I. Science Plan for the Climate Change Forcing Scientific Focus Area

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ABSTRACT

Terrestrial ecosystem interactions with climate significantly alter projections of atmospheric greenhouse gases and climate predicated on anthropogenic forcing alone. The Forcing SFA supports research to understand and predict the global terrestrial ecosystem forcing on the earth's climate. An important feature of the planned research is the elimination of the artificial distinction between experimental/observational studies and model building, parameter estimation, evaluation, and projection. Experimental findings and site-based measurements are used to build, test, and evaluate models, and to optimally parameterize and calibrate models. Regional and global networks of historical and current site, regional, and global scale measurements are used to improve model performance. This research will increase confidence in future climate change projections by concentrating on new understandings and model representations of interactions and feedbacks.

Research is organized into 5 tasks. Task F1 outlines the main approach of developing the analysis capability through structured modeling tasks. Tasks F2, F3, F4, and F5 address key research priorities necessary to resolve important uncertainties. Task F2 addresses environmental controls on resource allocation within ecosystems Task F3 develops alternative mechanisms and provides new data for decomposition dynamics, Task F4 introduces the consequences of extreme environmental events into models, and Task F5 resolves uncertainties in CO_2 fossil fuel emissions that will improve our ability to analyze terrestrial CO_2 forcing on climate.

CONTENTS FOR THE FORCING SFA

EXECUTIVE SUMMARY

The Forcing SFA supports research to understand and predict the global terrestrial ecosystem forcing of the earth's climate. The research is focused on how terrestrial ecosystems affect atmospheric CO_2 *and other greenhouse gases and how the ecosystem processes responsible for these effects interact with climate and with anthropogenic forcing factors. Initial Forcing SFA research is targeted at accurately quantifying the exchange of* CO_2 *between the atmosphere and land ecosystems through photosynthesis, autotrophic and heterotrophic respiration, disturbance, and land management practices. This research will increase confidence in making future projections by concentrating on new understandings and model representations of interactions and feedbacks: for example, interactions among* CO_2 *fertilization, nutrient dynamics, and disturbance or land use history, or nutrient-mediated feedbacks between climate change and land* CO_2 *fluxes. This research includes efforts to more accurately quantify uncertainty in anthropogenic emissions of* CO_2 *from fossil fuel burning, and takes advantage of ongoing efforts to quantify historical, present-day, and anticipated future greenhouse-gas consequences of land use and land cover change.*

As the influence of anthropogenic forcing on the climate system unfolds, there is also growing evidence that terrestrial ecosystem interactions with climate may significantly alter projections of atmospheric greenhouse gases and climate predicated on anthropogenic forcing alone (Cox et al. 2000, Friedlingstein et al. 2003). As recent model intercomparisons have shown (Friedlingstein et al. 2006, Sitch et al. 2008), our understanding of past and present dynamics of the terrestrial processes involved in climate forcing is inadequate for accurate prediction of likely future states for the Earth system. Significant knowledge gaps remain in ecosystem processes, land-atmosphere interactions, and climate-carbon cycle feedbacks involving natural and human modified components of the terrestrial system. The goal of ORNL's Climate Change Forcing SFA is to fill these gaps and produce the best possible capability for analysis of terrestrial ecosystem forcing of climate. This will be achieved through an in-depth integration of modeling, priority experiments and measurements, and assimilation of site, regional and global scale data.

Overarching Science Questions

Research under the Forcing SFA is designed to address the following overarching questions:

- **How do ecosystem processes influence the spatial and temporal pattern in terrestrial exchange of CO_2, other greenhouse gases, and physical forcings?**
- **What are the present-day fluxes (magnitude, variability, and uncertainties), how have they changed historically, and how will they likely change in the future?**

The scope of research under this SFA spans spatial and temporal levels of biological organization from detailed understanding of leaf- and plant molecular processes, through organism and plot-scale study of C flux partitioning under varying resource limitations, to evaluation of process understanding using flux, concentration, and C stock measurements at landscape, regional, and continental scales. These activities culminate in global-scale analysis and prediction of land ecosystem influence on greenhouse gas concentration in the context of fully-coupled models of Earth system dynamics. In consideration of that scope, the Forcing SFA is a tight integration of focused measurements, ecosystem-scale experimentation, and multi-scale process model development and application. Formal and objective integration of measurement, experimentation and modeling knowledge across scales is accomplished through model-data assimilation methods. Data assimilation is used to identify key model parameter and structural uncertainties, which are then addressed through targeted process-level investigations, continuously and efficiently bringing new process understanding and data into prognostic model systems. This objective approach to identifying and reducing sources of uncertainty will lead to better predictions of CO_2 and other greenhouse gases in Earth system models, which in turn will produce better predictions of likely future climate under assumed levels of anthropogenic forcing.

In the first 3 years of activity of the Forcing SFA we will employ modeling, experiments, and landscape C measurements to advance our understanding of terrestrial C cycle processes for characterizing natural and anthropogenic components of the land C cycle. Research is organized into 5 tasks (Figure F1). Task F1 outlines the main approach of developing the analysis capability through structured modeling tasks. Tasks F2, F3, F4, and F5 address key research priorities necessary to resolve important uncertainties. Task F2 addresses environmental controls on resource allocation within ecosystems Task F3 develops alternative mechanisms and provides new data for decomposition dynamics, Task F4 introduces the consequences of extreme environmental events into models, and Task F5 resolves uncertainties in CO_2 fossil fuel emissions that will improve our ability to analyze terrestrial CO_2 forcing on climate.

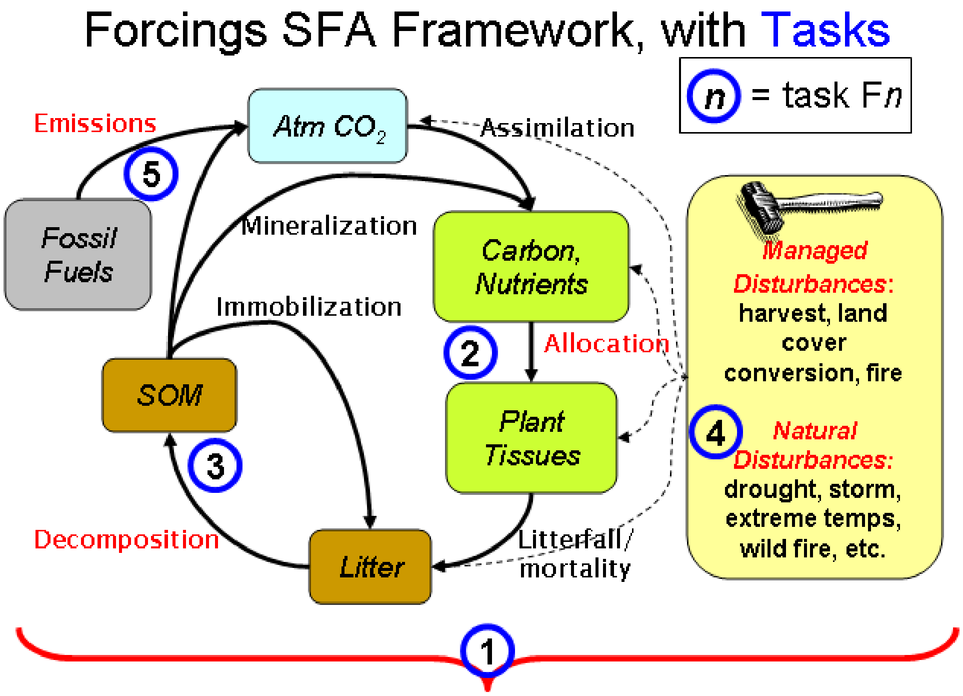

Figure F1. Overview of Forcings SFA. Terrestrial ecosystem processes are considered in the context of their impact on atmospheric CO_2 (and other greenhouse gas fluxes). Red text identifies major process-level uncertainty which will be addressed as part of the near-term SFA effort. Blue circles identify *primary* action-points for specific Forcing SFA tasks. For clarity, a single primary action point has been identified for each task in this figure - other secondary connections are described in the task details. Bottom bracket indicates that Task F1 considers the comprehensive Forcings Framework as its primary scope. (SOM: soil organic matter)

The experimental measurements, results and new process understanding from Tasks F2 through F5 will result in significant reductions in outstanding structural uncertainties. Their explicit incorporation into Task F1 prognostic models for C cycle attribution and prediction analyses will increase our precision in quantifying terrestrial climate forcings.

Approach for the Forcing SFA

The tasks of reducing uncertainty through identifying and improving structural deficiencies, and developing robust parameter estimation procedures for global terrestrial C cycle models are best addressed through an organized interaction among data, experiments, and model development at all scales—local, regional, and global. We will use model-data assimilation and multivariate model benchmark evaluation in all aspects of this SFA's research program. The SFA will use a multi-model approach in all analyses since multiple models provide richer and more robust findings than analyses of any single model. Because CO_2 concentrations are the dominant forcing, we include research to quantify fossil fuel emissions, including their spatial and temporal distributions and associated uncertainties. Products of this SFA Science Plan will include primary research publications, synthesis activities (e.g., critical review papers, model-data intercomparisons, and international workshops), new datasets, and a multi-scale model-data assimilation system delivering analyses of climate change forcings from leaf to globe.

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Each individual's role is further defined in the section titled Management Team and Integration.

NARRATIVE

INTRODUCTION AND BACKGROUND

With a growing realization of the importance of terrestrial C processes in the global C cycle and climate change (e.g., Post et al. 1990, Keeling et al. 1995, Bousquet et al. 2000, Friedlingstein et al. 2006) significant resources have been invested in observational and modeling studies of the terrestrial C cycle. On the observational front, large networks of manipulative experimental sites such as FACE (Free-Air CO_2 Enrichment) (Long et al. 2006, Norby and Iversen 2006) and in-situ, continuous CO_2 flux monitoring sites using the eddy covariance technique (Baldocchi et al. 2001, Gu and Baldocchi 2002) exemplify those investments in measurement and experimental systems. On the modeling front, terrestrial C cycle models with increasing levels of process representation have been developed (Post et al. 1997, Friend and White 2000, White et al. 2000, Stitch et al. 2003, Woodward and Lomas 2004, Post and King 2005, Gu et al. 2006, Thornton et al. 2002, 2007). Progress on these twin fronts has greatly advanced our understanding of the terrestrial C cycle at local scales and contributed to understanding of how the C cycle operates at the global scale. However, the observation and modeling fronts remain largely independent. Models of land C uptake and release are developed based on an understanding of the relevant processes. These models are then integrated forward in time to produce predictions of the temporal and spatial variability of land-C sinks (Cramer et al. 2001). Estimates of the land C balance produced by simulation are constrained by theory and understanding of the system embodied in the model (e.g. conservation of C and N), but are not adequately constrained by direct observations of the C cycle (e.g. flux measurements, forest inventories, CO_2 flask measurements). Similarly, observations and experiments are made with an awareness of models, but observation protocols and experimental designs are seldom optimized to best constrain or inform the models. The lack of formal and rigorous integration of observations and modeling has hindered efforts to explain regional, national, continental or global spatial and temporal patterns of CO_2 exchange.

Recent efforts to synthesize multiple datasets for C cycle model evaluation have started us on the path of improved model-data integration (e.g. Randerson et al., in press). To further advance terrestrial C cycle science in general and the robust representation of climate-C feedbacks in earth system models, observations and measurements must be formally and rigorously integrated with mechanistic, process-based models of terrestrial ecosystems. Under this approach models are developed and processes refined through explicit interaction with manipulative experiments and non-manipulative observational campaigns. The models are constrained, parameterized and validated by observations and experimental results. In turn, the modeling informs understanding of empirical results and guides the design of additional experiments and observations. Only through such integration may we produce reliable estimates of sources and sinks of CO_2 and extrapolate from observations in space and time to novel environmental conditions of the future that could lead to feedbacks on the climate.

We have identified a high priority set of terrestrial C processes that are insufficiently quantified and that require additional analysis, measurements and experimental results to be adequately represented in regional and global models. These are (1) how terrestrial C cycle sources and sinks are altered by changes in atmospheric chemistry, climate change, land use and broadscale disturbance [Task F1, see also Response SFA], (2) C and N allocation within plants as functions of changing environmental conditions [Task F2], (3) decomposition models to functionally represent an emerging physical-biological description of controls on soil organic matter distribution and turnover [Task F3, see also Mitigation SFA Theme M5], and (4) the role of extreme events and vegetation composition changes in short and long-term C dynamics [Task F4].

Anthropogenic fossil fuel emissions are the most significant climate change forcing factor. An accurate description of the temporal and spatial variability of these emissions is necessary for the evaluation of land ecosystem contributions to climate change forcing using both forward and inverse modeling methods. Measurements of seasonal and interannual variation in atmospheric CO_2 concentration are important constraints used to evaluate forward model predictions of C sources and sinks, but the value of this constraint depends on an accurate representation of the fossil fuel emission fluxes in space and time. Inverse methods which provide spatial and temporal patterns of C sources and sinks by minimizing errors associated with transported flux signals also depend on accurate fossil fuel source mapping. We therefore identify improved spatial and temporal resolution of fossil fuel sources as a high priority research area [Task F5].

