Postfire response of North American boreal forest net primary productivity analyzed with satellite observations, Global Change Biology, 9 (8), 1145-1157, 2003.

Hurtt GC, Pacala SW, Moorcroft PR, Caspersen J, Shevliakova E, Houghton RA, Moore B 2002. Projecting the future of the US carbon sink Proceedings Of The National Academy Of Sciences Of The United States Of America 99 (3): 1389-1394.

Houghton RA, Hackler JL, Lawrence KT 2000. Changes in terrestrial carbon storage in the United States. 2: The role of fire and fire management.Global Ecol Biogeogr 9 (2): 145-170.

IDADS US Forest Service Pacific Southwest Region Insect and Disease Aerial Detection Surveys. http://www.fs.fed.us/r5/rsl/clearinghouse/tree-mort.shtml

Irvine J, Law BE, Anthoni PM, Meinzer FC 2002 Water limitations to carbon exchange in old-growth and young ponderosa pine stands. Tree Physiology. 22 (2-3): 189-196.

Janssens, Ivan A., Annette Freibauer, Philippe Ciais, Pete Smith, Gert-Jan Nabuurs, Gerd Folberth, Bernhard Schlamadinger, Ronald W. A. Hutjes, Reinhart Ceulemans, E.-Detlef Schulze, Riccardo Valentini, and A. Johannes Dolman. 2003. Europe's Terrestrial Biosphere Absorbs 7 to 12% of European Anthropogenic CO2 Emissions. Science 300: 1538-1542.

Kittel, TGF, Rosenbloom, NA, Royle, JA, Daly, C, Gibson, WP, Fisher, HH, Thornton, P, Yates, DN, Aulenbach, S, Kaufman, C, McKeown, R, Bachelet, D, Schimel, DS. 2004. The Vemap Phase 2 Bioclimatic Database I: A Gridded Historical (20th Century) Climate Dataset for Modeling Ecosystm Dynamics Across the Conterminous United States. Submitted to Climate Change.

Lobell DB, Hicke JA, Asner GP, Field CB, Tucker CJ, Los SO. 2002. Satellite estimates of productivity and light use efficiency in United States agriculture, 1982-98. Global Change Biology 8 (8): 722-735.

LCMMP first Statewide Cycle. California Land Cover Mapping and Monitoring Program. http://frap.cdf.ca.gov/data/frapgisdata/select.asp

LCMMP second Statewide Cycle. California Land Cover Mapping and Monitoring Program. http://frap.cdf.ca.gov/data/frapgisdata/select.asp

Lin JC, Gerbig C, Wofsy SC, Andrews AE, Daube BC, Davis KJ, Grainger CA (2003) A near-field tool for simulating the upstream influence of atmospheric observations: The Stochastic Time-Inverted Lagrangian Transport (STILT) model - art. no. 4493. Journal of Geophysical Research-Atmospheres, 108, 4493.

Litvak, M., Miller, S., Wofsy, S., and Goulden, M.L. 2003 Effect of Stand Age on Whole Ecosystem CO_2 Exchange in Canadian Boreal Forest. Journal of Geophysical Research 108: 8225.

Lobell DB, Hicke JA, Asner GP, Field CB, Tucker CJ, Los SO 2002 Satellite estimates of productivity and light use efficiency in United States agriculture, 1982-98 Global Change Biology 8 (8): 722-735

Mahoney et al. 2003 Strategic Plan for the Climate Change Science Program Final Report, July 2003 http://www.climatescience.gov/Library/stratplan2003/final/default.htm

Marland, G., and R.M. Rotty. 1984. Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-82. Tellus 36(B):232-61.

METAR Aviation Routine Weather Report http://www.wrh.noaa.gov/sandiego/obs/obs-srnca.html and http://www.ncdc.noaa.gov/oa/ncdc.html

Minnich RA, Barbour MG, Burk JH, Fernau RF. 1995. 60 Years Of Change In Californian Conifer Forests Of The San-Bernardino Mountains. Conservation Biology. 9 (4): 902-914.

