PROJECT DESCRIPTION

NSF: Integrated Research Challenges: Biological Control of Terrestrial Carbon Fluxes

Principal Investigators: Dennis Ojima, Colorado State University
William J. Parton, Colorado State University
David S. Schimel, Colorado State University and Max Planck Institute
Co-Principal Investigators: Roger A. Pielke Sr., Colorado State University
Ron P. Neilson, USFS, Oregon State University
Steven W. Running, University of Montana
A. Scott Denning, Colorado State University
Larry E. Band, University of North Carolina
Keith Paustian, Colorado State University
Michael B. Coughenour, Colorado State University
Tomi Vukicevic, Colorado State University
Timothy G.F. Kittel, National Center for Atmospheric Research
Niall Hanan, Colorado State University

INTRODUCTION

Atmospheric CO_2 is an important control over climate, and because of recent political initiatives a currency of considerable consequence. From a global perspective, understanding the role of terrestrial ecosystems in the carbon cycle is crucial (Schimel 1995, Schimel et al. 1996, 1997, Houghton et al. 1998). From a domestic perspective, understanding the US carbon budget is a foundation requirement for sound planning and ecosystem management. Great progress has been made in recent years in measurement networks (e.g., LTER, AmeriFLUX, SOMnet), in the re-analysis of inventory data and in modeling (VEMAP 1995, Schimel et al. 1997, Paustian et al. 1996) relevant to the US C budget. In addition, 'inverse' analyses of atmospheric data (Enting et al. 1995, Ciais et al. 1995) are beginning to provide information on continental scales (Rayner et al. in press, Fan et al. 1998). Carbon research requires a high degree of integration between disciplines; and, the tools of ecology and atmospheric science have reached a point where an ambitious synthesis is feasible. We can now develop an integrated data-model system that allows us to analyze consequences of different assumptions about biology and land management on spatial patterns of atmospheric CO_2 and its stable isotopic composition. This is a powerful complement to traditional model testing against site-specific data, but the development of measurement networks and gradient studies (Hunt et al. 1996, Baldocchi et al. 1996) also greatly improves the power of in situ data-model comparisons (Schimel et al. 1997). Thus the time is ripe for an ambitious integrated analysis of terrestrial ecosystems and the carbon cycle.

The carbon cycle links biological, geochemical and atmospheric processes. For several decades, uncertainty has persisted about a major term in the carbon cycle, the so called 'missing' sink. The missing sink is associated with biological processes and stems from an imbalance in the estimated global carbon budget and is widely assumed to result from these processes in Northern Hemisphere ecosystems. However, while atmospheric inversion methods have persistently identified a CO_2 sink in Northern Hemisphere ecosystems (and one recent analysis places the bulk in North America; Fan et al. 1998), direct evidence from field studies, inventories and process modeling cannot fully account for this flux. It is unacceptable that the degree of uncertainty and conflict regarding the terrestrial sink has persisted for over a decade. To date, strategies for identifying the sink have been largely directed by geoscientists, have relied on local process studies, or have been reliant only on models without adequate validation.

Our basic hypothesis is that the magnitude and spatial distribution of net carbon fluxes (storage or release) between ecosystems and the atmosphere is controlled mainly by prior disturbance and land use, controlling the sensitivity of ecosystem carbon storage to 'ecosystem physiological' controls by CO_2, climate, nitrogen deposition and other factors.

Studies of the terrestrial carbon cycle pose a serious methodological problem of scale. Processes in terrestrial ecosystems exhibit high variability in time and space, yet from the perspective of the global carbon cycle, we are interested in ecosystem's aggregate impact on the atmosphere. Spatial variability is high enough that measurements alone cannot provide adequate estimates of either fluxes or pools over large regions, implying that models must be used for interpolation of observations. This is particularly true given our basic postulate: ***that prior disturbance and land use dominate present-day fluxes.*** This is because disturbance and land use vary in a fine-grained fashion. Yet, without regional observations, such models cannot be convincingly evaluated. Several types of measurements provide regional data not derived from point measurements. Remote sensing techniques are our principal source of wall-to-wall data and have advanced dramatically over the past few years, yet provide only weak constraints on carbon budgets (providing, basically, information on photosynthetic potential and phenology: Running et al. 1994, 1995, Hunt et al. 1996, Asner et al. 1998). Atmospheric CO_2 measurements can be analyzed to produce estimates of regional to continental net CO_2 exchange, but have wide confidence intervals and almost no spatial resolution (Enting et al., 1995, Fan et al., 1998).

We propose an innovative approach to dealing with this problem of scale mismatch by designing a model-data fusion system to allow simultaneous validation at multiple scales. We will develop a terrestrial ecosystem model drawing on the scientific advances in ecosystem modeling over the past decade (VEMAP 1995, Pan et al. 1998, Schimel et al 1997) coupled to an atmospheric model. The results of the coupled model will include:

! site-specific pools and fluxes, which can be compared to site and regional inventory data, as in conventional modeling. Fluxes due to physiological processes and disturbance (fire, harvest) will be accounted for separately.

! simulated leaf area, albedo and vegetative cover, and the resulting computed spectral reflectance, for direct comparison to remote sensing products. This will allow rigorous evaluation of spatial patterns of leaf area and of phenology.

! computed CO_2 concentrations and isotopic composition at the location of extant atmospheric sampling sites. By coupling the ecosystem and atmospheric models, we can translate the CO_2 fluxes into 'maps' of surface and upper air concentrations. Comparisons can also be made to aircraft missions.

Together, these three levels of validation, none sufficient individually, constrain:

1) Local fluxes and pools, hence the basic processes in the model;
2) Spatial-temporal patterns of leaf area and hence phenology; and
3) The continental scale integral of the fluxes.

Satisfying these three constraints will provide strong evidence of whether the model estimates are reasonable, and the extent to which the underlying processes are represented correctly. While there may be multiple explanations consistent with these constraints, systematic evaluation will also certainly exclude many hypotheses.

Our approach to the scaling problem is thus to develop hierarchical methods, each of which can be tested and evaluated against specific extant data. The process-based model components developed by the project will be tested against plot- to landscape-scale data (e.g., inventory, FACE, and eddy covariance studies) for well-studied sites across gradients in climate, edaphic setting, and land-use. The model will then be used to predict spatial patterns and mosaics of biological properties over larger areas using climate and soils data and land-use data, and these scaling algorithms will be tested against remotely sensed vegetation state (AVHRR, MODIS, LandSat 7, Running et al. 1994, 1997). In addition, the interactions between ecological and atmospheric processes in the model will be tested across spatial scales at the tall tower sites in Wisconsin and Oklahoma.

The 450 m tall WLEF-TV tower in Wisconsin has been instrumented for measurement of climate and CO_2 at 6 levels (11 m to 400 m), and for fluxes of CO_2, heat, and moisture at 3 levels (30 m, 122 m, 396 m) since 1996 (Bakwin et al., 1998). In 1998, a boundary-layer wind profiling radar was installed at the site (Angevine et al., 1998; Ken Davis, personal communication), allowing a quantitative evaluation of the coupling between ecosystem fluxes and atmospheric mixing at the site. The system allows direct evaluation of simulated fluxes from a heterogeneous forest landscape across scales with a footprint of 10^4 m^2 at the bottom of the tower to 10^7 m^2 at the top (http://biocycle.atmos.colostate.edu/WLEF). A second 100 m tall tower is being instrumented in Oklahoma (Joe Berry, Stanford University, personal communication), which will allow us to test scaling algorithms over grassland and cropland ecosystems. Ancillary data available at this site includes detailed meteorological data (radiation, winds, boundary-layer height). Using the observational constraints available at the tall tower sites, the scaling algorithms can be confidently applied to make continental scale estimates of ecosystem carbon exchange in a completely self-consistent manner with the simulated atmospheric transport in RAMS. These calculations will produce full 3-dimensional gridded estimates of the concentration and isotopic composition of atmospheric CO_2 over the US, which can be directly compared to flask samples, in situ-data, and aircraft sampling which will take place in 2000 and beyond (S. Wofsy, COBRA program, personal communication).