RESEARCH PLAN

Task F1. Mechanistic modeling for the diagnosis, attribution, and prediction of terrestrial C feedbacks with climate change

Key ORNL Personnel: Post, Ricciuto, Thornton, Gu, King, Nichols, West

Objectives and Science Questions

Task F1 describes research in the fusion of experimental results, observations, and modeling to improve understanding and simulation of terrestrial C cycle processes involved in positive and negative C-climate feedbacks. Task F1 will deliver a first-generation capability for multi-scale analysis of terrestrial forcing of greenhouse gases and climate. This analysis framework will be used to answer the question:

> *What is the sign and magnitude of the global climate-carbon cycle forcing from land, and what are the process contributions to that overall forcing across a range of spatial and temporal scales, and across multiple land ecosystems?*

The scales of interest for this task range from biochemical processes within leaves and plants, amenable to direct measurement and detailed process-level modeling, up to global climate-C cycle feedback processes that are best studied and evaluated in the context of coupled global Earth system models. We approach this overall question by focusing on processes already known to play a critical role in determining the feedback sign and magnitude, and which are as yet poorly characterized for Earth system analysis and prediction. We address the following specific process-level questions:

1. How will photosynthesis and C allocation respond to CO_2 fertilization and changing nutrient availability, and how and on what time scales will these changes propagate through ecosystems to influence growth, respiration and net C flux?

2. How will changes in temperature, water availability, and the amount and quality of solar radiation (through clouds and aerosols) affect terrestrial C sources and sinks?
3. Will changes in phenology and the acclimation of photosynthesis and respiration (autotrophic and heterotrophic) alter the nominal response to CO_2 and climate?
4. How and on what time scales do changes in land use and land cover associated with natural disturbance and land management practices influence gross and net C fluxes?

Approach

Answering these questions requires (a) improved understanding, model formulation, and parameterization of ecosystem C flux processes at the site or local scale, (b) the extension ("scaling-up") of this improved understanding and modeling to continental and global scales with verification and validation through historical reanalysis and diagnosis ("now-casting") and (c) improved skill in predicting terrestrial biogeochemical response to changes in land-use/land-cover, atmospheric composition, climate, or other changes that result in terrestrial feedbacks on climate.

The research described in Task F1 has three main components designed to meet those requirements. These are: site-scale model-data assimilation using multiple observational and experimental data streams and two different classes of ecosystem models (Task F1a); regional-scale model-data assimilation to quantify, spatially interpolate, and temporally extrapolate current regional, continental, and global patterns of daily, seasonal, and interannual CO_2 exchange with the atmosphere for feedback diagnosis and attribution (Task F1b); and prediction of feedbacks among CO_2, climate, land-use, N deposition and terrestrial ecosystem processes using partially- and fully-coupled Earth system models and data at regional and global scales (Task F1c). These three components are brought together in an Integrated Terrestrial Carbon Model System (ITCM; Figure F2), a multi-scale framework for analysis of climate forcing using a tight integration of models and data. The relationships among these components and the flow of information required for each component are depicted in broad terms within Figure F2. Detailed diagrams for information needs and flows for components are presented in subsequent sections.

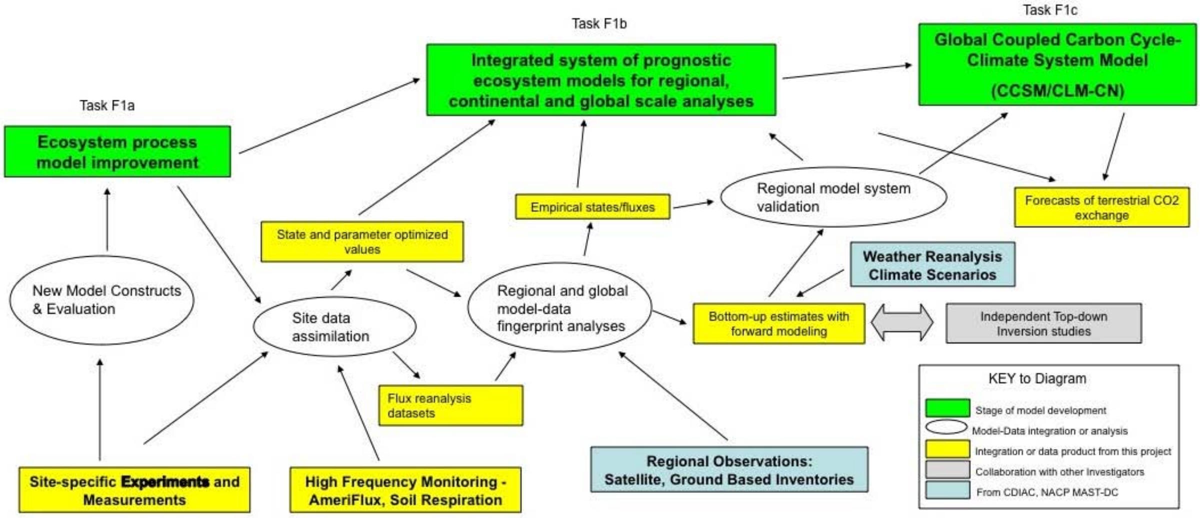

Figure F2. Overall outline for the development of the Integrated Terrestrial Carbon Model system. Flows of information and data are highlighted. Research activities include database assembly, hypothesis testing, model calibration through data assimilation, and integration of data and models for regional and global scale analysis and prediction.

While the progression of research tasks in Figure F2 begins at the bottom left and flows toward increasingly complex integration at the upper right, the research tasks are structured to allow progress on all three components nearly simultaneously. Analysis and prediction of climate-carbon cycle feedbacks at regional and global scales will begin, using current best knowledge of processes and parameters, while site-level model-data fusion is underway to evaluate and improve these processes and parameterizations. Efforts are organized to allow multiple iterations of analysis and prediction: new process-level knowledge acquired through site and regional-scale model-measurement fusion will be incorporated in regional and global-scale simulations, producing refined estimates of the sign, magnitude, and spatial and temporal patterns of climate-carbon cycle feedbacks. Information on predicted feedbacks at the global scale will also be used to guide model-observation fusion and analysis efforts at the site-scale. We will use models which are designed for application across a range of spatial scales, from point simulations to regional and global integrations. This provides a simple and direct avenue for integration of new process-level knowledge gained at the site and regional scales into fully-coupled Earth system models. Such integration depends, of course, on development of new understanding at a suitable level of generality, which is a primary objective of process-level modeling (Waring and Running, 1998). The ITCM will be designed and implemented so that scientific findings and improved parameterizations and mechanistic functional representations can be integrated into the Community Land Model (CLM) of the Community Climate System Model (CCSM) supported by DOE through SciDAC (see Annex A, Global Climate Modeling at ORNL). We will work directly with the SciDAC and CLM-CN development teams and the CCSM Land Model and Biogeochemistry working groups on this activity.

Proposed Task F1 research will lead to next-generation large-scale terrestrial C cycle models that reflect our best understanding of terrestrial C processes using modeling and software engineering practices to facilitate adaptability and timely upgrades. Task F1 effort will produce analytical tools and methodologies for synthesizing diverse experimental datasets and for confronting and constraining models with data. It will also develop robust scaling methods that allow the use of information obtained at fine scales to contribute toward solutions of broad-scale questions. Descriptions for these Task F1 sub-tasks are provided in the following sections.

Task F1a. Improve ecosystem process models with site-level observations and experimental data

In the current context, improved ecosystem models (Fig. F3) entail:

1. improved fidelity of simulated C, water and energy fluxes, on temporal scales from hours to seasons;
2. the ability to accurately simulate longer-term, low-frequency changes in ecosystem C stocks in response to changes in environmental forcings (e.g., ENSO weather, anthropogenic disturbance);
3. effective representation of the local plant-soil-ecosystem processes involved in global climate-carbon feedbacks.

Site-level model-data fusion will be used to constrain model parameterizations and process representations. Detailed measurements from the network of eddy covariance flux stations will provide critical constraints on C, water, and energy flux predictions across a range of climate and vegetation types. Fuller understanding to inform model prognostication, however, requires manipulative field experiments designed to simulate the perturbation leading to the feedbacks. In every case it is desirable that functional process representations be faithful to current best biological, physiological and ecological understanding of mechanisms.

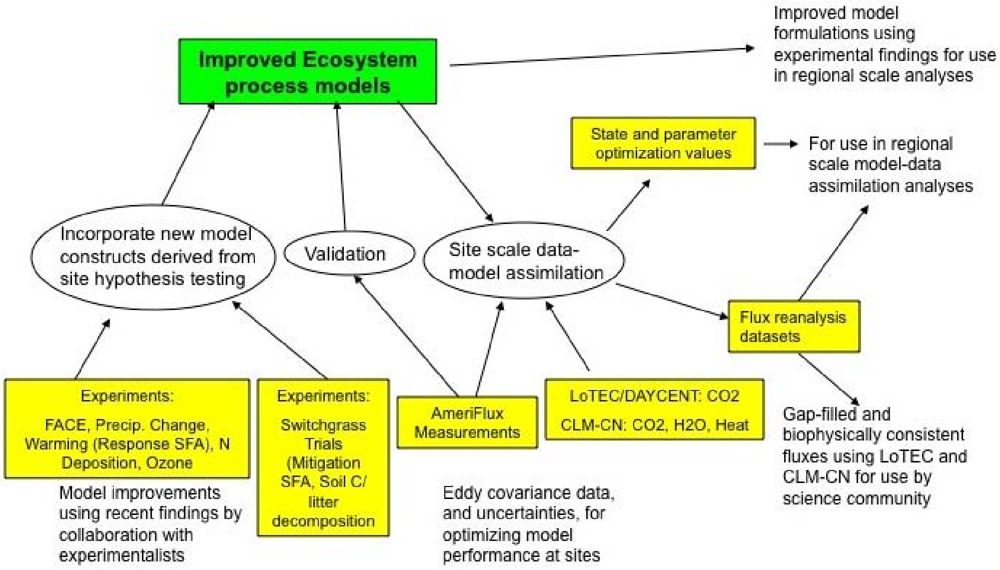

Figure F3. Model-data assimilation at the site scale will be completed for intensively studied sites that have rich data streams. Experimental results will be used to inform particular processes. Experimental data are sparse in time, but provide useful constraints on process representation. This diagram is an expansion of the left portion of Figure F2 with additional details. See Figure F2 for color and symbol key.

There has been much progress in model-data fusion at eddy covariance sites (Braswell et al. 2005, Williams et al. 2005, Sacks et al. 2006, Ricciuto et al. 2008), yet an accepted approach for quantitative assessment of model and data uncertainties is lacking, resulting in unclear confidence in the results (Trudinger et al. 2007, Fox et al. in press). A site-level probabilistic reanalysis and short-term prediction product with multiple fully prognostic biogeochemical models is required. We are uniquely suited to this challenge because of several advantages: 1) Strength in both model development and implementation of data assimilation techniques, 2) Partnership with world-class data centers that already manage large eddy covariance data sets and will be crucial for managing large volumes of model output, and 3) high-performance computing resources. We envision that this effort will lead to a similar functionality as numerical weather prediction models today: nowcasting and reanalysis of the terrestrial biogeochemical cycle with a full model ensemble.

Task F1a efforts will use eddy covariance flux data, ancillary biological measurements at eddy covariance sites, previous manipulative experiments and new experimental data from tasks F2 to F4 to address the following:

1. How do optimized model parameters vary among sites within a biome, and over time at a single site, and in response to experimental forcing?
2. Will identifying sources of parameter variation lead to model improvement and will new model formulations with stable parameters lead to better estimation of fluxes over space and time?

3. What are the types, locations, spatial density and temporal frequency of observations useful for reducing uncertainty in model predictions? What observations or experiments would be effective in further reducing uncertainty?
4. What are the optimal values and uncertainties of model parameters for each plant functional type?

Eddy covariance (EC) towers provide continuous ecosystem-scale measurements of CO_2 and energy fluxes yielding a constraint on terrestrial biogeochemical models (Baldocchi et al. 2001). Measurements are supplemented with extensive meteorological and biometric observations, making EC sites even more useful for model parameterization and validation. Manipulative experiments also provide data about the response of ecosystems to environmental changes as CO_2, temperature, and precipitation. Both observational and experimental data will be used in a formal data assimilation framework to estimate probability density functions (PDFs) of model parameters, which can then be used to make projections with uncertainty estimates.

Data from over 100 EC sites are archived by CDIAC in the AmeriFlux network with more than 300 global sites archived by FLUXNET. All eddy covariance sites measure net ecosystem exchange (NEE), latent heat (LE), and sensible heat (H) fluxes on an hourly or half-hourly basis together with recorded meteorological drivers including air temperature, precipitation and photosynthetically active radiation. A great deal of progress has been made recently in compiling ancillary biological data at EC sites, which provide necessary site history information and initial conditions (e.g. stem and soil C), and help constrain parameters not well addressed by the flux data (e.g. specific leaf area, litterfall, component respiration).