Moore et al. 1998 Global Environmental Change: Research Pathways for the Next Decade http://books.nap.edu/catalog/6264.html

MTCLIM v4.3 Mountain Climate Simulator Version 4.3 http://www.ntsg.umt.edu/bioclimatology/mtclim/

NLCD National Land Cover Data
http://landcover.usgs.gov/nlcd/show_data.asp?code=CA&state=California_South

O'Neill et al. 1986 A Hierarchical concept of ecosystems, Princeton University Press, Princeton, N.J.

ORNL-NPP Data Oak Ridge National Laboratory DAAC NPP Database www-eosdis.ornl.gov/NPP/npp_home.html

Pacala, S. W., G. C. Hurtt, D. Baker, P. Peylin, R. A. Houghton, R. A. Birdsey, L. Heath, E.T. Sundquist, R. F. Stallard, P. Ciais, P. Moorcroft, J. P. Caspersen, E. Shevliakova, B. Moore, G. Kohlmaier, E.

Holland, M. Gloor, M. E. Harmon, S.-M. Fan, J. L. Sarmiento, C. L. Goodale, D. Schimel, and C. B. Field. 2001. Consistent Land- and Atmosphere-Based U.S. Carbon Sink Estimates. Science 292: 2316-2320.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51:1173-1179.

Penuelas J, Pinol J, Ogaya R, Filella I. 1997. Estimation of plant water concentration by the reflectance water index WI (R900/R970). International Journal of Remote Sensing. 18 (13): 2869-2875

Peterson DL, Waring RH. 1994. Overview of the Oregon Transect Ecosystem Research-Project. Ecological Applications 4 (2): 211-225.

Potter, C.S., J.T. Randerson, C.B. Field, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Klooster, Terrestrial ecosystem production: A process model based on global satellite and surface data, Global Biogeochemical Cycles, 7, 811-841, 1993.

Prince SD, Haskett J, Steininger M, Strand H, Wright R. 2001. Net primary production of US Midwest croplands from agricultural harvest yield data. Ecological Applications 11 (4): 1194-1205.

Randerson, J.T., C.B. Field, I.Y. Fung, and P.P. Tans, Increases in early season ecosystem uptake explain recent changes in the seasonal cycle of atmospheric CO2 at high northern latitudes, Geophysical Research Letters, 26 (17), 2765-2768, 1999a.

Randerson, J.T., M.V. Thompson, and C.B. Field, Linking 13C-based estimates of land and ocean sinks with predictions of carbon storage from CO2 fertilization of plant growth, Tellus Series B Chemical and Physical Meteorology, 51 (3), 668-678., 1999b.

RAWS Remote Automated Weather Station. http://www.wrh.noaa.gov/sandiego/obs/obs-srnca.html and http://www.wrcc.dri.edu/wraws/ and http://www.fs.fed.us/raws/

Riley WJ (2004b) Predicting the $\delta^{18}O$ value of the soil-surface CO_2 flux using a high-dimension model representation technique. submitted to J. Ecol Modelling.

Riley WJ, Still CJ, Helliker BR, Ribas-Carbo M, Berry JA (2003) ^{18}O composition of CO_2 and H_2O ecosystem pools and fluxes in a tallgrass prairie: Simulations and comparisons to measurements. Global Change Biology, 9, 1567-1581.

Riley WJ, Still CJ, Torn MS, Berry JA (2002) A mechanistic model of $H_2{}^{18}O$ and $C^{18}OO$ fluxes between ecosystems and the atmosphere: Model description and sensitivity analyses. Global Biogeochemical Cycles, 16, 1095-1109.

Roberts, D.A., Adams, J.B., and Smith, M.O., 1993, Discriminating Green Vegetation, Non-Photosynthetic Vegetation and Soils in AVIRIS Data, Rem. Sens. Environ., 44: 2/3 255-270.

Roberts, D.A., Ustin, S.L., Ogunjemiyo, S., Greenberg, J., Dobrowski,S.Z., Chen, J. and Hinckley, T.M., Spectral and structural measures of Northwest forest vegetation at leaf to landscape scales, Ecosystems, in press.

Roberts, D.A., Green, R.O., and Adams, J.B., 1997, Temporal and Spatial Patterns in Vegetation and Atmospheric Properties from AVIRIS, Remote Sens. Environ 62: 223-240.