We will use a powerful mathematical technique in operating this system. In meteorology “data assimilation” is used to continually adjust model state variables towards observations. The atmosphere is chaotic (in the mathematical sense) and hence models are dependent upon imperfectly-observed initial conditions. Data assimilation adjusts all of the state variables in a model domain towards observations, interpolating between observations in a manner consistent with the model physics. Thus, a knowledge of fluid dynamics and thermodynamics ‘constrains’ the interpolation, blending a knowledge of theory with observations. We will operate the coupled atmosphere-ecosystem model in a data assimilation mode, relying at least initially, on atmospheric observations. This will allow us to use the atmospheric model to provide radiation, temperature and precipitation to the ecosystem model in a way completely consistent with the computed transport of CO_2. We will also assimilate site and satellite data experimentally in order to test whether they can be used operationally to improve the fidelity of ecosystem models.

Developing the data assimilation system also requires the development of an important mathematical tool for understanding the system. This tool, known in the earth sciences as the ‘adjoint’ can, in this application, be thought of as a transformation of the matrix of partial derivatives of the state variables with respect to the model parameters. While this is used in the interpolation process, it also provides a powerful tool for sensitivity analysis. Specifically, it helps identify the parameters that most influence the model solution and under what conditions (values of state variables) those influences change. We will develop the adjoint to the entire coupled model and it will be available for a unique analysis of the sensitivity of the ecosystem processes to their controls as well as a tool for the potential ‘assimilation’ of ecosystem observations. This proposal is a serious effort to deal 1) to multiple scales in ecosystem dynamics, 2) to deal up-front with the dominant role of land use in North American ecosystems, and also 3) an initiative to introduce powerful new analytical (mathematical) tools into ecology, a tool that provide a new formalism for ecologists to blend theory and observations.

RESEARCH SCOPE

We will conduct a detailed analysis of data and models of carbon fluxes to test the hypothesis that the United States region is a large sink of CO_2. Our hypothesis is that the magnitude and spatial distribution of a sink in the US must be determined by prior land use and disturbance, modifying the sensitivity of ecosystems to other controls (e.g., CO_2, climate, N deposition). Preliminary results suggest that ecosystem physiological processes can result in a sink in 1990 of about 0.1-0.3 gigatons of carbon based on an intercomparison of 8 models. Direct analyses of inventory data suggest a sink of 0.4 (by inventory) to 1.7 (by atmospheric inversion) for southern North America. We further hypothesize that community processes (forest regrowth) initiated by logging and disturbance dominate sink processes, in synergism with direct physiological effects of CO_2 and nitrogen deposition.

While a comprehensive experimental and empirical effort to quantify the terrestrial sink is beyond the scope of this program, we propose a systematic study integrating extant observational data (flux and inventory studies), experimental data and modeling, and results from global and regional scale atmospheric analyses. This activity builds on a number of ongoing, but fragmented, initiatives and links them using an overarching biological framework. We bring as tools to this study the detailed climate data for 1895-1995 prepared by the Vegetation and Ecosystem Modeling and Analysis Project (VEMAP). In addition we will incorporate the biological expertise developed during the past decade on biological determinants affecting carbon assimilation, storage, fluxes, and losses of the terrestrial biosphere.

Our understanding of the biological controls of carbon fluxes between the atmosphere and the land surface (referring to the soil, vegetation, water system) is critical to our estimation of net terrestrial carbon fluxes and the connection of key natural resources (e.g., water, vegetation, soils, etc) to climate and land use changes (Figure 1). Terrestrial biological processes respond strongly to atmospheric temperature, humidity, CO_2 levels, N-deposition, precipitation, and radiative transfers. In addition, biological changes due to disturbances such as fire, pest outbreaks, herbivory, cultivation, or deforestation, have a large impact on the processes that affect the net carbon exchange. Changes in the plant community and the composition of plant functional types alter the rate of carbon assimilation and carbon released through decomposition.

Integration of land use with biological, atmospheric and hydrological processes will allow us to estimate net carbon exchange from the terrestrial biota.. However, proper handling of scale is critical to the success of the analysis of this set of complex interactions (Rastetter et al. 1993). Some of our recent efforts have made progress in the understanding of the ecosystem metabolic feedbacks that couple the terrestrial biosphere to the atmosphere (i.e., photosynthesis, decomposition, evaporation, transpiration) (Figure 1) which control carbon, energy, and water exchanges (Walko et al. in press, Vidale et al. 1997, Eastman et al. 1998). These feedbacks operate rapidly and are calculated many times each hour. Biogeochemical and ecosystem interactions with atmospheric processes have recently been implemented using the Century-RAMS models at Colorado State University (Lu et al. 1997, Ojima et al. 1997, Pielke et al. 1997). These research efforts have been directed at developing a better understanding of how the biosphere coupling to the atmosphere change over time as ecosystem processes changes the constraints on water, carbon, and energy fluxes (Schimel et al., 1990, 1994, Ojima et al., 1991, Ojima 1992). Slower changes in ecosystem state through woody biomass and soils also affect net carbon exchanges in response to climate and land use changes. Our understanding of the long term changes in the terrestrial

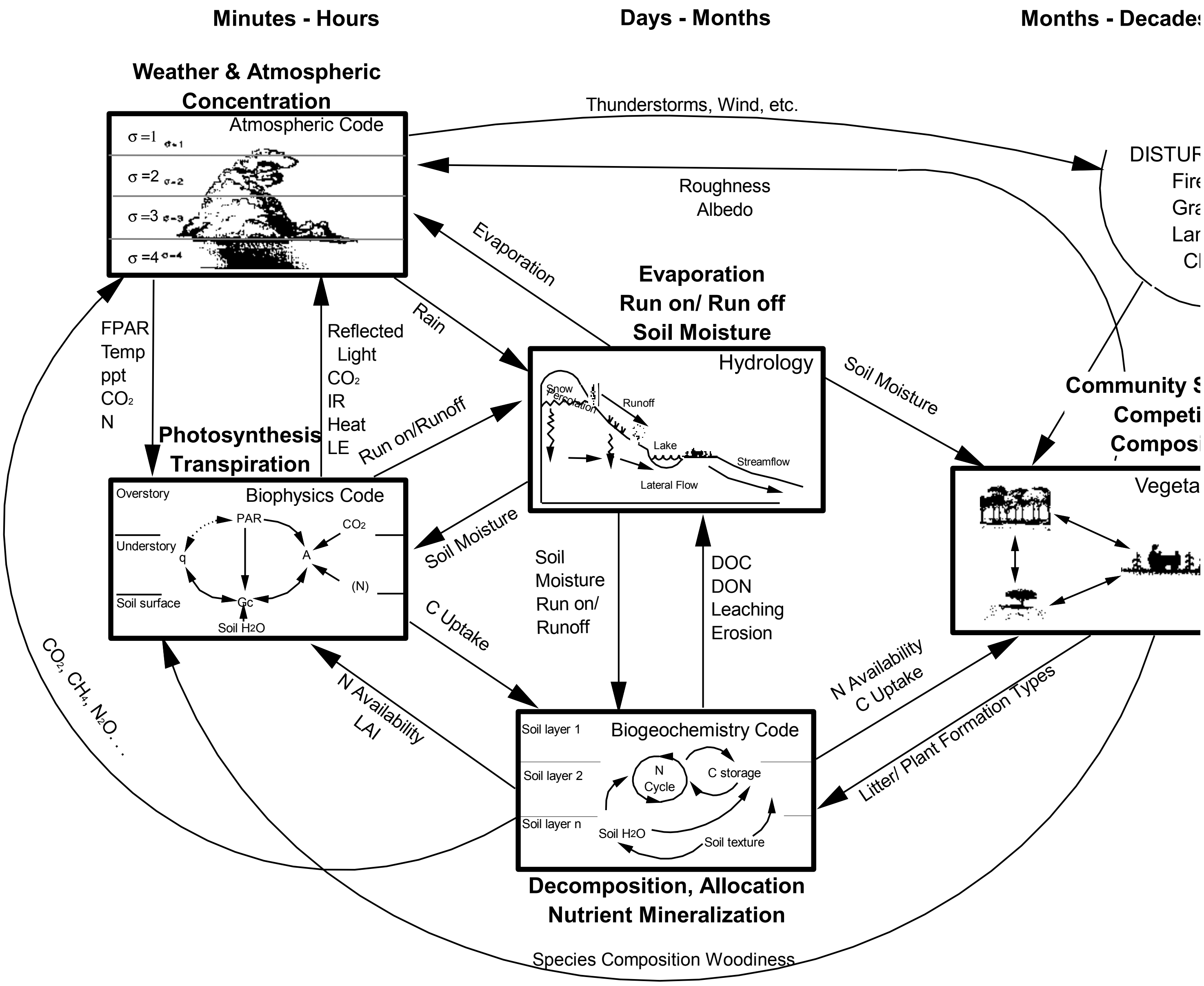

Figure 1. Conceptual framework for understanding and evaluating net carbon fluxes from terrestrial ecosystems. Atmospheric component includes processes needed to predict precipitation, temperature, shortwave and longwave radiation, humidity, winds, and atmospheric chemical composition of CO2 and nitrogen. The biophysical processes include photosynthesis, transpiration, stomatal conductance, and respiration and provides estimates of fluxes of carbon, water, and energy exchange. The hydrology components represent processes controlling runon/runoff, infiltration, evaporation, storage and flow of water. The biogeochemical component represents the decomposition, allocation, nutrient turnover, and microbial process accumulation. The vegetation component represents the plant community dynamics related to competition, land use management, disturbance responses, and successional dynamics that affect land cover dynamics, stand age, and vegetation structure. A disturbance generator is included to trigger fire, grazing, and other land use events which are appropriate for the biome and land use.