Manipulative experiments complement the integrative nature of eddy covariance data by constraining subsets of model parameters under controlled conditions. We will incorporate both past experiments and new experiments outlined in tasks F2 to F4 into the parameter optimization. Key past or ongoing experiments critical to the effort include Free-Air Carbon Enrichment FACE (e.g. Norby and Iverson 2006, Iversen et al. 2008), the Throughfall Displacement Experiment (Hanson et al. 2003a), soil warming experiments (e.g. Bradford et al. 2008, Melillo et al. 2002) and the Enriched Background Isotope Study (e.g. Hanson et al. 2005; Swanston et al. 2005; Gaudinski et al. 2009). In addition to these existing datasets, experiments planned for Tasks F2, F3 and F4 will lead to improved model representations of C allocation, decomposition, and response to extreme events, all of which remain important deficiencies in current terrestrial C cycle models.

We will use several approaches for model parameter optimization, including Markov Chain Monte Carlo (MCMC) and the ensemble Kalman filter (EnKF). Where possible, we will use literature-based prior PDFs for model parameters. We will perform parameter optimizations for both the LoTEC model and CLM-CN. If the model(s) cannot reproduce these observations even after parameter optimization, this indicates that (a) the model structure is insufficient to represent the actual system, and/or (b) the model cannot account for observation biases and uncertainties. To prevent incorrect parameter estimates, biases in observations (e.g. underestimation by eddy covariance of fluxes under low turbulence conditions) must be corrected to the best of our abilities before the optimization. We will use a calibration cost function based on the model-data residuals that accounts for two types of error: (1) random observation error and (2) model error, which represents the inability of the model structure to reproduce observations. To make accurate predictions and uncertainty ranges, care must be taken to ensure the distribution of the model-data residuals after optimization match the a priori error assumptions. For eddy covariance random errors, we will assume Laplacian, heteroskedastic error distributions, as outlined by Richardson et al. (2006).

Individual optimizations will be performed for each eddy covariance site and for each experiment, providing information about how optimized parameters vary spatially and temporally. We will also perform several pseudodata optimization experiments in which hypothetical observations are incrementally added to the optimization in order to assess the value of new constraints in reducing parameter and prediction uncertainty. Finally, we will perform synthesis optimizations in which all available data for a plant functional type are used to obtain a single set of parameters and uncertainties. These PFT-level parameters and uncertainties will then be combined with gridded input datasets (Task F1b) to produce regional-scale model reanalyses and predictions.

Task F1a. Deliverables

FY 2010

Oct 2009 – Gap-filled input forcing datasets for conducting simulations at AmeriFlux and FLUXNET sites.

Mar 2010 – Submit manuscript with tables of optimized model parameters and associated uncertainties in conjunction with types of constraining data for selected AmeriFlux and FLUXNET sites.

Sep 2010 – Documentation of site-scale data assimilation framework for continual updating and analysis.

FY 2011

Mar 2011 – Submit manuscript quantifying parameter uncertainty when considering various data streams and constraints with EC data (CO_2, H_2O, sensible heat) and biometric data.

Sep 2011 – Submit manuscript evaluating parameter variability across space and time from EC network and indicate implications for continental flux uncertainty.

FY 2012

Mar 2012 – Submit manuscript describing parameter optimization based on preliminary results from allocation (Task F2) and soil carbon (Task F3) studies.

Sep 2012 – Submit manuscript describing parameter optimization based on preliminary results from extreme event (Task F4) studies.

Task F1b. Geographically distributed, continental and global scale simulation of the terrestrial biosphere to investigate terrestrial C cycle feedbacks on climate

The integration of the understanding, improved model formulation and parameterization obtained in the site-scale investigations of Task F1a require spatial and temporal extrapolation to geographical scales relevant to significant terrestrial feedback on global climate. We must answer the classical ecological question: How does one use information obtained at fine scales to solve broadscale problems (Levin 1992, Wiens et al. 1993)? Observations related to quantifying terrestrial C budgets are made at scales of centimeters to kilometers (leaf and soil chambers, eddy covariance flux towers, biomass inventories, crop yields, etc.). Our understanding of terrestrial C processes and mechanisms is best achieved at similar scales (for example, photosynthetic biochemistry, autotrophic and heterotrophic respiration, C pool dynamics, etc.).

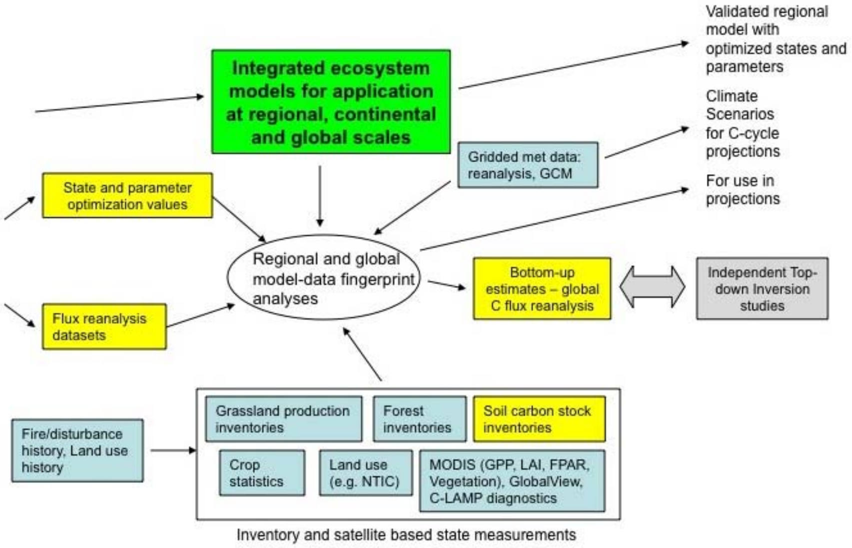

Figure F4. Model-data assimilation at the regional scale will be completed for North America followed by global efforts. This diagram is an expansion of the center portion of Figure F2 (see Figure F2 for color and symbol key).

A key challenge to extending site data to continental scales is that biogeochemical models generally assume that model parameters are constant within a given biome. However, model parameters calibrated at site levels often do not agree among sites within a biome. Constant parameter assumptions will therefore cause incorrect predictions of regional-scale fluxes, especially if the parameter variations are correlated with key driving variables. This source of error must be minimized by 1) removing within-biome variability as much as possible through the identification of invariant processes, and when this is not possible by 2) including this variability in error estimates using formal uncertainty analysis techniques.

Task F1b will use gridded data sets of model inputs and boundary conditions, to construct "bottom-up" estimates at high spatial and temporal resolutions of net C, water, and energy fluxes for terrestrial North America (Canada, United States, and Mexico).

We will use eddy covariance measurements, forest inventory and agricultural data products, and remotely sensed vegetation properties in conjunction with spatially distributed model simulations to address the following questions:

1. What biological, physical, and land use factors affect the spatial distribution and magnitudes of terrestrial C fluxes?
2. How do spatial relationships of measured C/water/energy fluxes change with temporal scales?
3. What is the uncertainty of the estimated ecosystem C budget globally and for North America?
4. What locations and types of additional information do we need most?

Answers to these questions will be synthesized to answer the following overall question:

> *How much detail and heterogeneity is necessary to produce broad scale C budget estimates with acceptable levels of uncertainty?*

Regional model-data fusion analyses will use results from Task F1a. The data assimilation approach at the regional scale will extrapolate site scale results using geographical relationships and databases of soil, vegetation, climate, land-use, and N-deposition. Simulations will be conducted in a factorial fashion and then be compared to observational data at regional scale for diagnosis and attribution of changes in C fluxes and stocks. These observation-based datasets include satellite estimates of GPP, NPP, LAI, NDVI, FPAR, inventory estimates of soil C, biomass, forest and crop productivity. We will use the fingerprint analysis that has been successfully applied in climate studies to detect and identify the patterns of greenhouse warming signals in climate (Santer et al. 1995, 2007). We will use principal components analysis of modeled and observed C cycle change patterns to assign the relative impact of climate, CO_2, N-deposition, biological, and land-use change in increasing or decreasing C sources and sinks.

Task F1b. Deliverables

<u>FY 2010</u>

Oct 2009 – Operational procedures to transfer information contained in observations and understanding of terrestrial C processes at local scales into models applied at regional and continental scales.

Mar 2010 – Spatially uniform ecosystem initial conditions for use in future projections with forward ecosystem models.

Sep 2010 – High spatial resolution simulations of C, water and energy fluxes, and associated modeled biomass and soil C stocks for North America and globally.

<u>FY 2011</u>

Dec 2010 – Submit manuscript comparing ITCM model simulations to observation-based measurements including Carbon Tracker and other inversion model estimates of net terrestrial C exchange.

Mar 2011 – Submit manuscript employing fingerprint analysis of factors influencing historical C fluxes using ITCM and CLM-CN with MODIS based observations.

<u>FY 2012</u>

Sep 2012 – Submit manuscript incorporating preliminary parameter optimization results from allocation and soil carbon studies (Task F1a, Tasks F2 and F3).

Task F1c. Prediction and analysis of sign and magnitude of climate-carbon cycle feedback at regional and global scales

The sign and magnitude of the global-scale carbon-climate feedback are critical metrics integrating the forcing influence of terrestrial ecosystems on greenhouse gas concentrations (Friedlingstein et al. 2006, Matthews et al. 2007). A central theme of the Forcing SFA science plan is to focus our research efforts on improved understanding of ecosystem structure and processes which exert significant control over atmospheric greenhouse gas concentrations. The climate-carbon cycle feedback framework, as formalized by Friedlingstein et al. (2003) and extended for transient estimation of feedback strength by Thornton et al. (2009) provides a set of objective metrics that will help guide our investigations throughout Task F1. For Task F1c we will deploy an operational capability to estimate the sign and magnitude of the global climate-C feedback, including methods to disaggregate the feedback signal in space and time. This estimation is accomplished using both partially- and fully-coupled climate system models with detailed land biogeochemistry process representation, as described in Thornton et al. (2007, 2009). Under Task F1c we will perform a sequence of simulations in parallel with Tasks F1a and F1b to investigate the regional and global-scale forcing consequences of new process-level knowledge as advances are made through site- and regional-scale data-assimilation and diagnosis. This sequence of experiments will be used to produce and regularly update an answer to our overall Task F1 science question:

> *What is the sign and magnitude of the global climate-carbon cycle feedback forcing from land, and what are the process contributions to that overall forcing across a range of spatial and temporal scales, and across multiple land ecosystems?*

By frequently re-evaluating a range of feedback parameters through updated global simulations, results from Task F1c will help to prioritize effort under other Forcing tasks. Task F1c will identify processes and structural characteristics with the largest uncertainties and strongest influence for further observation. We will evaluate all new parameterizations and process representations against an existing set of global C cycle metrics (Randerson et al. in press), and will contribute to periodic updates of those metrics as new analyses are completed under Tasks F1a and F1b. In addition to improved understanding and reduced uncertainty for the climate-C feedback, these simulations will also provide estimates of future CO_2 concentrations and future climate under assumed anthropogenic forcing from fossil-fuel consumption and land cover change.

Approach

This task will employ the Community Climate System Model (CCSM, Collins et al. 2006), a fully-coupled Earth system model with prognostic land and ocean biogeochemistry (Thornton et al. 2009). Our efforts will focus on the Community Land Model component of CCSM (CLM: Dickinson et al. 2006, Oleson et al. 2008), using its prognostic C and N cycle capabilities (CLM-CN: Thornton and Zimmermann 2007). The CLM framework, including CLM-CN, has a flexible spatial scale, and is regularly used for prediction at single points (e.g. Stockli et al. 2008) as well as for regional and global simulations. CLM-CN is included in the suite of models under Tasks F1a and F1b, and will provide a seamless mechanism for incorporating new process knowledge gained through site- and regional-scale data assimilation and diagnosis into a global-scale Earth system model.

Previous work has demonstrated the possibility of strong interactions among CO_2 fertilization, nutrient availability, changing temperature and precipitation dynamics, and both natural and managed disturbances as determinants of the forcing strength of land ecosystems on climate (Pacala et al. 2001, McGuire et al. 2001, Melillo et al. 2002, Thornton et al. 2002). More recent work suggests that these interactions could play a fundamental role in determining the sign and magnitude of the global-scale climate-carbon cycle feedback (Thornton et al. 2007, Sokolov et al. 2008, Thornton et al. 2009), with important consequences for prediction of future greenhouse gas concentrations under various levels of assumed anthropogenic forcing.

To quantify these interactions at global and regional scales and provide an evolving metric of their importance as new process knowledge is incorporated in models, we are planning the following core set of global-scale offline forcing simulations (OFS):

- OFS1: Control simulation, CO_2, N deposition, and land cover circa 1850.
- OFS2(a/b): Transient simulation, time varying CO_2 for 1850-2100

- OFS3(a/b): Transient simulation, time varying N deposition for 1850-2100
- OFS4(a/b): Transient simulation, time varying land use and land cover for 1850-2100
- OFS5(a/b): Transient simulation, time varying CO_2, N deposition, and land use.

This set of simulations will be repeated frequently, so for computational efficiency we plan to perform them in offline mode, with atmospheric forcing of the land model component provided by stored data as opposed to a prognostic atmospheric model (Thornton et al. 2007). Historical atmospheric CO_2 concentration, N deposition (Lamarque et al. 2005) and land cover (Hurtt et al. 2006) datasets are applied through present-day. A business-as-usual scenario for future anthropogenic forcing out through year 2100 extends the driving data set for prognostic runs. Simulations marked (a/b) in the previous list will be carried out with surface weather forcing saved from a fully-coupled control simulation (a) and with similar forcings saved from a fully-coupled simulation experiencing radiatively-forced climate change (b).