Roberts, D.A., Dennison, P.E., Gardner, M., Hetzel, Y., Ustin, S.L., and Lee, C., 2003, Evaluation of the Potential of Hyperion for Fire Danger Assessment by Comparison to the Airborne Visible/Infrared Imaging Spectrometer, IEEE Trans. On Geosci. Remote Sens, 41 (6 Part 1): 1297-1310.

Sabol DE, Gillespie AR, Adams JB, Smith MO, Tucker, CJ. 2002. Structural stage in Pacific Northwest forests estimated using simple mixing models of multispectral images. Remote Sensing of Environment 80(1): 1-16.

Sarmiento and Wofsy 1999 A U.S. Carbon Cycle Science Plan http://www.carboncyclescience.gov/planning.html

Schimel, David, Jerry Melillo, Hanqin Tian, A. David McGuire, David Kicklighter, Timothy Kittel, Nan Rosenbloom, Steven Running, Peter Thornton, Dennis Ojima, William Parton, Robin Kelly, Martin Sykes, Ron Neilson, and Brian Rizzo. 2000. Contribution of Increasing CO2 and Climate to Carbon Storage by Ecosystems in the United States. Science 287: 2004-2006.

Schoenherr, Allan A 1995 printing A natural history of California University of California Press, Berkeley

Sellers, P. J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collelo, and L. Bounoua. 1996: A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model formulation. Journal of Climate 9, 676-705.

Sellers PJ, Hall FG, Kelly RD, Black A, Baldocchi D, Berry J, Ryan M, Ranson KJ, Crill PM, Lettenmaier DP, Margolis H, Cihlar J, Newcomer J, Fitzjarrald D, Jarvis PG, Gower ST, Halliwell D, Williams D, Goodison B, Wickland DE, Guertin FE. 1997. BOREAS in 1997: Experiment overview, scientific results, and future directions. Journal Of Geophysical Research-Atmospheres 102 (D24): 28731-28769.

Sellers PJ, Hall FG, Asrar G, Strebel DE, Murphy RE. 1992. An Overview Of the 1st International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE). Journal Of Geophysical Research-Atmospheres 97 (D17): 18345-18371.

Sims DA, Gamon JA. 2003. Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: a comparison of indices based on liquid water and chlorophyll absorption features. Remote Sensing of Environment 84 (4): 526-537.

SNOTEL SNOwpack TELemetry . http://www.wrh.noaa.gov/sandiego/obs/obs-srnca.html and http://www.wrcc.dri.edu/wraws/ and http://www.wcc.nrcs.usda.gov/snow/

SSURGO Soil Survey Geographic (SSURGO) Database http://www.ncgc.nrcs.usda.gov/branch/ssb/products/ssurgo/

SOCCR Terms of Reference For a First State Of The Carbon Cycle Report http://www.carboncyclescience.gov/soccr-tor30may2003final.htm

STATSGO State Soil Geographic (STATSGO) database http://www.ncgc.nrcs.usda.gov/branch/ssb/products/statsgo/index.html

Tans PP, Fung IY, Takahashi T 1990. Observational Constraints On The Global Atmospheric CO2 Budget. Science 247 (4949): 1431-1438

Tanrikulu S, Stauffer D. 1995. A numerical simulation of the transport of atmospheric tracers in the San Joaquin Valley of California. Pages 354-357 in Seventh Conference on Mountain Meteorology. AMS

Thompson, M.V., J.T. Randerson, C.M. Malmstrom, and C.B. Field, Change in net primary production and heterotrophic respiration: How much is necessary to sustain the terrestrial carbon sink?, Global Biogeochemical Cycles, 10, 711-726, 1996.

Thornton, P.E., S.W. Running, and M.A. White, 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology, 190: 214-251.

Trinidad Head, California Observations by Scripps Institution of Oceanography and NOAA-CMDL http://www.cmdl.noaa.gov/obop/thd/index.html

Trumbore SE, Chadwick OA, Amundson R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change Science 272 (5260): 393-396.

Trumbore, S., Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics, Ecological Applications, 10 (2), 399-411, 2000.