biosphere will provide greater insight to the environmental sustainability under different stresses and provide an indication of how different regions may respond to changes in climate, disturbance regimes, and land use (Schimel et al., 1991, Schimel 1992).

RESEARCH APPROACH

! Model Development. The project will develop a modular framework linking disturbance and management to life form distribution and biogeochemistry to estimate terrestrial net carbon exchanges. This framework will be developed by our team, but with input from colleagues and potential users on a regular basis. The model will be a ‘community’ model designed to be operated remotely and on multiple platforms. Both model code and large output data sets from important experiments will be made available to the community, with documentation and metadata. This model will take advantage of lessons learned by the participants and will use science from extant models. However, instead of simply ‘linking’ extant models, we will integrate the important components and processes in order to evaluate changes in terrestrial carbon fluxes.

! Input Parameter Development. We will a synthesize existing data needed to operate the model. These include soils, meteorology and land use histories. The soils and weather data are straightforward (www.ucar.cgd.edu/VEMAP/: Kittel et al. 1997, NCEP reanalysis, Kalnay et al., 1996). We will emphasize the development of spatial land use histories (e.g., LUHNA, FIA, NRI, Crop statistics) containing sufficient information to operate the model. This activity will draw on existing efforts being conducted by Ojima, Parton, Paustian, Joyce, in developing agricultural, forestry, and natural disturbance patterns for biomes in the United States. This is a large task, that will be progressively refined over time.

! Validation and Data Development for the analysis of the US carbon budget. We will begin by evaluating our model system against ‘traditional’ in situ observations such as NPP, soil carbon/biomass data. We will then integrate the continental model and compare the simulated patterns of atmospheric CO_2 against observations. This requires coupling the terrestrial model and estimated spatial/seasonal fossil fuel fluxes to an atmospheric model. We will use a well-tested model (RAMS, Pielke et al. 1992, Uliasz et al.1996) operated in a ‘data assimilation mode’, a mathematical approach where the model is continuously adjusted to observations of key variables widely used in forecast studies. Data assimilation is a mature technology in the atmospheric sciences and will permit the model to produce transport winds, turbulent fluxes, and weather close to observed conditions. This will make both the weather used as input to the ecosystem model and the transport used to compare simulated to observed CO_2 consistent and close to reality. We will thus evaluate the carbon budget spatially, and against pools and processes in an integrated fashion via the atmospheric winds.

Relevancy of Biological Interaction to Global Cycles

Carbon is the major building block of life on Earth, and is also, as CO_2 , a major greenhouse gas. One cannot adequately address the changing atmospheric CO_2 concentrations without understanding the dynamics of the terrestrial biota. This proposal addresses the 1) the role of terrestrial biological systems in modifying net carbon exchange and 2) evaluating the consequences of global environmental change on terrestrial biosphere. The interdisciplinary research team will incorporate analysis of field experimentation into the development of a multi-scaled, multi-process terrestrial biosphere model linked to hydrological and atmosphere transfer models to assess the net carbon exchange from terrestrial ecosystems.

PROJECT DESCRIPTION

We build upon several recent advances in evaluating interactions among plant physiology, plant community, land use management, ecosystem, and biogeochemical processes which affect carbon exchange and biogeochemical cycles of terrestrial ecosystems. Recent analyses indicate that changes in climate modify properties of the terrestrial biosphere and biogeochemical processes that cause lags in the exchange of carbon and water (Braswell et al. 1997, Houghton et al. 1998). In addition, changes in plant communities and disturbances regime, such as fire patterns, may be altered and modify the vegetation structure resulting in changes in the terrestrial biosphere properties (Ojima et al. 1997, Lenihan et al. 1998). Analysis of these interactions between long-term changes in the terrestrial biosphere and the fast response time of biophysical-atmosphere feedback is a fundamental component of the carbon exchange being studied in the global sciences (Ojima 1992). The focus of the project will be the development of an integrated approach to evaluate terrestrial biological controls on carbon dynamics and estimate the net carbon fluxes from managed and natural ecosystems of the conterminous United States.

The project will be implemented to accomplish the three sets of tasks identified above:

C Model Development
C Input Parameter Development and Analysis
C Validation Data Development

The following sections will provide detail of the research tasks.

MODEL DEVELOPMENT: Nature of the Interacting Processes

Parton, Ojima, Neilson, Band, Running, Pielke, Coughenour, Schimel in collaboration with Wedin, Chapin, Joyce

Modern landscapes are diverse mosaics where lands that were originally native grasslands or forests have been heavily modified for agriculture, urban, or industrial uses. We will define various submodel components such as photosynthesis model, carbon allocation, biogeochemisty, disturbance generator, land use management, soil hydrology, succession, plant community development. We will use scientific concepts developed from field and laboratory analysis and evaluated in models. The plant community will be represented as plant functional types (e.g., evergreen needle-leaf trees, deciduous broadleaf trees, evergreen shrubs, N-fixing shrubs, cool season tall-grasses, warm season short-grasses, etc). The biogeography will determine the structural attributes of the plant community and leaf longevity and type (e.g., broadleaf-needleleaf, evergreen-deciduous and other physiognomic characteristics). Each of these plant functional types will be defined by structural, lifeform, physiological, biogeochemical, and disturbance response characteristics (Neilson 1995). Crop types will be included with the definition of the different plant functional types. The vegetation structure will have a multiple layer structure to represent canopy and understory components. The soil processes will be represented with multiple soil water layers to represent rooting depth of different functional types and water availability for different soil conditions. This soil profile representation will accommodate root differentiation and soil water dynamics which would control plant and near surface layer for soil microbial processes.

The atmospheric CO_2 levels affect the land surface-atmosphere interactions since these interactions control the transpiration from terrestrial ecosystems. These processes are tightly coupled through biophysical and atmospheric processes with rapid feedbacks (i.e., minutes to hours) of water and energy fluxes between these two components. The land surface biophysical properties are controlled by the state of the soil moisture and the vegetation (Schimel 1992). The rate of transpiration, evaporation, and carbon assimilation, are affected by the partitioning of water and energy fluxes from the land surface. These rates are also dependent on the amount of leaf area, dead plant material, and bare ground.

Plant carbon uptake responds rapidly to changes in temperature, light, moisture, and CO_2 levels. We will capture diurnal processes such as leaf and soil energy balance and photosynthesis, and longer temporal domains for other plant growth processes (i.e., weekly to monthly; Schimel et al. 1991, Chen et al 1994, Coughenour and Chen 1997). Daily weather data will be used to modify these processes. Photosynthesis will be based on concepts of Farquhar et al. (1980), that considers the relative limitations of rates of ribulose 1,5-biphosphate (RUbP) carboxylase fixation of internal leaf CO_2 and RUbP regeneration, and RUbP oxygenation. Reaction rates respond to temperature according to Arrhenius functions, that generally exhibit temperature optima. The CO_2 fixation of RUbP is limited by mesophyll CO_2 concentration in C_3 species and by bundle sheath CO_2 concentration in C_4 species. Assimilation rate is reduced by low soil water content and leaf nitrogen. Dark respiration responds to temperature with a Q_{10} function.