The influence of individual and combined factors (CO_2, N deposition, land use, climate change) on the sign and magnitude of climate-carbon cycle feedback will be estimated by differencing contrasting simulations. The influence of new process representations will be estimated by differencing simulations across repeated execution of the OFS1-OFS5 sequence.

At strategic intervals (approximately annually), the same sequence of simulations will be undertaken in the context of a fully-coupled climate simulation, with active land, atmosphere, ocean, and sea ice components (coupled forcing simulations, CFS1-CFS5). For the CFS sequence, the (a/b) distinction is between radiative forcing in the atmosphere experiencing either fixed (a), or prognostic (b) CO_2 concentration. The CFS sequence of simulations will provide information on forcing of physical climate components through changes in land ecosystem traits such as albedo and roughness, and will also be used as needed to periodically update the offline climate drivers for the OFS sequence. The coupled climate system model provides an internally consistent framework within which we can fully resolve the integrated influence of land ecosystem forcing of climate, generating predictions of the trajectory of atmospheric CO_2 and associated changes in regional and global scale patterns of temperature and precipitation.

As each iteration through the OFS or CFS sequence is completed, we will perform an analysis of the climate-carbon cycle feedback components in space and time, as well as a diagnosis of the major processes contributing to spatial and temporal variation, following and expanding upon the analysis framework described in Thornton et al. (2009). Information from these analyses regarding changes in forcing and feedback strength due to new process representation or parameterization will immediately inform the efforts under Tasks F1a and F1b. We also anticipate frequent interactions across Forcing SFA Tasks F1 to F5, organized in part around the regular updates on forcing and feedback estimation produced under Task F1c.

Task F1c. Deliverables

FY 2010

Oct 2009 – Operational capacity to carry out OFS and CFS sequence of simulations with CCSM.

Sep 2010 – Submit manuscript describing the interactions among CO_2, N deposition, climate change, and land use disturbance and their individual and combined influence on global-scale climate-carbon cycle feedbacks, using the existing structure, process representations, and parameterizations of CLM-CN.

FY 2011

Mar 2011 – Submit manuscript investigating the influence on climate-carbon cycle feedbacks of new parameterizations emerging from site-level data assimilation of eddy covariance observations.

Sep 2011 – Submit manuscript investigating the influence on climate-carbon cycle feedbacks of new parameterizations emerging from regional-scale data assimilation and fingerprint analyses.

FY 2012

Mar 2012 – Submit manuscript incorporating preliminary results and optimized parameterizations from allocation and soil carbon studies (Tasks F1a, F1b, F2, and F3) at global scale to study climate-carbon cycle feedbacks.

Task F2. Partitioning in Trees and Soil (PiTS)—A field research facility for developing dynamic C and N partitioning representations for global models and applications

Key ORNL Personnel: Norby, task leader; Iversen, plant-soil interactions; Garten, stable isotope labeling; Weston, physiological/biochemical measurements; Warren, sap flow and water relations; King and Thornton, ecosystem model; Gu, physiological model

Objectives

Our objective is to improve the C partitioning routines in existing ecosystem models based on the concepts gathered from plant partitioning models and tested against field observations and manipulations. We propose to use short-term, comprehensive field measurements of processes related to C partitioning from leaves to roots and roots to soil, including subsequent effects on N dynamics. These measurements are tied to specific hypotheses that generate general response functions based on measureable environmental attributes and lead to model algorithms and parameters.

Many aspects of plant physiology are involved in C partitioning and can vary according to phenology, life-phase, biotic and environmental conditions. We will focus on a narrow aspect of belowground C partitioning and associated nutrient uptake dynamics. FACE experiments have shown that tree growth in elevated CO_2 can result in a stimulation of fine-root production and a deeper distribution of roots in the soil profile (Iversen et al. 2008). Distribution of C to ephemeral tissue such as fine roots rather than to long-lived tissue (wood) has larger-scale implications for turnover of soil C, ecosystem C storage, and feedbacks through N metabolism. An improved understanding of the relative amount and fate of belowground partitioning will lead to improvements in model representation of C partitioning and the fate of C under elevated CO_2 and other climate perturbations; this is seen as a high priority in C cycle research.

Background

All models of ecosystem C cycling start with a representation of photosynthetic assimilation of atmospheric CO_2 by vegetation. This representation can be quite explicit, relying on the biochemistry and biophysics of photosynthesis, or it can be more general, representing relationships between light and leaf area modified by relationships to environmental conditions. In either case, the model representation is based on a strong, fundamental understanding of the processes involved. As a result, the models are well-tested, robust, and dynamic, meaning that as conditions change (e.g., rising CO_2, climate change, N feedbacks), the model produces predictable changes in C uptake by vegetation.

The next step in a model, as in the plant, is for the newly assimilated C to be distributed to different pools and processes, commonly referred to as C allocation, or more properly, C partitioning (Litton et al. 2007). There have been four main approaches used to model C partitioning in plants (Génard et al. 2008): (1) empirical models, (2) functional balance and optimization models, (3) models based on source-sink relationships, and (4) mechanistic models based on metabolite transport. Each of these different approaches has strengths and weaknesses, and they vary in the extent to which they can be useful in ecosystem models. Empirical models which use allocation coefficients or allometric relationships among plant parts can provide reasonable predictions under conditions for which the coefficients were measured but may be less useful under new conditions (e.g., climate change). Optimization approaches (e.g., Franklin et al. 2009) have been useful for providing insights into responses to perturbations such as elevated CO_2, but they suffer from relying on major simplifications and a biologically unreasonable assumption of the plant anticipating environmental conditions (Chen and Reynolds 1997). Models based on source-sink relationships assume that allocation depends on the relative ability of different sinks to import available assimilates from sources. They can provide a basis for changing C partitioning in relation to environmental heterogeneity (Yang and Midmore 2005), but the rules for determining sink strength can be difficult to determine. More mechanistic models based on transport and biochemical conversions of metabolites can be very powerful predictors for highly simplified model plants, but with more complex plant geometries the models "quickly result in mathematical bedlam" (Lacointe and Minchin 2008). Ultimately, ecosystem models suffer because they need relatively simple approaches that are biologically reasonable and dynamic enough to capture responses to new conditions.

It is especially important that ecosystem models improve in their representation of partitioning to belowground structures and processes because it is in the soil where critical interactions among C, water, and nutrient cycles occur. Previous field studies using techniques such as phloem chilling (Johnsen et al. 2007), ^{14}C and ^{13}C labeling (Carbone et al. 2007, Högberg et al. 2008), and statistical analysis of variation in PAR (Liu et al. 2006) have indicated that these are useful tools for analysis of photosynthesis and belowground partitioning of photosynthate, but they have not attempted to measure how specific processes contributing to CO_2 efflux from autotrophic and heterotrophic respiration are altered, nor do they link changes in partitioning to follow-on responses of soil C metabolism, N availability and uptake, or effects on the biotic community. By coupling short term experimental manipulations with intensive measurements above and below ground, we will advance our understanding of the biological and environmental influences on C partitioning, and their consequences for C-N interactions in plant and soil.

Hypothesis

Developing organs (i.e., leaves or fine roots) have the first priority for newly assimilated C and soil N. For example, the fraction of GPP partitioned to all belowground processes will be relatively low when canopy expansion is occurring and higher when demand for leaf production and metabolism is reduced. Conversely, if fine-root production increases in response to increased N demand or to exploit a zone of increased N availability, the N taken up from the soil will be partitioned first to satisfy N demand for the new fine-root production and metabolism, and then to the canopy.

PiTS Experiment Construction

Belowground observation units will be constructed adjacent to relatively small (<10 m height) trees. A 1 m wide × 3 m long pit will be dug between two trees of different species (preferably a deciduous vs. evergreen species, or a VA vs. ectomycorrhizal species), using individual trees rather than forest stands so that we can unambiguously associate roots with specific trees. For each experiment there will be three replicate pits. Each pit will be dug to a depth of 1.5 m, and a removable Plexiglas panel will be placed against the tree-side wall of the pit to maintain soil structure and moisture and root integrity. Scaffolding adjacent to the tree will provide access for canopy measurements and support temporary deployment of an enclosure to facilitate short-term isotopic labeling or environment manipulation. Unlike large, permanent rhizotron research facilities (http://www.nrs.fs.fed.us/research/facilities/rhizotron/), the approach used here will permit destructive sampling and labeling that would not be possible if it was necessary to maintain the integrity of the tree and soil system for many years.

The system will be instrumented to track C and N dynamics throughout the plant-soil continuum. PAR sensors above and throughout the canopy will support continuous calculation of PAR absorption. Sapflow gauges on the stem will support continuous measurement of transpiration and calculations of canopy-integrated stomatal conductance and photosynthesis (GPP). During specific measurement campaigns, xylem sap can be collected from stem segments and analyzed for sugars and N compounds. The belowground system will be outfitted with sensors through the wall of the trench. Minirhizotron tubes and soil moisture probes will be inserted horizontally at different depths. Soil gas sample tubes will be deployed throughout the profile and connected to a Picarro $^{13}CO_2$ analyzer. An automated CO_2 efflux analysis system will be placed on the soil surface. Soil water samplers also will be deployed throughout the profile.

Experimental Design

Pits will be dug and instrumented in fall or winter to allow a period of adjustment prior to measurements beginning in spring. Experimental campaigns will be conducted in spring when the canopy is rapidly expanding; early summer after canopy expansion is complete; and late summer when the canopy is senescing and resources are being remobilized.

We will test the hypothesis by measuring how C flux belowground varies with short-term changes in GPP in each campaign. This will involve a sequence of manipulations to alter the C balance of the canopy: (1) 5 days baseline data, (2) 5 days C starvation using shade cloth, and (3) 5 days C enrichment using high CO_2. These manipulations will be conducted on all three replicates at each season, but just one of the replicates will be labeled with $^{13}CO_2$ for each seasonal campaign to avoid the confounding of, for example, the spring-applied label with a summer label. GPP will be calculated based on sap flow data. Root vs. soil sources of respiratory CO_2 will be separated based on their distinct ^{13}C label, using a continuous measurement of $^{13}CO_2$ from throughout the soil profile (Picarro analyzer). Periods of fine-root production will be determined through minirhizotron observations.

Concurrently with ^{13}C labeling, ^{15}N (as nitrate or ammonium) will be applied to specific locations (hot spots) and at different depths in the soil profile. Subsequent distribution of the label will be determined by analyzing ^{15}N content in leaf, stem, and root tissue using an isotope ratio mass spectrometer. Root-specific N uptake rates will be measured as a function of soil depth using *in situ* measurements of root-specific uptake velocities (BassiriRad et al. 1999) by gently separating root systems from the pit face at 10-cm depth increments. We will characterize nutrient heterogeneity in horizontal cores throughout the soil profile using the methodology described in Hart et al. (1994) and Kellogg et al. (2006) to measure gross and net NH_4^+, NO_3^- and PO_4^- fluxes, as well as total N and P pools.

In the second year of manipulations, we will focus on C partitioning in relation to water uptake. New pits will be constructed and similar manipulations conducted, but soil moisture will be manipulated rather than N availability. We anticipate many other manipulations as well – the value of the facility we propose will be its flexibility. Additional investigations of soil C cycling will be conducted at the FACE site after the FACE experiments is ended in September 2009, following on a 12-year time series of soil C dynamics and making use of the distinct ^{13}C signature of soil in the elevated CO_2 plots.

Model Interaction

Our objective is to develop a dynamic, individual tree-based C partitioning model (DICP) that operates at diurnal time scales but can be integrated over the life time of a tree. It will be a comprehensive tool that is capable of simultaneously simulating C flows between source and atmosphere (CO_2 assimilation) and between source and various sinks at different positions of a plant (translocation of nonreducing sugars, mostly sucrose). The intention is that such a model will become the foundation for simpler C partitioning models can be developed and evaluated for use in large-scale terrestrial C cycle models.

Following Thornley (1991) and Thornley and Cannell (1992), we will divide biomass into categories of foliage, branches, stem, coarse roots and fine roots and mycorrhiza. Each category consists of pools of structure, meristem, C substrate and N substrate. Translocation of carbohydrates to different sinks (pools) will be described by the Münch pressure-flow theory, which assumes that the hydrostatic pressure gradients inside the sieve tubes induced by osmotic gradients is responsible for mass flow through which solutes are transported. We will assume that sucrose is the only sugar transported in phloem and chemical/biochemical conversions occur at substrate sinks (Salisbury and Ross 1992). Phloem loading and unloading processes will be modeled through Michaelis-Menten kinetics (Moing et al. 1994, Minchin et al. 1993, 1996). Photosynthates (soluble intermediates) will be partitioned into non-reducing sugars (sucrose, sorbitol, etc), starch, and an insoluble residue based on measured ratios reported by Moing et al. (1994) and measurements taken during the study. Photosynthesis at the leaf level will be described by the Farquhar biochemical model. To couple water flux in xylem (the apoplast) with sugar flux in phloem (the symplast), we assume that the plasma membrane allows water but not sugar move freely across it (a perfect semi-permeable membrane) with transverse water flux determined by a resistance factor as well as water potential differences between xylem and phloem along the paths (Daudet et al. 2002).

