Fiscal Year 2010 Annual Progress Report
for the
Forcing Science Focus Area (Forcing SFA)
of the
Oak Ridge National Laboratory
Climate Change Program

Submitted by Peter E. Thornton
and members of the Forcing SFA

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Wilfred M. Post for PET	6/30/2010	Gary K Jacobs for:	6/30/2010
Dr. Peter E. Thornton, Forcing SFA Lead	Date	Dr. David C. Bader, CCP/CCSI Manager	Date

1. Program Overview

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. 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 aims to increase confidence in future climate 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.

The Forcing SFA employs 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 using CLM-CN and CCSM as its scientific core. Research is organized into 5 tasks (Figure 1). 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.

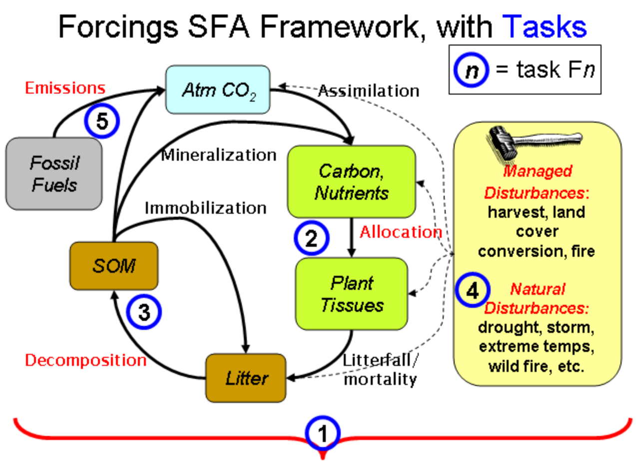

Figure 1. Overview of Forcing SFA. Terrestrial ecosystem processes are considered in the context of their impact on atmospheric CO_2 (and other greenhouse gas fluxes). Red text identifies major process-level uncertainty which will be addressed as part of the near-term SFA effort.

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 forcing and carbon-climate feedbacks.

2. Outline of Scientific Objectives

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 forcing?**
- **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.

3. Description of Program Structure

A. Management scheme

Dr. Peter Thornton leads the overall Forcing SFA, reporting to the ORNL CCP Manager (Dr. David Bader). Dr. Thornton has overall responsibility for research coordination across the five Forcing SFA Tasks, and for communicating with leaders assigned to each Task. Dr. Wilfred M. Post leads the multi-scale modeling effort (Task F1). Dr. Richard J. Norby leads the C-N allocation experiment (PiTS, Task F2). Drs. Paul J. Hanson and Charles T. Garten, Jr. lead the soil carbon modeling effort (Task F3). Dr. Lianhong Gu leads the landscape-scale flux measurement and extreme events effort (Task F4). Dr. Gregg Marland leads the fossil-fuel CO_2 emissions quantification effort (Task F5).

B. Science personnel

The following (alphabetical) list shows the people who contribute research effort to the Forcing SFA, along with affiliation and the primary Tasks to which they contribute:

Robert Andres, ORNL Research Staff Member (F5)
Deanne Brice, ORNL Technical Staff (F2, F3)
Joanne Childs, ORNL Technical Staff (F2)
Charles T. Garten Jr., ORNL Distinguished Research Staff Member (F2, F3)
Lianhong Gu, ORNL Research Staff Member (F1, F2, F4)
Thomas Guilderson, Lawrence Livermore National Laboratory (F3)

Paul J. Hanson, ORNL Distinguished Research Staff Member (F3)
Colleen M. Iversen, ORNL Research Staff Member (F2)
Julie Jastrow, Argonne National Laboratory (F3)
Anthony W. King, ORNL Research Staff Member (F1)
Gregg Marland, ORNL Distinguished Research Staff Member (F5)
Roser Matamala, Argonne National Laboratory (F3)
Karis McFarlane, Lawrence Livermore National Laboratory (F3)
Tilden Meyers, ATDD/NOAA (F4)
Jeffrey Nichols, ORNL Postdoctoral Associate (F1)
Richard J. Norby, ORNL Corporate Fellow (F2)
Stephen G. Pallardy, University of Missouri – Columbia (F4)
Wilfred M. Post, ORNL Distinguished Research Staff Member (F1)
Daniel Ricciuto, ORNL Research Staff Member (F1)
Peter E. Thornton, ORNL Research Staff Member (F1, F2)
Donald E. Todd, ORNL Technical Staff (F3)
Margaret S. Torn, Lawrence Berkeley National Laboratory (F3)
Dali Wang, ORNL Research Staff Member (F1)
Jeffery M. Warren, ORNL Research Staff Member (F2)
David Weston, ORNL Research Staff Member (F2)
Bai Yang, ORNL Research Staff Member (F4)

4. Fiscal Year 2010 (FY2010) Performance Milestones and Metrics

A. Major Forcing SFA milestones for FY2010

In this section we report on progress made across all Forcing Tasks (F1-F5) as it relates to the high-level milestones we defined for the project and provided to DOE program managers in January of 2010. The following section takes a more detailed look at progress by Task.