Net fixed carbon can be stored as labile carbon within the plant. Respiration costs associated with tissue biosynthesis and maintenance are calculated after Ryan (1991). Maintenance respiration is a function of nitrogen content, as well as temperature according to a Q_{10} function. Carbon is allocated to structural root vs. shoot tissues dependent upon water and nitrogen stress (Coughenour 1991, 1993, Coughenour and Chen 1997). Tissue mortality rates respond to water stress, and to tissue age in the case of leaves. Nitrogen is taken up by roots and allocated in relationship to leaf age. Nitrogen is retranslocated during tissue mortality to still living tissues. Biomass production models interact with tillering and phenology submodels. Tillering depends on water, temperature, nitrogen and labile carbon. Phenology advances in response to growing degree day sums and daylength, but soil temperature and moisture may also trigger phenological change. Carbon assimilation concepts will be related to plant community type, stand age, resource limitations, phenology, and plant functional type.

The biogeochemical scheme will be based on multi-pool soil organic matter representation utilized by Parton and others (Parton et al., 1987, 1996, Jenkinson 1990, Jenkinson et al. 1991). Processes related to soil-plant interactions controlling organic matter dynamics will be represented in three major components which include active, slow, and passive soil C. Active SOM includes live soil microbes plus microbial products (the total active pool is approximately 2 to 3 times the live soil microbial biomass), the slow pool includes resistant plant material (for instance, lignin-like components) and soil-stabilized plant and microbial material, while the passive material is very resistant to decomposition and includes physically and chemically stabilized SOM. The flows of C are controlled by the inherent maximum decomposition rate of the different pools and the water and temperature-controlled decomposition factor. Microbial respiration occurs for each of the decomposition flows. The partitioning of decomposition between stabilized SOM and CO_2 flux is a function of soil texture for the stabilization of active C into slow C (increasing CO_2 flux for sandy soils and less soil C storage). Justification for these assumptions are presented in the earlier CENTURY paper (Parton et al., 1987, 1994, 1996).

The N submodel has the same general structure as the soil C model. The organic-N flows follow the C flows and are equal to the product of the carbon flow and the N:C ratio of the state variable that receives the C. Each soil state variable has prescribed bounds on its C:N ratio, and within those bounds, the C:N ratio varies as a function of soil mineral N. Based on the C:N ratio, and microbial respiration, each compartment can either release or take up N. The model also uses simple equations to represent N inputs due to atmospheric deposition and N fixation and calculates N losses due to N_2, NO, N_2O, and NH_3 gas fluxes and NO_3 leaching. A more complete description and justification for the N submodel is presented by Parton et al., (1987, 1994, 1996).

Disturbance regimes, such as storm, fire and grazing, will be either endogenous to the system or prescribed from local land use histories. When simulated, fire regimes will be triggered by combinations of climatic and vegetation characteristics (Lenihan et al., 1998). The frequency and intensity of fires can be generated within the disturbance generator. The fire model determines when to burn and the characteristics of the burn. Detailed information about the burn is communicated back to the biogeochemistry model for adjustments of carbon and nitrogen pool sizes in numerous live and dead vegetation compartments. The fire model contains an allometric rulebase for detailed determination of 'stand' structure and calculations of live and dead fuel loadings (Rothermal 1972). The allometry includes height information useful for succession and biosphere-atmosphere feedbacks. Grazing impacts will be prescribed based on known patterns of herbivory of shoots and leaves. Losses of carbon and nitrogen through erosional events will also be included.

The model will be represented for grain, vegetable, and tuber crops. Fruit-bearing systems will be represented as a modified forest. In cropping system, the impact of different land management practices on crops and on soil organic matter dynamics will be represented. These include types of tillage practices, harvesting techniques, crop residue management, irrigation, fertilizer application and herbicide use. The managed forest systems include management practices such as harvest rotations, fire regime, clear felling, selective harvesting, seedling establishment and so on.

The agricultural systems will be tested against a number of crop data sets including detailed analysis of the impact of different organic and fertilizer inputs. Historical patterns (1930-1990) for crop yields for irrigated and dryland crops in the Great Plains are available for different counties across the United States and can be used to evaluate the trends in crop yields as a function of changes in management practices (e.g. fertilizer and tillage practices) and crop varieties. The managed ecosystems will be evaluated and tested against site and regional data sets of different land use practices on plant production, nutrient cycling, soil organic matter dynamics and other environmental factors used earlier by our research team (Schimel et al., 1990; Paustian et al. 1992, Burke et al., 1991, 1994, Ojima et al., 1993; Parton et al., 1993, Parton and Rasmussen 1994, Kelly et al. 1997).

Simulations and long-term observations strongly suggest land use changes influence climate and feeds back to land surface processes, vegetation changes, and watershed hydrology (Baron et al. 1998, Stohlgren et al. 1998, Chase et al. 1997). The net flux of carbon is affected by a number of process interactions between components of the land-atmosphere, and are presented in Figure 1. These include atmosphere-biophysical transfers with rapid response times (e.g., minutes to hours); interactions with hydrological routing that modifies soil water balance, runon-off partitioning, snow-melt and streamflow. Biogeochemical processes also interact with the biophysical-atmosphere interactions and the hydrologic routing. Hydrological and climate properties affect process rates of decomposition, mineralization, trace gas fluxes, mass loss of nutrients and carbon. Vegetation processes, including establishment, competition, mortality, and community development, determines vegetation type (Sykes et al., in press). The vegetation type and state of the vegetation determine land surface properties related to leaf area, woodiness, height of vegetation, allocation of biomass to shoots and roots. These properties have major influences on biogeochemical cycling and on the biophysical processes (Ojima et al., 1991).

Hydrological Considerations

Hydrological processes are potentially important to tracking carbon. Non-uniform redistribution of water may have a significant and nonlinear impact on soil moisture and hence biogeochemistry. Bob Stallard (1998) recently advanced the hypothesis that burial of carbon eroded from managed lands in local depositional sites and in reservoirs could be quantitaively significant in the carbon cycle. We will, in an experimental fashion, design our modeling system to couple to a spatially-explicit hydrological model. The hydrological representation related to different land surface characteristics will be important for us in evaluating the importance of these erosional events. The issue of subgrid-scale variability has been a concern in land surface process modeling due to the potential bias in mean grid cell computed storage and flux. Within the dimensions of grid cells we will be using (10-50km.) there will be a range of surface conditions characterized by varying topography (altitude, slope, exposure, upstream drainage area), land use, soils and vegetation. Locally, this can cause significant variation in the storage and flux of carbon, water, and energy. We have experimented with a number of ways of representing and computing the range of landscape soils, topography, vegetation and wetness conditions within watersheds by coupling TOPMODEL with FOREST-BGC and BIOME-BGC over a range of watershed sizes (Band 1993, White and Running 1994, Baron et al. 1998), using a statistical area-weighting of flux. This approach has been extended to include an interacting, rather than prescribed, atmosphere by coupling LEAF with TOPMODEL as a distributed land surface process model for RAMS (Walko et al. in press). We will continue developing this approach with a goal of finding the minimum number of land surface elements that need to be represented and area weighted to gain unbiased estimates of grid cell flux. Much of this work will begin by running the land surface process models off-line for a set of different physiographic, climatic and land cover scenarios to find the optimal weighting schemes (minimum number of land elements gaining a prescribed level of accuracy) appropriate for the different regions of the country. Part of this work will be used to define those cases in which sub-grid scale variability is significant or is not significant, and can be ignored. For those cases in which land use and topography vary significantly within a grid cell, we may need to combine the areal weighting approach within grid cell mosaics.

Programming Framework:

During the past decade, terrestrial biologists have made great strides in better understanding process linkages across fields of community, landscape, and ecosystem level dynamics. The integration of these biological fields has been a major aspect of environmental studies during the past decade. Projects like the Vegetation Ecosystem Model and Analysis Project (VEMAP) exemplify the level of development in the integration of terrestrial biology to investigate the impact of climate change on biomes in the United States. Building on the experimental, analytical, and theoretical development of our understanding of the biosphere interactions with other environmental components, we will begin to fully integrate this knowledge into a modular framework which will incorporate the best aspects of terrestrial biosphere models.