The model will operate at half-hourly time steps and will be driven by meteorological measurements at the site. Sugar measurements at different positions of the tree and different times of the day and the season will be used to test model behavior. Allometric relationships obtained with destructive sampling at the end of the study will be used to test the long-term integration of the model; that is, can a dynamic C partitioning model based on the concepts of sources and sinks and the pressure–flow theory simulate the diurnal variations in different C pools of a tree while maintaining functionally balanced allometric relationships when integrated over the life history of the tree?

Task F2. Deliverables

FY 2010

Mar 2010 – We will identify sites for pits and construct and instrument the first phase of the PiTS Facility by March 2010.

Sep 2010 – Observations will be made during the 2010 growing season, and by September have preliminary data sets and an evaluation of the second phase for the facility. DICP code will be developed in 2010.

FY 2011

As 2010 observations are completed and synthesized, new trenches will be constructed. Based on progress in using the 2010 data to inform both physiological and ecosystem models, new measurements and manipulations will be proposed. DICP code will be tested against measurements in 2011.

FY 2012

Improved belowground allocation routines will be added to models. Additional trenches can be constructed if critical uncertainties are identified. DICP is integrated over the life time of the trees and compared with allometric relationships.

Task F3. Representing soil C in terrestrial C cycle models—Achieving a generalized mechanistic formulation

Key ORNL Personnel: Hanson, Todd, Garten, Post
Collaborators: Jastrow, Matamala, Torn, Guilderson, McFarlane, Parton

Task F3a. Characterizing organic C flux from litter sources to mineral-soil sinks—The operation of a distributed enriched isotope study for eastern hardwood forests

This research provides data on C flux from litter sources to mineral soil sinks for United States eastern hardwood forests necessary for testing process hypotheses and judging efficacy of soil C cycling models. We previously used ^{14}C-enriched material collected from local releases of radiocarbon resulting in whole-ecosystem isotopic label near Oak Ridge, Tennessee to study fundamental terrestrial soil C cycle of upland forests (Trumbore et al. 2002; Hanson et al. 2005; Swanston et al. 2005; Gaudinski et al. 2009). The original Enriched Background Isotope Study (EBIS-Oak Ridge) supported conclusions that intra- and inter-annual soil C cycling in hardwood forest soils be characterized as a two-compartment system where surface leaf-litter and belowground root turnover represent primary C sources for organic-layer and mineral-soil C cycles, respectively. In 2004 and 2005, new atmospheric pulses of $^{14}CO_2$ on the Oak Ridge Reservation produced additional enriched plant material and the opportunity to deploy enriched materials for soil C cycle studies along a climatic gradient of AmeriFlux hardwood sites (EBIS-AmeriFlux). EBIS-AmeriFlux was implemented to evaluate soil C cycles over a wider range of climatic, edaphic, and biological conditions. Task F3a research provides data for addressing the CCP's goal of understanding mechanisms controlling C flux in soils, and for the improvement of stand, region and global models for application to fundamental C cycle calculations. Research on Task F3a will be completed within the next three years.

Background

Soil C plays a quantitatively important role in the global C cycle; the soil stores more C than all terrestrial biomass and the atmosphere combined (Post et al. 1990; Schimel 1995). Enhancing C accumulation in above- and below-ground terrestrial ecosystem C pools can help mitigate greenhouse gas accumulation in the atmosphere (Johnson 1995, IPCC 1996, IGBP 1998, Johnson and Curtis 2001). Carbon increases in soils are preferential to aboveground C accumulation because the C is better protected from periodic disturbance (i.e., wind throw, fire, pests) and has the potential for much longer retention (McFee and Kelly 1995). Despite the importance of soil C to local and global C cycles, the basic mechanisms controlling the flux and stabilization of belowground C are imperfectly understood, and they are often treated as black boxes in ecosystem models. Data on the detailed processes controlling soil C cycling are available for only a limited number of research sites and an evaluation of the climatic and biological controls is needed for prognostic models.

AmeriFlux studies have generated detailed, whole-ecosystem, intra- and inter-annual data on the net flux of C from a wide range of ecosystems, but those studies typically conclude that soil C changes are nonexistent or represent only a small component of annual net C accumulation because direct observations of soil C pool changes have not been attempted (e.g., Curtis et al. 2002; Ehman et al. 2002). Where gradients have been used to evaluate soil C turnover times, as a substitute for repeated site-specific observations (Sun et al. 2004), they lack the temporal resolution for comparison to eddy flux data. Because the soil C pool is very large and unquantified below shallow soil layers, more work is needed to characterize the true turnover times and rates of change in soil C pools. Soil respiration represents a huge annual loss of terrestrial C to the global atmosphere that may be balanced by C from leaf-litter and root turnover within established ecosystems (Raich and Nadelhoffer 1989). Many undisturbed ecosystems, however, are not at steady state and continue to accumulate C aboveground (Wofsy et al. 1993; Barford et al. 2001; Hanson et al. 2003ac, 2004) and probably belowground as well (e.g., Kelly and Mays 2005). Traditional soil C studies demand long-term observations to resolve rates of change in measured soil C pools (Trettin et al. 1999; Johnson and Todd 1998; Richter et al. 1994; Post and Kwon 2000), and such studies are not a good match for the information on dynamic intra- and interannual change resolved by the AmeriFlux network.

When C pools can be characterized by distinct isotopic signatures, tracking isotopic sources and fates can be a powerful tool with short and long temporal resolution that is better suited for the interpretation of the soils' contribution to ecosystem net C flux (Gaudinski et al. 2000; Trumbore 2000). The processes responsible for soil C sequestration, e.g., biomass production and soil respiration are most often characterized and manipulated at short time steps (Davidson et al. 1998; Edwards 1975; Edwards and Sollins 1973; Edwards et al. 1977; Hanson et al. 1993; Paul et al. 1999). Linking records of soil C change over time with the processes responsible for soil C sequestration will allow estimates of current and future rates soil C change. The Enriched Background Isotope Study (EBIS, Trumbore et al. 2002; Hanson et al. 2005) has taken advantage of ecosystem-scale ^{14}C-enrichments of an upland mixed deciduous forest ecosystem to enhance our understanding of processes responsible for both short- and long term changes in soil C cycling processes. Soil organic matter has a range of turnover times that is normally associated with an 'average' based on bulk measurements. The advantage of tracking C with a ^{14}C-label is that it allows us to identify the faster cycling components of bulk pools that are most likely to respond on timescales comparable to AmeriFlux observations (years-to-decades), allowing more accurate constraints to the long-term cycling components as well. The ongoing manipulations and observations allow us to address the following hypotheses:

Hypotheses

H1. Carbon sources from leaf-litter, surface humus, or fine-root organic sources will exhibit distinctly different rates of accumulations into mineral soil C when common litter is applied to different AmeriFlux sites.

H2. Carbon transport from organic to mineral soil C pools will be slower in colder and drier environments. Variable microbial populations and activity will contribute to this difference.

H3. Variation in the population densities of macro-biota (esp. earthworms and millipedes) will impact the rate of surface to mineral soil incorporation across the eastern United States. In contrast to the EBIS-Oak Ridge, which had very low populations of such biota, sites with more active or larger biotic populations may show greater coupling between the organic- and mineral-soil C cycles.

H4. In addition to climate factors, the stabilization of newly derived litter C in mineral soils will depend on the distribution and character of mineral surfaces and exchange complexes.

Experimental Sites

In fall 2007, we established enriched litter manipulations at four AmeriFlux sites that span the climatic extent of the eastern deciduous hardwood forests and are appropriate for testing our hypotheses related to climatic controls on soil C cycling processes. Another Michigan site with heavier textured soils was added in fall 2008 (Table F1). Although each site's vegetation composition is not identical to the source forests on the Oak Ridge Reservation (ORR), we have selected sites with similar annual litterfall and many overlapping species to minimize the biases associated with applying non-native litter, while taking advantage of the ability to make cross-site comparisons with a common-litter application. We emphasize that part of EBIS-AmeriFlux is designed to determine if the fundamental discoveries from the EBIS-Oak Ridge (for example, that mineral soil organic matter is derived more from root than leaf litter) scale to other sites or are in part reflecting site specific characteristics of the Oak Ridge site (e.g. lack of earthworms, or the surface characteristics of minerals in that Ultisol).

The EBIS-AmeriFlux work addresses soil C cycling on a variety of timescales. Time-zero measurements of radiocarbon in soil organic matter fractions (Figure F5) will be used to characterize decadal to millennial timescales for C cycling and provide a constraint for models of soil C cycling (e.g., Gaudinski et al. 2000; Torn et al. in press). Initial ^{14}C and soil C observations have been completed for the MO, MI #1, HF, and BEF sites. The data provide a solid baseline for interpreting climate driven controls on the soil C cycle. The unique and 'younger' ^{14}C profile for MI#1 prompted the addition of a second MI sites in the fall of 2008 with heavier textured soils and thus a ^{14}C depth profile more consistent with the other sites and those in Oak Ridge.

Table F1. Characteristics of the AmeriFlux sites in the proposed ^{14}C soil C cycle study and the EBIS-Oak Ridge site. Climatic data are annual means. Litterfall data are from on-site collections. Earthworm assessments are approximate pending planned surveys.

Site Local Host	State	Lat. Long.	Temp. (°C)	Precip. (mm)	Dominant Species	Litterfall mass (g±sd)	Earthworm activity
MI Site 1 Knute Nadelhoffer	MI (MI#1)	45°33'N 84°42'W	6.2	750	*Populus, Pinus, Quercus*	*289±78*	*Low*
MI Site 2 (MI#2) Knute Nadelhoffer	MI (MI#2)	45°29'N 84°41'W	6.2	750	*Acer, Populus, Fagus*	*233+96*	*Medium*
Harvard Forest William Munger	MA (HF)	42°32'N 72°10'W	7.9	1066	*Quercus, Acer, Betula, Tsuga*	*292±22*	*Low*
Bartlett Exp. For. David Hollinger	NH (BEF)	44°3'N 71°17'W	6.5	1400	*Fagus, Acer, Betula, Tsuga*	*255±26*	*Low*
Missouri Ozark Stephen Pallardy	MO	38°44'N 92°12'W	12.8	940	*Quercus, Carya, Acer*	*353±54*	*High*
EBIS-Oak Ridge	TN	35°58'N 84°17'W	14.6	1348	*Quercus, Acer, Liriodendron*	*493±98*	*Low*

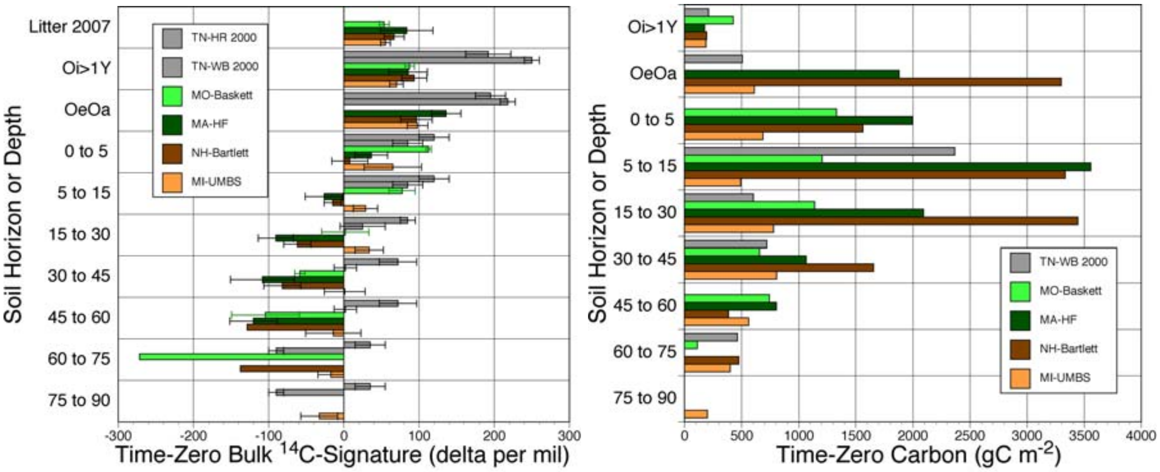

Figure F5. Time-zero data for the EBIS-AmeriFlux study sites plotted together with comparative data from the completed EBIS-Oak Ridge observations. These data are provided to show progress. Year-1 data for MO, MI#1, MA, and NH sites are currently being processed. Time-zero samples for MI#2 are analyzed.

Experimental Design

^{14}C-enriched materials – ^{14}C-enriched Enriched leaf-litter (^{14}C~1000 ‰), humus (Oa-horizon; ^{14}C~400-500 ‰), and fine root (top 20 cm; ^{14}C~500 ‰;) materials were collected and archived in 2005 for the proposed multi-site AmeriFlux manipulations. Because AmeriFlux field site operators had logical concerns about the importation of invasive species seeds, fungal pathogens, or other pests or disease vectors from the Oak Ridge litter. All of the ^{14}C-enriched litter to be added to the plots was or will be irradiated prior to deployment at the field sites. A study of the decomposition characteristics of control versus irradiated litter on the Oak Ridge show no long-term impact of the sterilization once redeployed in the field.