F-01: Aug2010 — Complete multi-scale modeling framework for Forcing SFA using CLM-CN and CCSM as its scientific core that includes (1) Single point prediction mode – computationally efficient capability for plot-scale simulations, (2) Single point data assimilation mode, (3) North America regional mode, and (4) Global prognostic land use mode.

We are on track to fully achieve this milestone, with necessary progress completed or underway on all modeling scales.

A single-point simulation capability for CLM-CN has been developed, implemented, and exercised at multiple sites in the AmeriFlux network. The single-point functionality has been released to the CCSM community for additional testing and preliminary research applications. Our own efforts within the Forcing SFA to evaluate and improve the single-point simulation mode are continuing. We expect to contribute these developments to the main CLM software repository in FY2010. The purpose of the single-point mode is to allow model evaluation, development, and application at the spatial scale at which our most reliable observations and experimental results are available, i.e. at the plot-scale. Model evaluation and improvement at this scale is a necessary precursor to the quantification and eventually reduction of prediction uncertainty at larger spatial scales characteristic of global scale modeling and prediction of future climate change.

Point model development includes formatting of surface weather input data files, to be able to take advantage of high-quality surface weather observations from the AmeriFlux, Fluxnet Canada, and similar data sources. Other development steps included capability to extract relevant information from global gridded surface data products, and to replace these generic model input requirements with local site data as available. Examples include the specification of site-specific species mixtures, ecophysiological parameterizations, soil physical description, atmospheric nitrogen inputs, and site-level disturbance history information.

The single-point capability has recently been implemented in a data assimilation framework, using a genetic algorithm approach to improve model prediction of half-hourly net ecosystem carbon fluxes at the Howland Forest, Maine, AmeriFlux site by simultaneously optimizing five sensitive and poorly-constrained ecophysiological parameters associated with spruce forest, the dominant site vegetation.

A similar data assimilation approach has been implemented at the North American regional scale, using a simpler model (LoTEC) to test the data assimilation framework at this more challenging spatial scale. We have also contributed modeling results over North America from both LoTEC and CLM-CN to a multi-model, multi-observation intercomparison project, through a collaboration organized by the North American Carbon Project (NACP) Modeling and Synthesis Thematic Data Center (MAST-DC).

We have now succeeded in coupling a prognostic land use component of an integrated assessment model (IAM) to CLM-CN, and are currently performing the first-ever fully coupled carbon-climate-prognostic land use change experiments implemented within an atmosphere-ocean general circulation model (AOGCM). Our coupling experiments use the Community Climate System Model (CCSM), including CLM-CN as the land physics and biogeochemistry package. We are coupling now with the IMAGE integrated assessment model, through collaboration with the IMAGE development team in the Netherlands. This collaboration is sponsored in part by ORNL LDRD funds (see section 5.D).

F-02: Oct 2010 — Quantify the sensitivity of CLM-CN/CCSM prediction of carbon-climate feedback to uncertainty in model structure and model parameterization that includes (1) influence of global-scale land use and land cover change on carbon-climate feedback, including interaction terms with increasing CO_2 and changing nitrogen deposition, (2) sensitivity of carbon-climate feedback to structure and parameterization of litter and soil organic matter model, (3) sensitivity of carbon-climate feedback to natural disturbances, and (4) dynamic allocation algorithms.

We are on track to fully achieve this milestone, with necessary progress completed or underway on all feedback topics.

We have completed a global-scale analysis of simulation results that used single forcing factor experiments to isolate the effects of land use and land cover change, increasing CO_2 concentration, and increasing nitrogen deposition, as well as interactions among these factors, on climate-carbon cycle feedbacks. This work is being prepared now as a manuscript for submission in July 2010. Major findings are that the land use and land cover change effects are the largest single forcing factor, and that present-day simulations suggest the land biosphere is currently close to neutral with respect to carbon exchange with the atmosphere, due to carbon losses from land use and land cover change approximately balanced by carbon gains due to CO_2 fertilization and the influence of increasing nitrogen deposition. The balance is shifting gradually towards a net land carbon uptake as land use effects have declined in recent decades while CO_2 and nitrogen deposition effects have increased. We also find that the interaction effects among land use, CO_2 and nitrogen deposition presently account for about 10% of the total change in land carbon inventory since 1850, with the expectation that this interaction effect will grow to approximately 20% by the end of the century. This result suggests that accurate predictions of future CO_2 concentration and associated climate change require that the multiple forcing factors must be accounted for in an integrated modeling framework.