This modular framework will integrate portions of existing models that have been tested and evaluated over the past decade. This development will greatly improve current linked model studies since it will reduce the redundancies among the models and provide an additional benefit to allow for testing of alternate hypotheses of various representations of different processes. This framework will assist in model development and experimentation since the support routines are common across submodels. The essential nature of this framework is:

C Modularize the model to separate out the science modules
C Centralize uniform I/O set routines
C Integrate space and time coordination among processes
C Provide distributed computing support
C Support a friendly user interface

One benefit is that the support structures (input file specification, output variable selection, time and space looping) can be developed and tested separate from the science modules. This is especially valuable in developing and debugging distributed computing applications. Input and output specifications will handled by a component of this modular framework.

INPUT PARAMETER DEVELOPMENT AND ANALYSIS: Model Input Requirements and Output Parameters

(Ojima, Paustian, Parton, Kittel, in collaboration with Joyce, Wedin, Harmon, Houghton, Chapin, Foley, Brown)

The project will develop a modeling framework to incorporate the critical biological components controlling carbon dynamics. It integrates aspects of disturbance regimes and management activities to estimate net carbon exchange in the conterminous United States. This framework will be used in conjunction with a range of observational and experimental data bases, and considerable effort will be put into organizing and synthesizing these data so they can be used in tandem with models and other analyses. We will reconstruct historical industrial fossil fuel emissions for the US based on compiled information available at the Carbon Data Information Analysis Center (CDIAC, Marland et al., 1999, http://cdiac.esd.ornl.gov/ndps/ndp030). Data sets include reprocessed data from the USFS Forest Inventory Assessment (FIA, http://srsfia.usfs.msstate.edu), process-level data from the LTER network and other similar studies, such as the Oregon Transect and the La Copita, TX savanna site, soils data from USDA data bases as well as the VEMAP project gridded climatology of the US. Land use patterns for cropping systems across the US will be developed for analysis and input into models. We will incorporate information from the National Resource Inventory and the NASS data bases of land use in the nation for the past 3 decades. Longer-term land use patterns will be developed using historical data, county level statistics of agricultural yields, and from information compiled by the USGS Land Use History of North America (website: www/biology.usgs.gov/luhna). While the available data are insufficient to use alone in calculating a carbon balance, they provide strong multiple constraints on model based estimates. Thus, we will emphasize a model-data fusion approach to produce improved estimates and most importantly estimates in which sources and magnitude of uncertainty are well-defined.

We are actively engaged in assembling a variety of national level database on climate, soils, landuse and management of US agricultural lands, many of which are fully spatial and incorporated into GIS. Some of the major databases being used to support regional and national analysis and modeling of soil C dynamics in agricultural lands are listed in Table 1.

Table 1. Land use management data sources.

Database	Description	Source
PRISM - climate	precipitation, max and min temperature for 4 km2 grids, topographically adjusted, for conterminous US	Natural Resource Conservation Service (NRCS)
STATSGO (Soil Survey Geographic Data Base)	Comprehensive soil properties for assoc-iations 1:250,000 for conterminous US	NRCS
MUIR (Map Unit Interpretation Record)	Soil characteristics for soil series in the US	NRCS
NRI (National Resources Inventory)	Land use, management and soils information for > 800,000 points in the US, with re-measurement in 1982, 1987, 1992 and 1997	NRCS
GIRAS	Land-cover and vegetation (50 m2 resolution), derived from air photos, for conterminous US	USGS
AVHRR based landcover maps	1 km2 resolution for land-cover and vegetation in conterminous US	USGS
CTIC (Conservation Tillage Information Center)	County-level information on crop acreage by tillage practice for 1978-present, for conterminous US	CTIC, Purdue Univ.

Conservation Reserve Program (CRP) database	Acreage, soil type, yields and type of conservation practice for all CRP contracts (since 1985) in US (> 350,000)	USDA
NASS (National Agriculture Statistics Service)	Crop yield and acreage for all major crops, at the county-level, for US (1972-present); state-totals from 1866-present	USDA
Agriculture census	Crop acreage, crop yields, economic information, at county level for conterminous US (most recent in 1997)	Bureau of the Census, Dept. of Commerce
Long-term agricultural experiment network	Soil C and N measurements, crop yields, climate summaries, detailed management histories for 40 long-term experiments (> 10- > 100 years in duration) in US and Canada	Colorado State University

VALIDATION AND DATA ASSIMILATION METHODOLOGIES:

(Schimel, Pielke, Denning, Running, Hanan, Vukicevic in collaboration with Wofsy, Baldocchi, Randerson)

Validation.

Selected sites, such as the First ISLSCP Field Experiment (FIFE) site and the Cooperative Atmosphere Surface Exchange (CASES) at the Walnut River Watershed in Kansas, provide invaluable information of fluxes of water, energy, and CO$_2$, simultaneous observations of meteorological conditions, soil moisture status, and vegetation condition for several time periods across different years. Data to test the coupled model will take advantage of the LTER sites, such as the Harvard Forest, HJ Andrews, Coweeta Watershed, the Short-Grass-Steppe, and the tallgrass prairie site at Konza. In addition, land surface flux studies are available from the CASES data (LeMone and Grossman in eastern Kansas), FIFE data, and other data sets that will be available as part of the Department of Energy Atmospheric Radiation Measurements (ARM) Program's Cloud And Radiation Testbed (ARM/CART) sites in Kansas and Oklahoma and the Global Continental-Scale International Project (GCIP) of Global Energy and Water Experiment (GEWEX) initiatives of NOAA in the central U.S. resource systems to extreme hydrological events. This evaluation of the model at these sites will provide a critical test of the overall structure of interactions implemented in the model.

Biogeochemical and vegetation components will be evaluated by grid cell comparison to Long Term Ecological Research (LTER) observations and with remote sensing data sets. We will verify hydrological routing by comparing simulated hydrological output with observations from unregulated stream flow data for areas of the Rocky Mountains and other regions (USGS records). We will use satellite data to estimate snow cover and water equivalent in various areas, as well as moisture stress indices.

In addition to comparing simulation results with observations from intensive study sites, we will make use of remote sensing data to perform extensive spatial and temporal evaluations of several of the key model prognostic variables. The past decade or more of AVHRR data provides a long baseline period for evaluating modeled phenology and for use in the analysis of terrestrial biosphere dynamics in conjunction with the observed historical atmospheric CO$_2$ data. New sensors will provide similar data but of much higher quality. In particular, we will be able to take great advantage of the daily 1-km^2 resolution multispectral data collected by the MODIS instrument. MODIS (Moderate Resolution Imaging Spectroradiometer) is the primary daily global monitoring sensor on the NASA Earth Observing System (EOS) satellites, scheduled for launch in 1999 and 2002 (Running et al., 1994). These satellite data from TM, AVHRR, and MODIS sensors will provide spatial and temporal estimate of land surface features such as, vegetation LAI, vegetation structure using BRDF algorithms, and productivity over complex terrain and larger regions (Asner et al. 1998). The availability of new sensors that provide greater information of atmospheric and land surface vegetation and soil moisture conditions will enhance our ability to test the new model. The combined analysis of MODIS and MISR sensors in the coming year will provide an ideal verification data set of several important parameters.

As the primary EOS sensor collecting data relevant to terrestrial biospheric processes, the MODIS instrument is designed to provide the land science community with information critical to the investigation of carbon cycles and human-induced changes at large spatial scales (Asrar and Dokken, 1993, Running et al. 1994). There are two such sets of products particularly relevant to our proposal: landcover and landcover change (LC-LCC), and leaf area index and fractional absorption of photosynthetically active radiation (LAI-FPAR). The LC-LCC products are updated annually, and the LAI-FPAR products are generated once every eight days using composited daily data. Both sets of products have global coverage on a grid with 1 km spacing.

There is a clear conjunction between these MODIS products and the prognostic variables of the terrestrial biosphere NEP model we aim to create, and the spatial and temporal coverage of the MODIS products will provide us with a unique opportunity for model evaluation. There are three groups of model prognostic variables of fundamental importance to the goal of a regional carbon cycle assessment that can be directly compared with MODIS products for model evaluation: landcover and landcover change, leaf area index and radiation absorption, and the seasonal timing of changes in leaf area.

In addition to an analysis of the spatial patterns of LAI and FPAR on the basis of landcover type, the MODIS LAI-FPAR products will provide a powerful tool for assessing the seasonal dynamics of leaf area change (leaf phenology). The model logic will include predictions of the timing of new leaf growth and leaf litterfall, based on reasoning from plant physiology as well as empirical parameterizations (e.g. White et al., 1997, Thornton et al., in prep.). The 8-day frequency of the MODIS LAI-FPAR products will permit a direct comparison of modeled and observed relationships between leaf area changes and climatic indices over a range of landcover types.