USDA-NASS National Agricultural Statistics Service Published Estimates Data Base available at http://www.nass.usda.gov:81/ipedb/

USDA-NASS 1997 National Agricultural Statistics Service Census of Agriculture http://www.nass.usda.gov/census/

USDA-NASS 2002 National Agricultural Statistics Service Census of Agriculture http://www.nass.usda.gov/census/ (preliminary as of March 2004)

USDA-NRI 2000 National Resource Inventory for 1997 http://www.ca.nrcs.usda.gov/technical/nri/NRIresults.html

Van der Werf, G.R., J.T. Randerson, G.J. Collatz, L. Giglio, P.S. Kasibhatla, A.F. Arellano, S.C. Olsen, and E.S. Kasischke, Continental-scale partitioning of fire emissions during the 1997 to 2001 El Nino/La Nina period, Science, 303 (5654), 73-76, 2004.

Van der Werf, G.R., J.T. Randerson, J. Collatz, and L. Giglio, Carbon emissions from fires in tropical and subtropical ecosystems, Global Change Biology, 9 (4), 547-562, 2003.

VEMAP2 VEMAP Phase 2 Transient Climate Dataset. http://www.cgd.ucar.edu/vemap/v2climate.html

Vogelmann, J.E., S.M. Howard, L. Yang, C.R. Larson, B.K. Wylie, N. Van Driel, 2001. Completion of the 1990s National Land Cover Data Set for the Conterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources, Photogrammetric Engineering and Remote Sensing, 67:650-652

Wieslander, A.E. 1935. A Vegetation Type Map of California. Madroño 3:140-144

Weislander, A.E. and H.A. Jensen 1946 Forest areas, timber volumes and vegetation types in California. California Forest and Range Experimental Station, Berkeley.

Wofsy and Harriss 2002 The North American Carbon Program Plan (NACP) A Report of the Committee of the U.S. Carbon Cycle Science Steering Group. http://www.esig.ucar.edu/nacp/index.html

VII. Management Plan

Mike Goulden will serve as Principal Investigator, and will be responsible for the overall project. The CoIs will be responsible for individual components of the project, including the development of deliverables and the synthesis of research. All team members have experience working on large interdisciplinary projects, including BOREAS, LBA, and NASA IDS teams. Much of the team's current funding expires in the next few years. For example, Goulden's research projects in Brazil and Canada wind down in 2004 and early 2005, at which point Goulden will shift his research focus to California and make the proposed research his highest priority.

Mike Goulden and Sue Trumbore will share responsibility for the Field Site Selection and Field Measurements. They will supervise research technicians who will do most of the work. Dar Roberts and Phil Dennison will share responsibility for analyzing and preparing remote sensing data. They will supervise a graduate student who will help with the work. Mike Goulden and Jim Randerson will share responsibility for assembling existing data sets. They will supervise a GIS technician who will do most of the work. Bill Riley will be responsible for the ISOLSM modeling. He will supervise a postdoc who will do most of the work. Jim Randerson will be responsible for the CASA modeling. He will supervise a graduate student who will do most of the work. Mike Goulden and Jim Randerson will share responsibility for the fossil fuel emissions data. They will supervise a GIS technician who will do most of the work. Bill Riley and Jim Randerson will share responsibility for the tracer modeling. They will supervise a postdoc and graduate student who will do most of the work. Mike Goulden will be responsible for the field observations of CO and CO_2 concentration. He will supervise a research specialist who will do most of the work. All team members will contribute to developing agriculture budgets, understanding the controls on California's carbon budget, and testing, validation, and uncertainty assessment.

Collaboration and data exchange, both within the group and with other groups, will be facilitated by internal and external web sites. Most of the collaborations within the group will involve subsets of the team. For example, Randerson and Riley will work together on the tracer modeling, and this research will progress without the direct involvement of the science team at all steps. At least twice a year we will hold day-long meetings with the entire science team (the travel time between the three institutions is ~2 hours, allowing us to avoid overnight trips). The initial meetings will focus on project architecture. The later meetings will concentrate on synthesis. Tentative topics and dates for the initial meeting are: (1) Site selection, September 2004 at the Burns Pinyon UC Natural Reserve located between the Mojave Desert and the San Bernardino Mountains. (2) Remote sensing products and project kickoff, January 2005 at UCSB. (3) Data exchange (format) and resolution (time and space), May 2005 at LBL.

This project is heavily leveraged off past and ongoing research. Nonetheless, it is important to realize that none of the PIs has support to work on California's carbon budgets, and the research described will not happen if the proposal is not funded.