Litter Type manipulations **–** Leaf, humus, and root litter manipulations were initiated at each EBIS-AmeriFlux site. In all cases, plot-specific time-zero measurements of the ^{14}C-signatures of the resident Oi, Oe/Oa (if present), 0-to-5 cm, and 5-to-15 cm mineral soils are serving as baseline controls for the enriched litter additions. Time-zero collections were made in the

November or December of 2007 for MI Site #1, MO, HF, and BEF or in November of 2008 for MI Site #2. We realize that use of a common litter across sites has both advantages (climate, minerals and local soil fauna/microbes will be the main reason for differences in decomposition rates) as well as disadvantages (decomposition rates won't map on to local conditions because of litter quality differences). We emphasize that (1) measurement of time-zero (pre-manipulation) radiocarbon will yield information on the in situ rates of C cycling in litter and soil organic matter, and (2) our goal is to follow the fate of the labeled litter so as to understand how the pathways and rates of C sequestration in mineral soil vary between (a) sites with different climate and soil conditions and (b) leaf vs. root inputs. In other words, we can test hypotheses 1 to 4 within the experimental design, while at the same time providing information critical to construction of site-specific C cycle models through the time-zero measurements and modeling efforts.

Leaf Litter Manipulations – Ambient site litter is replaced with enriched Oak Ridge litterfall for three sequential years to track transfer rates of leaf litter C to mineral soil C pools. At each AmeriFlux site, 5 replicate 2 x 2 m plots were established in year 1. Landscape cloth is placed on each plot in August/September of years following enriched-litter additions to exclude native litterfall (on-site participants facilitate this process). When autumn leaf senescence is complete at each site, the landscape cloth is set aside for reuse and a constant mass of enriched litter is added to all plots. Constant rather than site-specific litter additions are done at all sites to allow comparisons across climate conditions.

Humus Litter Manipulations – To evaluate the fate or rate of transfer of humus (Oa-layer) C to the mineral soils, enriched humus additions are also deployed at all AmeriFlux sites. These independent manipulations are important because EBIS-Oak Ridge *in situ* DOC observations and mesocosm research has shown that humus-derived DOC can be a dominant form of C leached from organic horizons (Park et al. 2002, Park and Matzner 2003; Fröberg et al. 2005, Hagedorn et al. 2003). Five replicate 1 x 1 m humus plots were established adjacent to the leaf litter manipulation plots to allow the same time-zero (i.e., pretreatment) data to be applied to both studies. Enriched-humus will allow us to resolve a C transfer pathway (organic humus to mineral soil) that is seldom quantified. Ambient litter is allowed to fall onto these humus plots; the amount of litterfall is monitored at each AmeriFlux site, and we will characterize the radiocarbon content of ambient litterfall (which should be similar across sites).

Fine-root litter Manipulations – Enriched fine-root materials for root-to-soil C transfer manipulations were deployed at each site to characterize the influence of climate extremes on root-derived C inputs. Manipulations targeting fine root to soil C transfers could not be accomplished at the square meter plot scale, but instead were based on *in situ* enriched-root incubations. *In situ* root turnover incubations consist of reconstructed surface-soil bags (9 cm long x 10 cm deep) with site roots removed and replaced with enriched fine root materials. The incubation bags were constructed of a fine membrane to exclude new root (but not fungal) growth and were repacked with homogenized site soils to a determined bulk density. Enough bags were installed in the surface mineral soils at each site to allow multiple replicated samplings over time. Root-free incubation bags were also deployed to control for any changes in the decomposition rates of native SOM pools caused by soil physical disturbance during incubation bag construction. Several replicate incubations per site per year are being assayed to determine the rate of root disappearance and the rate of ^{14}C transfer to and between soil fractions. Site litter is allowed to fall over the area where the incubation bags are installed.

Macrobiotic surveys – Surveys of macrobiotic populations (earthworms, centipedes, etc.) at each site are being subcontracted in FY2009 to help interpret site-to-site differences that may not be driven by local climatic conditions.

Planned Annual Measurements and Protocols

The multi-site nature of this work, the large distances between AmeriFlux sites, and the cost of ^{14}C analyses logically dictate an annual sampling regime for the proposed leaf-litter and humus manipulations. This plan covers completed annual sampling in late-fall 2007 (time-zero), late-fall 2008 (1-year), and anticipates continued sampling in November/December of 2009, 2010 and 2011. This sampling plan with ^{14}C-enriched litter added in 2008, 2009, 2010 (and 2011 for the MI#2 site) will allow us to track the fate of ^{14}C-labeled litter C forms for a 5-year cycle. Root incubation bags will be removed more frequently over the same period (1, 6, 12, 18, 24, 30, 36, and 42 months after installation). Annual measurements for bulk soil horizons (bulk Oi and Oe/Oa horizons, bulk 0 to 5 cm and 5 to 15 cm mineral soil) and soil organic matter fractionations will be made for all replicate plots and periodically for root incubations at the five EBIS-AmeriFlux sites along the climatic gradients. Due to imposed page limits for the overall Forcing SFA science plan we have not outlined specific measurement and sampling handling protocols, but they can be made available for review and comment on request. Protocols for EBIS-AmeriFlux measurements that are financial responsibility of other DOE National Laboratories are detailed in their respective SFA documents: LLNL – extensive ^{14}C assessments and soil incubations; LBNL – soil separations to characterize the fate of C within mineral soils, and ANL – root turnover assessments and additional soil separations.

Task F3b. Modeling soil C turnover times at AmeriFlux sites

Conceptual models of soil C dynamics are growing increasingly complex with time to accommodate newly acquired knowledge about soil structure, the bio-physico-chemical protection of organic matter, and the numerous mechanisms and factors that control soil C stocks at local, regional, and global scales. Although there is a concerted effort within the soil science community to develop a structure for soil C models that is increasingly related to measureable C pools (Six et al. 2002, Stewart et al. 2008), minimalistic or reduced representations of soil C balance (Andren et al., 1997; Garten et al., 1999) are still frequently encountered in coupled C-climate models where one or a few abstract pools are used to represent the dynamics of soil organic matter. More detailed descriptions of belowground processes require more complicated mathematical models whose expanded parameter sets, along with laborious methodological quantification of different soil C pools, may temporarily limit their application over large spatial scales. Considering the time required to research and develop new paradigms for soil C models, reliable quantification of soil C dynamics in older and simpler representations continues to be a research priority. The purpose of this research task is to use data from forests along a latitudinal gradient to estimate soil C turnover times at AmeriFlux study sites that differ in climate, soil type, and forest N status through the use of reduced, generalized formulations of soil C dynamics.

In both FY 2008 and FY 2009, soil samples were collected from five AmeriFlux sites in proximity to EBIS-AmeriFlux study sites: University of Michigan Biological Station, MI; Harvard Forest, MA; Bartlett Experimental Forest, NH; Missouri Ozark, MO; and Oak Ridge, TN (see Task 3a for site descriptions). The two years of data from each study site include measurements of O-horizon (Oi, Oe, and Oa when present) and mineral soil C and N stocks and the partitioning of mineral soil C and N between two pools of soil organic matter (particulate organic matter and mineral-associated organic matter) that have been demonstrated to differ in relative rates of soil C turnover (cf. Garten and Wullschleger 2000, Garten and Ashwood 2002). In addition, we are measuring vertical profiles in soil ^{13}C abundance at each study site to test reported relationships between soil C turnover times and ^{13}C-enrichment factors (Garten 2006), as calculated from the Rayleigh equation (Mariotti et al. 1981) that describes ^{13}C abundance as a function of soil C concentration. Working from a set of equations with minimal data requirements, Monte Carlo methods are being used to predict the turnover time of soil C at each AmeriFlux site along with estimates of uncertainty in predicted rates of turnover. Measurements of CO_2 efflux from long-term laboratory incubations of soils from each site are also underway and in their 5th month of incubation. Time histories of CO_2 efflux from the different soils, measured using a soil respirometer, will be used with a two-compartment model to summarize soil C dynamics across the various sites.

We previously found that the commonly applied two-compartment isotopic mixing model was appropriate for estimating decomposition from isotopic enrichment of near-background soils, but it produced divergent results for isotopic dilution of a multi-layered system with litter cohorts having independent ^{14}C-signatures (Hanson et al. 2005). This discrepancy suggests that cohort-based models are needed to adequately capture the complex processes involved in litter mass-loss. We developed an enriched litter cohort model, ECHO, that models multiple-cohorts and include realistic representations of decomposition and leaching processes (driven by intra-annual temperature and litter and soil water conditions). This level of detail is needed to successfully capture organic layer C cycling and C transfer to the mineral soil but is not included in models used in global analyses of decomposition dynamics. The soil C model parameterized for AmeriFlux sites in this research task and ECHO, will be further developed and incorporated into the proposed Integrated Terrestrial Carbon Model (ITCM) (see Task F1) for improving predictions of intra- and inter-annual differences in organic horizon decomposition driven by scenarios of climatic change.

Task F3. Deliverables

FY 2010

Oct 2009 – Complete elemental and isotopic analysis and statistical analysis of data collected from five AmeriFlux sites during FY 2009.

Nov to Dec 2010 – Conduct the 2-year sampling of C pools for the Task F3a leaf and humus litter manipulations and add the third and planned final cohort of leaf litter to all plots.

Mar 2010 – Complete post-sample processing of all field collected sample.

Apr 2010 – Manuscript submitted on comparative soil C dynamics at five AmeriFlux study sites (MI-1, MI-2, MO, NH, MA), including estimation of soil C turnover times.

Jun 2010 – Complete bulk-^{14}C analyses for all sites, plots, and soil pools.

Jun 2010 – Complete and summarize the a priori FORCENT (improved EBIS version of the Century model) simulations for all research sites included in Task F3a to project leaf and humus migration and stocks through time.

Sep 2010 – Manuscript submitted on soil C cycling and vertical mixing by worms.

FY 2011

Nov to Dec 2010 – Conduct the 3-year sampling of C pools for the Task F3a leaf and humus litter manipulations.

Mar 2011 – Complete post-sample processing of all field collected samples.

Jun 2011 – Complete bulk-^{14}C analyses for all sites, plots, and soil pools.

FY 2012

Nov to Dec 2011 – Conduct the year 4 sampling for the Task F3a leaf and humus litter manipulations.

Mar 2012 – Complete post-sample processing of all field collected samples.

May 2012 – Final collections of the root turnover cores will be accomplished by Argonne National Laboratory.

Jun 2012 – Complete bulk-^{14}C analyses for all sites, plots, and soil pools.

Sep 2012 – A draft paper summarizing empirical cross-site findings for the bulk ^{14}C turnover and transport rates will be completed. Subsequent papers on the responsible mechanisms driving observed patterns, and the details of transport of C through specific component soil C stocks will be generated in future FYs.

Task F4. Terrestrial impacts and feedbacks of climate variability, extreme events, and disturbances

Key ORNL Personnel: Gu, Hanson, Yang, King, Parton, Post
Collaborators: Pallardy, Matamala, Meyers

Background and justification. A critical uncertainty in terrestrial ecosystem feedbacks to climate change and Earth system modeling is our poor understanding and low predictive ability of dramatic and often sudden shifts in sizes of and fluxes between different C reservoirs of the Earth system. These shifts can be caused by extreme weather and climate events (definition follows the 2008 report on 'Weather and Climate Extremes in a Changing Climate by USCCSP, thereafter USCCSP 2008) such as droughts, heat waves, hurricanes, ice storms, unseasonable freezes and wind storms and disturbance events such as fires and insect outbreaks. Past focus on global climate forcing and mean ecosystem responses has led to gross understudy of consequences of episodic Extreme Weather, Climate and Disturbance Events (EWCDEs) on the terrestrial C cycle and feedbacks to climate change. EWCDEs are not represented in current terrestrial C cycle models (Friedlingstein et al. 2006, Running 2008). To remedy this situation, Task F4 will seek to understand and quantify the roles of EWCDEs and seasonal to decadal climate variability in terrestrial C cycle feedbacks to climate change. This will be achieved through strategic flux measurements, data mining and integration, and network synthesis and via rapid, collaborative responses to developing EWCDEs. ***Its goal is to enable fundamental representation of terrestrial C cycle impacts and feedbacks of EWCDEs in Earth system diagnosis and prediction***.

At present our knowledge levels regarding how climate warming will affect intensities and frequencies of diverse EWCDEs are uneven and for most part, unsatisfactory (IPCC 2007, USCCSP 2008). However, regardless the relationships between climate warming and individual EWCDEs, their impacts and feedbacks must be studied as an integral part of climate change science because EWCDEs, once occurred, are often transformational for ecosystem structures and functions and will subsequently alter terrestrial C cycle feedbacks to climate change. The literature has no shortage of clear observational records on the powerful ecological, biogeochemical and biophysical influences of droughts (e.g. Allen and Breshears 1998, Gu et al. 2006, McDowell et al. 2008, Phillips et al. 2009), heat waves (e.g. Ciais et al. 2005), hurricanes (e.g. Chambers et al. 2007, Zeng et al. 2009), unseasonable freezes (e.g. Gu et al. 2008), massive ice storms (e.g. Millward and Kraft 2004, Stone 2008, Zhou et al. 2009), fires (e.g. Randerson et al. 2006, Page et al. 2002), insect outbreaks (Kurz et al. 2008), etc. A number of researchers have appealed to the climate change research community to increase investigation on impacts and ecological feedbacks of extreme events and disturbances (e.g. Gutschick and BassiriRad 2003, Jentsch et al. 2007, Running 2008, Gu et al. 2008).