Model predictions of ecosystem flux will be tested across spatial and temporal scales by prediction of the concentration and isotopic composition of atmospheric $CO_{2.}$ This approach allows a direct evaluation of scaling algorithms across the model components, as described above. In addition, the atmospheric properties allow evaluation of the integrated performance of the model at the largest spatial scales, by comparison to data collected by flask sampling networks, in situ sampling, and aircraft.

Simulation of the continental-scale CO_2 in the atmosphere is an ambitious task, requiring more than correct representation of ecosystem processes. Covariance between photosynthesis and atmospheric mixing must be correctly simulated (Denning et al., 1995, 1996, 1999), fossil-fuel emissions must be correctly prescribed, and the spatial and temporal structure of atmospheric properties at the lateral boundaries must be specified. We have developed methods for quantitative simulation of the ecosystem-atmosphere covariance (“rectifier”) effects in RAMS (Denning et al., 1996). Anthropogenic emissions will be specified from monthly data recently collated by Bob Andres at the University of Alaska and distributed according to population density. Lateral boundary conditions for the concentration and stable isotopic composition of atmospheric CO_2 will be specified from global simulations using the CSU GCM (Denning et al., 1996). Carbon isotopic fractionation will be calculated by methods similar to those of Fung et al. (1997), and the isotopic composition of oxygen in CO_2 will be determined by methods similar to those of Ciais et al. (1997).

Data Assimilation.

We will develop new applications of data assimilation from physical sciences for ecological systems. These advanced optimal data assimilation techniques have been developed for large forecast systems: 1) Kalman Filter (KF) based techniques (Cohn and Toddling, 1996) such as the Physical-space Statistical Analysis System (PSAS, developed at NASA Goddard) and 2) variational techniques such as the Statistical Spectral Interpolation (SSI) scheme (Parish and Derber, 1992; NCEP's global data analysis system) or regional 4D Variational (4DVAR) systems at NCEP and NCAR (Zupanski and Zupanski, 1996; Vukicevic and Bao, 1998; Zou and Kuo, 1996). These advanced techniques, although more demanding computationally, have significant advantages over more traditional local interpolation techniques. These advantages are: {1.} Data analysis is performed in a physically and dynamically consistent manner with a physical and dynamical model involved in the analysis; This model represents complex relations between different observed and unobserved quantities. {2.} Model and observation error statistics are included explicitly in the analysis procedure and the resulting analysis (data) errors are either given by definition (i.e., in KF techniques) or can be objectively derived. These error statistics are very useful because uncertainties associated with terrestrial and climate system model results using these data as input can be then accessed objectively. {3.} The optimality of data analysis is global over the entire spatial domain of interest (i.e., global or regional domain) and over a temporal domain, if temporal evolution is included in producing the analysis such as in the Kalman Smoother (Cohn et al., 1994) or in the 4DVAR systems (Zupanski and Zupanski, 1996; Vukicevic and Bao, 1998, Zou and Kuo, 1996). {4.} The analysis system is extremely flexible to adding new diverse observations such as precipitation products (Zupanski and Mesinger, 1995; Kou et al., 1996), radar reflectivity (Sun and Crook, 1997), satellite radiance (Eyre, 1989; Thepaut and Moll, 1990), and in situ and remote observed ecosystem properties.

These features are desirable when attempting to design a data set of terrestrial biosphere and land surface parameters of a large region. This is because the number of direct in situ or satellite observations of these parameters is too small to sample the existing spatial and temporal variability. In meteorological studies, this interpolation technique is necessary to incorporate observations, such as meteorological observations, that are related to the surface forcing via dynamical and physical interactions in the atmosphere and to interpolate them in a consistent fashion. We propose that our ability to make inferences related to net carbon exchange will be improved by using data assimilation techniques applied to a coupled land surface and atmosphere model, together with remote sensing data.

The successful integrations of regional climate models with interactive land surface physics [e.g., Giorgi et al., 1993a,b; participants of Regional-Scale Climate Model Inter-comparison Study, ({http://www.physics.iastate.edu/atmos/pircs.html})] suggest that the data driven/constrained integrations in our experiments will produce realistic results. This is because extant climate integrations using the regional models are constrained by the observations only via the lateral boundary forcing when this forcing is obtained from the actual atmospheric analysis (not from the global model integration). The boundary constraint is, however, weaker than the data constraint we will apply in the data assimilation procedure. Consequently, the influence of observations on the regional model solution will be much stronger in this study.

We will also take advantage of recent atmospheric developments and make use of the National Center for Environmnetal Prediction (NCEP) reanalyses of the large scale wind and temperature fields (e.g. as described by Kalnay et al.,1996), the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992, Uliasz et al. 1996, Pielke and Uliasz 1998) will be used in a four dimensional data assimilation mode (4DDA) (Vukicevic and Bao 1998) to diagnose wind, turbulence, and other weather variables at 10 kilometer intervals across the continental United States. The NCEP data is currently available up to 1998, and is routinely updated. The NCEP data is used as lateral boundary conditions for RAMS at 6 hour intervals and, in the interior of the RAMS domain, as constraints on the RAMS higher spatial and temporal diagnosis of the weather fields. RAMS will be integrated for consecutive 12 hour periods for the time period since 1981 to obtain the needed weather analyses.

Using RAMS with the NCEP re-analyses will provide the most accurate characterization available of the atmospheric influences on the carbon fluxes, and the vertical and horizontal carbon dioxide transport and dispersion. RAMS includes a representation of landscape at scales as small as 1 km, so that realistic influences of the specific type of land surface on the turbulent fluxes are included. The landscape representation in RAMS will be integrated with the ecosystem model as part of this project.

Advanced analysis techniques such as the `adjoint analysis' (section 5) are being used in meteorological and atmospheric chemistry transport studies to specifically address problems of interactions between different components of the time evolving systems (Rabier, 1993; Vukicevic and Raeder, 1995; Vukicevic and Bao 1998; Vukicevic 1998; Marchuk, 1995; Kaminski et al., in press).

Applications of the `adjoint analysis' technique require existence of an adjoint model. We will take advantage of the adjoint model to apply this model in the analysis of the coupling between the atmosphere and the land surface during the data assimilation period. Specifically, we will examine `conditional' interactions between atmospheric state and land surface state, focusing on how the previous state of the system influences its subsequent evolution. We will ask questions such as: Are there conditions of soil moisture, LAI or atmospheric state (e.g., stability, humidity, etc.) that predispose the coupled system to strong interaction of the carbon and climate systems? How do these interactions affect the comparison of models and observed CO_2?

PROJECT MANAGEMENT

Research Timeline

Year 1:	Workshop of Core Research Team and Collaborators. The objective of the workshop is to define the priorities of model development and land use data synthesis. Basic structure of analytical framework will be determined. Data bases will be identified and specific parameter scalars will be defined. Define specific needs from FIA and NRI/NASS data sets for managed systems. Qualifications of programming and post-doctoral fellows will be determined. Individuals for these positions will be hired.
Year 2:	Design team will test portions of net carbon exchange model against selected site flux observations. Plant community dynamics will be integrated into biophysical-biogeochemical model. Disturbance generator implemented. Strategy for defining and developing short-term and long-term land use histories will be finalized. Data structure for carbon analysis will finalized and data integration will begin. Data assimilation techniques will be tested against distribution of point data of flux observations, interpolated with regional vegetation and land use information.
Year 3:	Data set development near completion Testing of model code with different biomes and land use systems. Verify net carbon exchange model against site flux data for different regions of the US. Verify data assimilation structure against distributed flux data.
Year 4:	Complete analysis of conterminous US net carbon exchange. Verify that estimates correspond to site and regional estimates for different years. Verify 4D analysis of terrestrial carbon exchange.

During the four years, we will generate several papers on the data base developments, modeling techniques and tests, data assimilation applications to biological studies, and preliminary and final findings related to net carbon fluxes from terrestrial systems. The progress of this project will also be posted on a project website, which will serve as a major communication interface among participating researchers.

Personnel Responsibilities:

The research proposed here will be directed by a scientific steering committee, with Ojima, Parton, and Schimel as the principal investigators. Ojima will serve as the project coordinator, and also lead the data development activity. Parton will be responsible for model development. Schimel will be responsible for validation and data assimilation developments. SSC members will participate in all phases of the research development and implementation, though primary responsibilities will be assigned according to expertise. Neilson will be work on the biogeographical aspects of model and data inputs. Running will provide expertise for development and implementation of remote sensing derived land surface characteristics. Coughenour will provide expertise in physiological and community processes. Kittel will provide expertise in biogoegraphical and climatological relationships and data development. Pielke will provide 4D atmospheric transfer scheme and weather dynamics for terrestrial systems. Band will provide hydrological expertise for development of routing, soil moisture, and evaporation processes. Denning will provide global to regional atmospheric CO2 interpolation techniques for regional verification of aggregated net carbon exchange. Hanan will provide site carbon flux interpolation for validation tests. Vukicevic will provide methodological approaches to data assimilation and test these against data integrated on vegetation, physiological, carbon flux, and land use dynamics.

Programmers, Post-doctoral fellows, and students will implement much of the research designed jointly with the SSC. Additional expertise will be incorporated into the SSC as needed, for instance we have discussed with Dr. Linda Joyce of the USFS (see letter of collaboration) to join us in this project to work more directly with the FIA data; Steve Wofsy has agreed to work us to better integrate the Ameriflux data sets into this study; and we have contacted the LTER national office indicating our desire to work closely with as many of the LTER sites as possible (see letter from LTER).

Management Strategy:

This proposal describes an ambitious amount of work, even given the large budget. We propose to make use of three major resources in order to achieve these goals. First is integration. We propose a core team of programmers, students and post-docs, mostly co-located on the CSU campus. This team will work together with the PIs, rather than being allocated to different institutions or subprojects. While the programmers and junior scientific staff will have specialities, we have a history of encouraging collaboration, sharing of code, skills and tools and communication. Thus as new components are developed, we expect the group to work together to ensure compatability and minimize problems. While this is an idealistic management style, we have successfully carried out several projects using such teams with great success (the support for the VEMAP data sets was provided by such a team, working with Schimel and Ojima and provided a terabyte-size, quality-controlled data base to the entire US National Assessment in 12 months). We will also take advantage of the project web site to make interim data sets and codes, together with graphics and documentation available to the whole project as it is developed. Thus the distributed team will be able to see the entire group's progress in near real time.

The second resource is time. We will carry out our activities in a careful sequence. The development of the 'community ecosystem model' from precursor models will take place in years 1 and 2. The development of the data assimilation system (largely with DOD support for Vukicevic) for RAMS coupled to the BGC model will proceed in parallel, allowing the coding of the assimilation system to proceed in parallel with the assimilation system. Adaptation of the LUHNA and NRI data bases will also be done during this period as the model must be designed around the characteristics of this crucial data base. Once these two major codes are developed, they will be tested and debugged during year three separately and in coupled model. In year 4 we will conduct the major suite of model experiments and analyze the results. By phasing these large activities over time, but co-developing the components that must be coupled, we will use our staff resources with efficiency.

The third “resource” is our colleagues in the research community. Developing an integrated assessment of a continental carbon balance requires inputs from scientists with many specialities, as does designing a modeling system that can serve flexibly for many researchers. Accordingly, we plan a 'working group' of colleagues who will work with the PIs and core programmers and post-docs, providing input on data, model design and interpretation of results. The working group will bring a much wider range of expertise to the project and will also foster broad involvement in the development of community data sets and modeling tools. Membership in the working group will evolve, but we will ask members of other modeling teams, community and physiological ecologists, eddy flux measurement experts, and land use ecologists and historians to participate. Candidates for the working group include: Sandra Brown, Terry Chapin, John Foley, Lisa Graumlich, Mike Gulden, R.A. Houghton, Linda Joyce, Sandra Lavorel, David McGuire, Mark Harmon, Ian Noble, Jim Randerson David Wedin, and Steve Wofsy.

NSF PRIOR SUPPORT

Drs. Ojima and Parton:
We have been awarded a number of NSF grants during the past 5 years. We will summarize some of the relevant results for this specific proposal.

List of recent NSF projects include

DEB- 9632852, Long Term Ecological Research Program: Shortgrass Steppe, NSF-Biological Centers, 11/01/96-10/31/02

DEB-9523612, Models and Methods of Integrated Assessment (MMIA) of Climate and Land Use Changes in the Central US, 10/95 - 9/98

DEB-9416813, Trace Gas Cross-Site Comparison (TRAGnet), 10/94-3/99

DEB- Grassland Ecosystem Dynamics on the Mongolian Plateau, 3/95-6/99

Model development of CENTURY was funded by several US-National Science Foundation projects in which Drs. Parton and Ojima participated. These projects are the Great Plains Agroecosystem Project (BSR-8406628 and -8105281), the Tall Grass Ecosystem Fire project (BSR-82007015), and the Central Plains Experimental Range-Long-Term Ecological Research Project (BSR-865195 and 9011659). The projects tested CENTURY across a variety of ecosystems, land use practices, and environmental conditions. Recent projects have been funded to study the impact of climate change across the network of LTER sites. These analyses of ecosystem response to changing environmental factors provided further insight into the sensitivity of ecosystem processes at a variety of ecosystems across North america. From these projects, we can make three summary conclusions. First, the biogeochemical constraints are critical in prediction ecosystem dynamics and C storage and fluxes due to feedbacks in physiological and biogeochemical processes. Second, the effect of land use management on ecosystem processes can often outweigh the impact of climate change and needs to be considered in global change studies. Third, soil texture is an important determinant of soil C, biogeochemical cycles, and ecosystem dynamics. In subsequent and concurrent funding from NSF, NASA, DOE, EPRI, and the DOI, the CENTURY model has incorporated the direct and indirect effects of elevated atmospheric CO_2 changes. For the MMIA project, Century is the center piece for evaluating social-cultural, economic, and environmental factors affecting land use dynamics in the Great Plains (Ojima et al., in press). The TRAGnet project has continued development of Century for trace gas modeling (Parton et al 1998) and has been employed in cross-model comparisons of trace gas emissions (Frolking et al 1998). Century has been evaluated for land use impacts on ecosystem dynamics in the US and in the Mongolian Plateau.

Selected Publications from these projects:

Parton, W.J., D.S. Ojima, and D.S. Schimel. 1996. Models to evaluate soil organic matter storage and dynamics. Pp 421-448 In M.R. Carter (ed.) Structure and Organic Matter Storage in Agricultural Soils. CRC Press, Inc.

Ojima, D. S., D. S. Schimel, W. J. Parton, and C. Owensby. 1994. Short- and long-term effects of fire on N cycling in tallgrass prairie. Biogeochemistry 24:67-84.

Parton, W. J. and P. E. Rasmussen. 1994. Long-term effects of crop management in a wheat/fallow system: II. Modelling change with the CENTURY model. SSSAJ 58:530-536.

Seastedt, T. R., C. C. Coxwell, D. S. Ojima, and W. J. Parton. 1994. Impacts of photosynthetic pathways, management and climate on plant and soil carbon of semihumid temperate grasslands. Ecological Applications 4(2)244-253.

Parton, W. J., D. S. Schimel, D. S. Ojima. 1994. Environmental change in grasslands: assessment using models. Climatic Change 28:111-141.

Parton, W. J., D. S. Schimel, D. S. Ojima and C. V. Cole. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. p. 137-167 in R.B. Bryant and R.W. Arnold (eds) Quantitative modeling of soil forming processes. SSSA Spec. Publ. 39. ASA, CSSA and SSA, Madison, WI.

Burke, I. C., W. K. Lauenroth, W. J. Parton and C. V. Cole. 1994. Interactions of landuse and ecosystem structure and function: A case study in the Central Great Plains. In Likens, G.E. and P.M. Groffman (eds.) Integrated Regional Models: Interactions Between Humans and Their Environment. Chapman and Hall, ITP, New York.

Metherell, A. K., C. A. Cambardella, W. J. Parton, G. A. Peterson, L. A. Harding, and C. V. Cole. 1995. Simulation of soil organic matter dynamics in dryland wheat-fallow cropping systems. Chapter 22 pp 259-270 In R. Lal, J. Kimball, E. Levine, B.A. Stewart (eds.) Soil Management and Greenhouse Effect, Lewis Publishers, Boca Raton, Fl.

Mosier, A.R., W.J. Parton, D.W. Valentine, D.S. Ojima, D.S. Schimel and O. Heinemeyer. 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 2. Long-term impact of land use change. Global Biogeochemical Cycles 11:29-42.