EWCDEs are inherently difficult to study. The impact of an EWCDE on a terrestrial ecosystem depends on not only the event's characteristics but also the structure and past history of the ecosystem. No one can know for sure when and where an EWCDE will occur. When an EWCDE does occur, crucial pre-event ecosystem information for reference is often not available. The common, individual proposal–based research funding structure is not conducive to studying EWCDEs; by the time a funding opportunity arises and a proposal is written, reviewed and approved for funding, vital during- and post-event impact information is already lost. DOE BER Scientific Focus Area (SFA) Programs provides a unique mechanism for National Laboratory scientists to study the impacts and feedbacks of EWCDEs. The SFA structure permits research that requires integration, collaboration and flexibility. ***Integration, collaboration and flexibility is the key for successful studies of impacts and feedbacks of EWCDEs***.

Our recent studies on the unseasonable 2007 Easter freeze in southeastern US (Gu et al. 2008), the massive 2008 south China ice storm (Zhou et al. 2009) and a drought in 2005 in the Midwest (Gu et al. 2006) offer some lessons on how we should carry out Task F4. For both the Easter freeze study and the ice storm study, vigilance about a developing event, rapid formation of a research plan and team of diverse but complementary expertise, and flexibility in conducting unforeseen research enabled us to catch the two events in action. In the case of the drought study, continuous measurements in a strategic location paid off. The common lesson from all three studies was that it is almost impossible for a few independent scientists, no matter how hard working they are, to conduct effective research on impacts and feedbacks of EWCDEs that contributes to Earth system modeling. The spontaneous nature of EWCDEs and the broad spectrum of their biome-specific impacts and feedbacks require collaborative, interdisciplinary efforts. Thus we believe a successful research strategy for the ecological impacts and feedbacks of EWCDEs must have as its essential ingredients continuous measurements in targeted locations, community effort, data mining and integration, and network synthesis.

The research under Task F4 will be conducted in three subtasks:

- Subtask F4a—Strategic flux measurements
- Subtask F4b—Network synthesis and EWCDE database
- Subtask F4c—Rapid, collaborative responses to developing EWCDEs

Subtask F4a. Strategic flux measurements

We will conduct strategic flux measurements to quantify the variability, vulnerability, and resilience of C uptake and water use at both ecosystem and species levels in a biome ecotone. The focus will be on linkage with frontal activities, the timing and intensity of precipitation events, the magnitude and duration of droughts, large temperature fluctuations, and other episodic events. Subtask F4.1 will be carried out at the Missouri Ozark Forest AmeriFlux site (MOFLUX, Gu et al. 2006, Gu et al. 2007, Yang et al. 2007, Xiao et al. 2008). The MOFLUX site is strategically located in an ecologically important transitional zone (ecotone) between the central hardwood region and the central grassland region of the US. Although we cannot guarantee a particular extreme climate or weather event will occur, the site has shown great potential to capture seasonable and interannual variability in climate. Since the initiation in 2004, fluxes of CO_2, water vapor, and energy have shown striking seasonal and year-to-year fluctuations in response to large variations in precipitation (Gu et al. 2006). Superimposed on the precipitation variability was an unseasonable freeze in 2007 which disrupted phenological development (Gu et al. 2008). The time series collected so far are still too short to untangle the interactive effects of these alternating wet and dry conditions and large temperature fluctuations. But with continuous measurements, MOFLUX offers an opportunity to advance our understanding and test models of terrestrial C processes under diverse weather and climate conditions with a scope much wider than what may be experienced at flux sites located in biome interiors.

To maximize the advantage of large weather and climate variability and ecotonal vegetation at the MOFLUX site, we will use the passage of cold, warm and occluded fronts, precipitation events (which may or may not occur during a frontal passage) and phenological phases to organize the research at MOFLUX. The passage of weather fronts is often accompanied by sudden, dramatic changes in meteorological conditions within a period too short for vegetation adaptation or structural changes to take place. Thus contrasting pre- and post-frontal C and water processes can lead to better understanding of functional limits of ecosystems. Similarly, responses to contrasting precipitation regimes (timing, frequency and intensity) may yield deep insights into ecophysiological effects of presence and relief of water stress. With respect to phenological phases, they are the most important biological regulators of surface fluxes and are sensitive to temperature fluctuations. Using them to structure flux analyses is a logical way towards understanding the impacts of temperature variability on C and water processes.

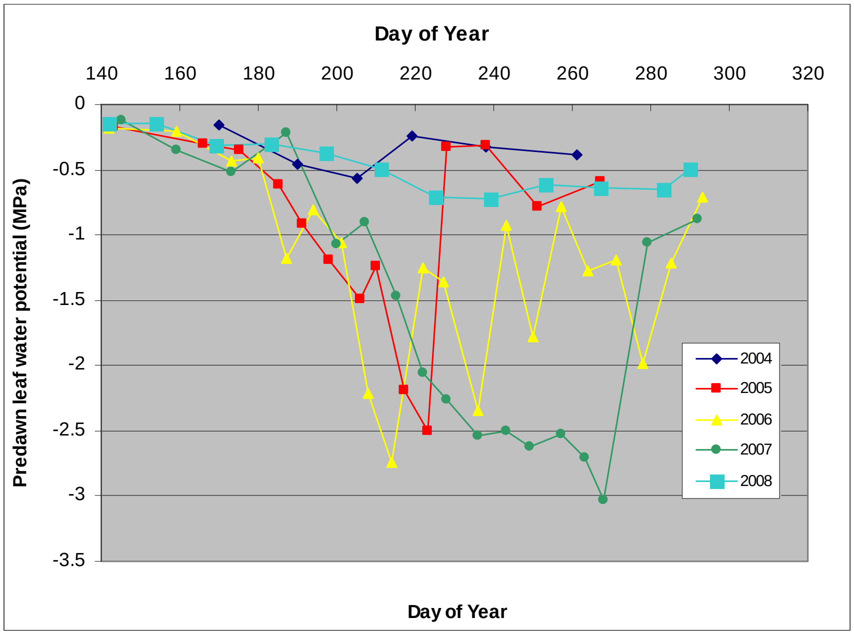

Figure F6. The MOFLUX site exhibits rich variations in precipitation regimes and stress levels, making it an excellent testbed for our understanding of how the variability, vulnerability and resilience of ecosystem, plant community, and species is affected by the timing and intensity of precipitation events, the magnitude and duration of droughts, and heat waves.

Subtask F4a will be guided by a set of questions that aim at advancing our understanding of the impacts and feedbacks of weather and climate variability and when opportunity arises, of extreme weather and climate events. These questions include:

1. How do ecosystem fluxes and leaf physiological properties of species vary in accordance with the timing, frequency, and intensity of precipitation events, with unseasonable temperature fluctuations, and with the phenological state of individual species and the plant community as a whole?
2. How do clouds and aerosols affect C uptake, water use and drought stress?
3. Are there any signatures in ecosystem flux dynamics that characterize different frontal activities?
4. How does the relationship between ecosystem fluxes and soil effluxes vary with the size and duration of precipitation events? Can the contribution of new photosynthates to soil effluxes be not only detected but also quantified with the existing instrumentation and analytical methods such as those of Liu et al. (2006)?
5. Can a comprehensive ecosystem model reproduce the observed progressions between events? If not, what improvements need to be made?
6. How do traits of individual species and ecosystem structure affect the resiliency of C uptake and water use to extreme weather and climate events and what are the thresholds?
7. What is the long-term implication of the variability, resiliency, and thresholds in C uptake and water use for the central hardwood forest – central grassland ecotone in a changing climate?

The MOFLUX automated instrumentation array strives to achieve a synergy among different data streams for constructing an integrative picture of atmospheric, physiological, biogeochemical and biophysical processes in controlling ecosystem C, water and energy exchanges. It consists of above-canopy eddy flux / meteorological systems, a 12-level vertical profiling system, an eight-chamber automated soil efflux monitoring system, sapflow monitoring system, and high precision CO_2 measurement system, forest floor eddy covariance system, and soil moisture/temperature monitoring system. The operations of the instruments are monitored on a daily basis at the site (hardware checking, Kevin Hosman) and from office (diagnosis with data streams, Bai Yang). The automated data streams are complemented by regular although less frequent, growing season measurements of leaf biochemistry and physiology (A/Ci curves, chlorophyll fluorescence, leaf N content, specific leaf area, predawn leaf water potential etc), soil C content and root profile. Furthermore, dendrometer bands are fitted to over 250 tagged trees. Plant community dynamics are characterized with inventory transects and plots and with the collection of litters which are sorted to leaves, reproductive structures, and woody material at varying intervals depending on expected rate of litter fall. The automated and complementary data streams are then integrated with the terrestrial ecosystem Fluxes And Pools Integrated Simulator (FAPIS, Gu et al. 1999a and Gu et al. 2007). In addition to its role as a site-data integrator, FAPIS will serve as a test framework for new process representations prompted by advances in process studies in Tasks F2, F3 and F4 as well as in the general science community. After testing, new process representations could then be implemented in large-scale models in Task F1.

To take full advantage of MOFLUX's strategic location and for better integration with the rest of the Forcing SFA, we will enhance current MOFLUX data streams. Our past research showed that clouds and aerosols are important driving factors of terrestrial C processes (Gu et al. 1999b, Gu et al. 2002, Gu et al. 2003). We have some evidence from MOFLUX data that even non-precipitating clouds could ease drought stress. However we have no direct cloud or aerosol measurements at the MOFLUX site. Therefore, we propose to install a total sky imager and a multi-filter rotating shadowband radiometer. The imager and the radiometer will provide much needed measurements of clouds, aerosols and diffuse/direct beam radiation to correlate with eddy flux measurements. We also need to enhance our physiological and biochemical measurements. Currently, we take leaf gas exchange and N measurements at two concentrated periods, one in early and one in late growing season, to control cost. This sampling protocol does not allow us to establish the seasonal course of vital leaf biochemical and physiological properties as well as their transient changes during sustained drought periods. We would like to sample on a weekly basis. An important issue is progressive decline in functional green area of leaves which occurs much earlier than scission. We will couple leaf gas exchange measurements with leaf image analysis to provide data to quantify this process.

The MOFLUX research will benefit from and contribute to the interdisciplinary Plants for Changing Environments program (PCE) proposed by University of Missouri – Columbia to the Integrative Graduate Education and Research Traineeship Program (IGERT) under the National Science Foundation. Three members (Pallardy, Hanson and Gu) of the Task F4 team will participate in the PCE IGERT program which has as its research theme understanding mechanisms of plant adaption to changes in abiotic stresses. Our participation in the PCE IGERT Program will facilitate MOFLUX as a platform for training next generation of integrative plant biologists. For the MOFLUX research agenda, our participation means the MOFLUX team will be augmented with additional talents with little additional cost and our focus on whole plant and ecosystem level issues will not prevent us from benefiting from advances in more fundamental levels of biological organization.

Subtask F4b. Network synthesis and EWCDE database

Subtask F4b has a dual objective. The first is to test the universality of the answers of event-oriented science questions pursued at the MOFLUX site across vegetation types and climate zones. The second is to build an EWCDE database and conduct synthesis supporting Earth system diagnosis and prediction.

Eddy covariance flux sites now exist in almost every major vegetation type and climate zone. Most of these flux sites are organized into regional or global networks whose data are open to the general climate research community with minimal limitation. Some of these sites have also experienced extreme events such as droughts and heat waves. Others have gone through or been established after major disturbance events such as lumber harvesting, fires and hurricanes. We will conduct event-based synthesis across networked flux sites. Initially, we will focus on frontal activities, droughts and heat waves and look for differences and similarities in impacts and feedbacks across vegetation types and climate zones. We will be also interested in the consequences of multiple EWCDEs that occur one after the other with relatively short periods in between (e.g. an unseasonable spring freeze followed by a drought, or droughts in two consecutive years). Such consecutive events, even if moderate individually, may prove to be much more damaging for ecosystem structures and functions because they may give little time for ecosystems and plant species to repair and recover.

Modeling of EWCDEs requires observational datasets for algorithm development and testing. There have been many studies recording damages of EWCDEs on forests that contain useful information for representing EWCDEs in Earth system diagnosis and prediction (Zeng et al. 2009). However, the data are scattered in the literature. Currently there has been no attempt to compile them systemically and integrate them into a form that is conducive to synthesis and to model building. Subtask F4b will change that by developing an EWCDE database. The EWCDE database will record the size, magnitude and action center of an EWCDE together with the pre-event and post-event vegetation states. Core variables, if available, will include degrees of damage and mortality of different species, abnormal litter productions, and secondary hazards (e.g. fire risk due to increased load of combustible materials). Societal impacts and responses will also be recorded. Initial focus will be on droughts, ice storms, tropical cyclones, windthrows, and fires. As the database expands, we intend to use it to quantify impacts of EWCDEs on historical terrestrial C budgets following the strategy of Zeng et al. (2009). We will also use it to develop and test functional algorithms of EWCDEs for large–scale prognostic models (Task F1).