Kelly, R.H., W.J. Parton, G.J. Crocker, P.R. Grace, J. Klir, M. Korschens, P.R. Poulton, and D.D. Richter. 1997. Simulating trends in soil organic carbon in long-term experiments using the Century model. Geoderma 81:75-90.

Ojima, D.S., K.A. Galvin and B.L. Turner II. 1994. The global impact of land-use change. BioScience 44(5):300-304.

Baron, J., D.S. Ojima, E.A. Holland, and W.J. Parton. 1994. Analysis of nitrogen saturation potential in Rocky Mountain tundra and forest: Implications for aquatic systems. Biogeochemistry 27:61-82.

Xiao, X., D.S. Ojima, W.J. Parton, Z. Chen and D. Chen. 1995. Sensitivity of Inner Mongolia grasslands to climate change. Journal of Biogeography 22:643-648.

Ojima, D.S., L. Stretch, T. Chuluun, L. Tieszen, A. Andreev, G. Erdenejav, H. Liu, S. Khudulmur, A. Preshchepa, B. Reed, H. Yamamoto, Z. Yu, S. Zhu. 1997. Development of the temperate east Asia land-cover (TEAL) database. In Y. Himiyama and L. Crissman (eds.) Proceedings of the IGU-LUCC '97 Meeting on Information Bases for Land Use/Cover Change Research, Brisbane, Australia 1-4 July 1997. pp. 77-83.

Ojima, D.S., W.E. Easterling, W.J. Parton, R. Kelly, B. McCarl, L. Bohren, K. Galvin, and B. Hurd. Integration of ecosystem and economic factors determining land use in the central Great Plains. Book Chapter in P. Puntenney (ed.) A Lasting Impression: Interpreting the Human Dimension of Global Environmental Issues. Lynne Reinner Press, Boulder, CO. (in press)

Frolking, S., A. R. Mosier, D.S. Ojima, C. Li, W.J. Parton, C. Potter, E. Priesack, R. Stenger, C. Haberbosch, P. Dorsch, H. Flessa and K.A. Smith. 1998. Comparison of N_2O emissions from soils at three temperate agricultural sites: Simulations of year-round measurements by four models. Nutrient Cycles in Agroecosystems 52: 77-105.

David Schimel:

Research conducted at the National Center of Atmospheric Research is funded largely by NSF, the David Schimel has been successful in diversifying his external funding, he has a significant amount of research being conducted through NSF resources. We provide a brief overview of three areas of research pertinent to this proposal.

The Effects of Interannual Climate Variability on Terrestrial Ecosystems

This research area involves David Schimel and collaborators Bobby Braswell, Berrien Moore III, and Ernst Linder (all of University of New Hampshire). In earlier modeling work, we suggested, based on the responses of the Century ecosystem model, that a substantial portion of the response of ecosystems to temperature anomalies should be lagged relative to the forcing. These lags occur in the model because of the long turnover times of soil organic matter and deep soil moisture compartments. We found a weak, instantaneous, positive correlation between temperature and growth rate, and a significant anti-correlation lagged 1.5 to 3 years. The sign and timing of this correlation are consistent with model-predicted responses. We conducted a further analysis of the satellite vegetation index, derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) instrument. This work provided important observational evidence for the mechanisms linking temperature to ecosystem dynamics but also showed that different biomes (northern versus tropical forests and grasslands) behave differently with respect to climate change. This work was published in *Science* in October, 1997.

Ecosystem Dynamics and the Atmosphere Section (EDAS) scientists (David Schimel and Rebecca McKeown), working with Robert Braswell (University of New Hampshire) and Tomislava Vukicevic (Cooperative Institute for Research in the Atmosphere, Colorado State University), developed a simplified terrestrial carbon model. The model parameters are estimated by inversion against global temperature and CO_2 growth rate anomalies. Constraints on the model parameters were derived from observations where possible and from a global forward integration of the Century model, when observations were unavailable. Sensitivity analysis of the model showed that coupling of terrestrial carbon dynamics to N cycling in soils was responsible for much of the signal observed in the atmosphere: inversion without an N cycle results in much lower modeled terrestrial fluxes.

Historical (1895-1993) "Bioclimate" and Future Climate Scenarios for VEMAP and the U.S. National Assessment

The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) is a multi-agency, international collaboration aimed at improving and intercomparing biospheric models for predicting the effects of climate and climate change on terrestrial ecosystems. The project is now in its second phase, after completing an analysis of ecosystem responses to current climatology and equilibrium climate change scenarios. The objectives of Phase 2 are to compare time-dependent ecological responses of biogeochemical models and dynamic global vegetation models (that simulate coupled biogeochemical biogeographical processes) to historical and projected transient forcings across the conterminous U.S.

An Integrated Land Model for the CSM

During the development of the Climate System Model (CSM), it has become apparent that a from-the-ground-up effort was needed to develop a new land model. Linking the existing NCAR codes (Land Surface Model (LSM) of Bonan and Century of Schimel and collaborators), while complementary in the processes and timescales they address, presented major conceptual problems. In addition, neither model addresses changes to vegetation type. As a consequence, a collaboration has developed with Jon Foley (University of Wisconsin) to develop a new version of Foley's IBIS model that would combine the science in LSM and Century. This model will be adapted for studying climate change, land use change, and paleoclimate interactions. It will be formulated for long-term climatological applications of the CSM, while Century and LSM will remain as alternate approaches with compatible mechanisms to the integrated model.

Ron Neilson:
DEB-952361, Vegetation Response to Mesoscale Climate Variability in the Mountainous West.
P.I. S.A. Ferguson, University of Washington; co-P.I.s L.O. Mearns, NCAR; R.P. Neilson, C. Daly, Oregon State University. (9/95-9/98, extended to 9/99).

The OSU component of this NSF grant was to develop the gridded 2.5' monthly temperature and precipitation 40 yr timeseries over Oregon (Daly) and the Dynamic General Vegetation Model to be implemented on the grid (Neilson). The climate data task has been completed and the full set of climate data, requiring all three groups has now been completed.

Development of the BIOMAP Dynamic Global Vegetation Model (DGVM) has also been completed and results from the coupling of the biogeographical model MAPSS (Neilson 1995) with the biogeochemical model BIOME-BGC. When linking both models with overlapping processes a single code is selected from one and shared by both, for example soil hydrology, and timesteps are reconciled (Neilson and Running 1996). A fire sub-model was added to the hybrid model (BIOMAP) to account for fire disturbance. BIOMAP was adapted to run on a full grid, to accept up to five soil layers and to simulate life form competition for light, water and nutrients.

BIOME-BGC simulates the processes involved in the water, carbon and nitrogen budgets and operates on daily and annual time steps. It simulates a single tree, shrub or grass lifeform over one soil layer. MAPSS is an equilibrium biogeography model that simulates the potential climax vegetation under any average monthly climate. It uses physiologically-based rules to determine woody lifeform type and simulates the competition for light and water between a woody overstory (tree or shrub) and a grass understory over three soil layers. A second rulebase uses the simulated information of overstory lifeform type, and the leaf area indices (LAI) (including phenology) of over and understory to arrive at a physiognomic community classification, such as xeromorphic subtropical shrubland.

Before coupling the two models, BIOME-BGC was generalized to the MAPSS structure with overstory/understory competition for light, water and nutrients. Beer's Law determines the understory light environment based on overstory LAI. Water uptake is determined by canopy demand and taken from the soil as a linear function of vertical root distribution. Competition for water is a function of the lifeform proportionality of roots within each soil layer. Nitrogen competition is treated in a similar way. The hybrid model is now complete and being tested over the VEMAP2 transient climate database and the new Oregon transient climate database. Early results indicate that the model appears to be performing quite well.

Neilson, R.P. 1995.A model for predicting continental-scale vegetation distribution and water balance, Ecol. Appl. 5, pp. 362-385.

Neilson, R.P. and S.W. Running. 1996. Global dynamic vegetation modelling: coupling biogechemistry and biogeography models. Pages 451-465 in B. Walker and W. Steffen, editors. Global Change and Terrestrial Ecosystems. Cambridge University Press, Cambridge.

Running, S.W. and E.R. Hunt. 1993. Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In Scaling processes between leaf and landscape levels, ed. Ehleringer, J.R. & Field, C., pp. 141-158, San Diego: Academic Press.