Subtask F4c. Rapid, collaborative responses to developing EWCDEs

Subtask F4c aims at collecting vital data about a significant, developing EWCDE that can be lost easily after the event is over. The ORNL Climate Change Program Science Plan calls for a small fraction of the program funding to be set aside for task-specific discretionary or directed research. The Subtask F4c takes advantage of this flexibility. We intend to build upon our studies on the 2007 Easter freeze (Gu et al. 2008) and the 2008 south China ice storm which is expected to significantly degrade Chinese forest C sequestration and to affect Chinese forestry policy for years to come (Zhou et al. 2009). We were somewhat lucky in our being able to respond rapidly to these two massive events. In the case of the Easter freeze, we had several on-going research projects in the affected region at the time of the event (MOFLUX, CSiTE, and EBIS); in the case of the ice storm, a workshop in which one of our investigators was invited to give lectures happened to be right after the event in the region. With the flexibility of the set-aside discretionary fund, we do not have to rely on the tyranny of chance to respond to a significant EWCDE whose impact may have regional or national importance.

Subtask F4c requires investigators to pay attention to weather and news reports and have a network of potential collaborators in different parts of the world and in different disciplines (meteorology, ecology, forestry, remote sensing, plant physiology etc). We already have a basic structure for such a network. We will continue to improve this network. A combination of ground- and remote sensing- based approaches is the most effective way to gathering reliable information about a developing EWCDE and its impacts. We will rely on existing facilities and local investigators as much as possible. Core variables collected through Subtask F4b will be the same as in the EWCDE database as described under Subtask F4c.

Task F4. Deliverables

FY 2010	Install the total sky imager and the shadowband radiometer. Submit flux and complementary biological datasets to AmeriFlux. Complete analysis on soil respiration, paper submitted. Develop, test and implement a model of mesophyll conductance in FAPIS. Develop EWCDE database backbone for fires and droughts.
FY 2011	Submit flux and complementary biological datasets to AmeriFlux. Complete analysis on effects of contrasting drought regimes, paper submitted.

Complete analysis on FAPIS drought response, paper submitted.
Complete analysis on effects of frontal activities, paper submitted.
Historical data on forest damage from fires and droughts are compiled and entered into EWCDE database.
Develop EWCDE database backbone for ice storms, tropical cyclones, and windthrows.

FY 2012 Submit flux and complementary biological datasets to AmeriFlux.
Complete analysis on effects of clouds and aerosols on C and water fluxes, paper submitted.
Historical data on forest damage from ice storms, tropical cyclones and windthrows are compiled and entered into EWCDE database.
First EWCDE data synthesis, at least one paper submitted.
EWCDE functional relationships developed.

Task F5. Increasing spatial and temporal resolution and quantifying uncertainties in fossil-fuel CO_2 emissions for modeling and synthesis activities

Key ORNL Personnel: Marland, Andres

Recognition that the global C cycle was being altered by humans depended on the availability of measurements of the growth in atmospheric CO_2 and concurrent estimates of the rate at which humans were releasing C from fossil fuels. Inventories of global CO_2 emissions from fossil fuels date to the 1950s. As interest in climate change and the global C cycle have increased there has been increasing need to have time series emissions estimates at finer spatial and temporal resolution; by political and economic sector categories; by characteristics such as mass, fuel source, and isotopic composition. We now also appreciate that our understanding of the global C cycle is being limited by the uncertainty in fossil-fuel emissions estimates (see also Marland, 2008, Piao et al., 2009). Task 5 addresses the following question:

> *Can our quantification of C cycling in the terrestrial biosphere be made more precise with better representation of the spatial and temporal distribution and uncertainty of the fossil fuel source term?*

Approach

Efforts under this proposal will follow two pathways to enhance ongoing emissions inventory activities. We will work to (1) improve the spatial and temporal resolution of the CO_2 emissions inventories, and to (2) understand and clarify the uncertainty in emissions estimates. Up to now, CO_2 emissions inventories have been at the scale of countries and years. However, we have developed, using new information, methods that increase the temporal and spatial resolution of emissions reporting data. Efforts led by Robert Andres and his students, and supplemented by Gregg Marland, have been aiming at inventories at the scale of states and months. Some values have been published for North America, China, and Brazil. Other values are in the Dissertations of London Losey and Jay Gregg. The objective is to carry this globally and with the longest time series that the available data permit. The effort will be led by Bob Andres with CDIAC support, with collaboration from Gregg Marland under this SFA. Data on fossil fuels permit estimates of the annual and spatial distribution of emissions within many large countries and these will be used as proxy to extend the analysis globally.

A second activity will focus on understanding the uncertainty of emissions estimates. This will include the spatial distribution of uncertainty. This will involve estimating the uncertainty by country and doing Monte Carlo analysis of the country data to reach global conclusions. Work will be led by Andres with support by Marland. Further insight into the uncertainty of emissions estimates can be established by looking at the evolution of emissions estimates over time, i.e. emissions for 2000 as estimated from data available in 2002 and as estimated by data available in subsequent years. Analysis will involve comparing national reports to the United Nations Framework Convention along with historic emission estimates from CDIAC and from the International Energy Agency. Work will include collaboration with scientists at the International Institute for Applied Systems Analysis in Austria.

Task F5 Deliverables

FY 2010

Sep 2010 – Preliminary emissions inventories at the scale of states and months at a global scale for use in Task F1b analyses.

FY 2011

Mar 2011 – Complete an analysis of the global and spatial distribution, and the evolution of global uncertainty with time.

FY 2012

Oct 2011 – Submit manuscript on state scale fossil fuel emissions and associated global uncertainty with time.

MANAGEMENT TEAM AND INTEGRATION

Peter Thornton will lead the management team of the Forcing SFA. He will have overall responsibility for the SFA and for communicating directly with Technical Leaders for a variety of tasks associated with the SFA. The Forcing SFA will include scientific staff and post-doctoral associates with the expertise needed to support the five SFA tasks. External collaborators at universities and other National Laboratories will participate under subcontract as appropriate to goals of the SFA's manipulative experiment.

Task F1 – The global modeling activities will involve Mac Post, Anthony King, Lianhong Gu, Tris West, Gregg Marland, and Peter Thornton who with national reputations in C cycle processes and emission inventories will lead activities related to the integration of experimental results, observations, and modeling to improve understanding and simulation of coupled C-climate feedbacks. This task will also involve Thomas Boden who will lead CDIAC and the development of the database organization and information systems required as a part of the model-data assimilation research.

Task F2 – Rich Norby with 30 years of research experience in tree physiology and global change biology will lead Task 2 and a team of scientists to develop dynamic allocation representations for global models and applications.

Task F3 – Paul Hanson and Charles Garten will provide key expertise in soil C experiments, use of isotopic tracers, and nutrient cycling feedbacks in collaboration with Julie Jastrow and

Roser Matamala at ANL, and Margaret Torn at LBNL. Tom Guilderson at LLNL will provide expert management, coordination and analysis of ^{14}C measurements through CAMS at LLNL.

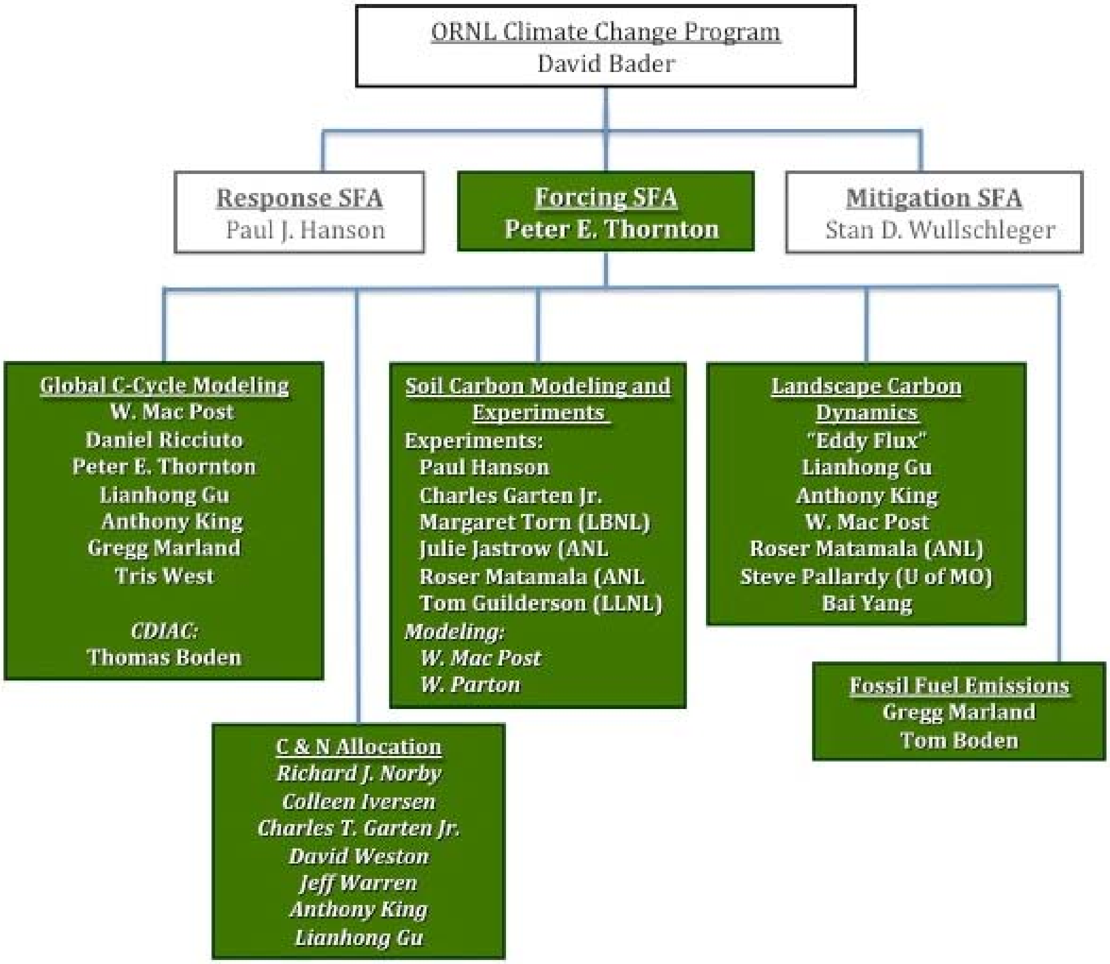

Figure F7. Forcing SFA organization and key personnel.

Task F4 – Lianhong Gu will lead activities in Task 4 associated with climate extremes utilizing eddy covariance data and associated experiments. Landscape scale observations of terrestrial C, water and energy dynamics will be the shared responsibility of Lianhong Gu and Roser Matamala at ANL.

Task F5 – Gregg Marland, Robert Andres, Tom Boden, and T.J. Blazing will be responsible for Task F5 which seeks to increase spatial and temporal resolution of fossil fuel emissions for model and synthesis activities from an integrative perspective.

Finally, because the breadth of Forcing SFA research activities involves cooperative interactions among four DOE National Laboratories, we will also establish a cross-laboratory management team consisting of Peter Thornton, ORNL; Julie Jastrow, ANL; and Margaret Torn, LBNL, and Tom Guilderson, LLNL.

Detailed person month contributions by Response SFA task for all researchers and some unnamed postdoctoral associates and students are provided in Table R2 for the FY2010 through FY2012 funding cycle.

Table F2. ORNL person hours by investigator and major Forcing SFA research task as defined in the text (160 hours = 1 person month).

Investigator (Affiliation)	Forcing SFA Tasks					3-Year Cumulative Hours By Investigator
	Task F1 C Modeling FY10,11,12	Task F2 Allocation FY10,11,12	Task F3 Soil C FY10,11,12	Task F4 Landscape Flux FY10,11,12	Task F5 Emissions FY10,11,12	
Scientific Staff						
Andres	---	---	---	---	160,160,160	480
Garten	---	160,160,160	330,160,160	---	---	1130
Gu	1000,1000,1000	80,80,80	---	320,320,320	---	4200
Hanson	---	---	320,320,320	---	---	960
King	600,700,800	---	---	---	---	2100
Marland	160,160,160	---	---	---	480,480,480	1920
Norby	---	200,200,200	---	---	---	600
Post	1300,1300,1440	---	---	---	---	4040
Thornton	800,800,800	100,100,100	---	---	---	2700
Weston	---	80,80,80	---	---	---	240
Yang	---	---	---	400,400,400	---	1200
Unnamed data staff	---, 160, 160	---	---	---	---	320
Postdoctoral Staff						
Iversen (ORISE)	---	280,960,960	---	---	---	2200
Nichols (ORISE)	1800,1800,1800	---	---	---	---	5760
Mao (ORISE)	1800,1800,1800	---	---	---	---	5760
Ricciuto (ORISE)	1800,1800,1800	---	---	---	---	5760
Shi (ORISE)	0,1800,1800					3840
Technical staff						
Todd (ORNL)	---	---	640,640,640	---	---	1920
Childs (ORNL)	---	500,0,0	---	---	---	500
Brice (ORNL)	---	---	480,160,160	---	---	800
Hours By Task	9260,11320,11560	1400,1580,1580	1770,1280,1280	720,720,720	640,640,640	-

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