We have recently completed an analysis that examines predictions of soil respiration from CLM-CN in light of a new database and meta-analysis of soil respiration observations carried out by Bond-Lamberty and colleagues at PNNL. We find that CLM-CN is in excellent qualitative and quantitative agreement with the global and zonal estimates of soil respiration from observations. Our single-forcing factor modeling approach allows us to test several alternative hypotheses explaining observed trends in global-scale soil respiration. Bond-Lamberty et al. (2010) suggest that these trends are most likely explained by sensitivity of below-ground (autotrophic and heterotrophic) processes to increasing temperature. Our modeling analysis suggests, however, that the most likely explanation for the observed trend is the influence of rising CO_2 concentration and nitrogen deposition, with changes in temperature playing a minor role. These results are being prepared as a manuscript now, for submission in July 2010.

We have collaborated with university partners to explore the influence of new global-scale parameterizations on climate-carbon cycle feedbacks in CLM-CN and CCSM. Multiple observational datasets suggested that model controls on late-season photosynthesis should be augmented to include the influence of daylength, in addition to the influence of temperature. We tested that hypothesis as a modification of the fundamental controls on photosynthetic enzyme activity in CLM-CN, and discovered that predictions of both the amplitude and phasing of seasonal cycle of atmospheric CO_2 concentration, as evaluated against measurements from sixty surface observation stations, were improved with the new model formulation. This is a very good early example of the benefits we expect to obtain in global-scale climate-carbon cycle feedback predictions through integration and interaction with observational and experimental research. This work has recently been submitted as a manuscript to Nature (Bauerle et al., 2010).

Through another university collaboration, we have explored the influence of modified parameterization of prognostic wild fire algorithm in CLM-CN, one of the most significant disturbance mechanisms influencing terrestrial carbon balance and climate-carbon feedbacks. That effort used remote sensing observations of fire occurrence and intensity to evaluate the existing CLM-CN algorithm, and to suggest an improved parameterization. This work is now published (Kloster et al., 2010).

Through the remainder of FY2010 we will focus effort on quantification of climate-carbon feedback sensitivity to alternative representations of litter and soil organic matter dynamics, and on new approaches to representation of carbon and nitrogen allocation. Our successful evaluation against soil respiration database suggests that some aspects of the litter and soil dynamics in CLM-CN are robust. We know, however, that there are important processes that the current model fails to represent. For example the EBIS experiments have provided a new framework for representing the connections between above and below-ground pools of litter and soil organic matter, and CLM-CN does not currently include the necessary separation of above and belowground litter pools to capture these observed dynamics. We have completed a model development exercise that separates above and below ground processes in CLM-CN, and over the next few months we will be implementing the multiple litter pool arrangement suggested by the EBIS experiments and evaluating its influence on CLM-CN predictions. We will also be experimenting with new and more realistic allocation dynamics, introducing dynamic controls on root:leaf allocation ratios as well as relationships associating root uptake of water and nutrients with standing fine root biomass.

B. Task-specific milestones to illustrate Forcing SFA progress

Task F1. Modeling of terrestrial C feedbacks (Lead: W.M. Post)

1. Model-Data and Model-Model inter-comparison at the global and regional scale:

Model-data and model-model inter-comparison and synthesis plays an important role in improving model performance by identifying infrastructural (data drivers, parameter estimates, etc.), and algorithm (representation of processes, accuracy of implementation) strengths and weaknesses and provides tools for model improvements. We have led 2 important synthesis activities involving over 30 modeling groups and 20 teams of data providers:

1. North American Carbon Program (NACP) interim synthesis of site scale models at nearly 40 eddy covariance sites in order to identify and quantify model and data uncertainties in carbon fluxes for a range of important ecosystems.
2. NACP interim synthesis of regional and continental scale models and data over North America during the period 2000-2005 in order to identify and quantify spatial and temporal patterns of C fluxes, and identify model uncertainty and bias.

In addition we have contributed CLM-CN results to:

3. TRENDY (trends in net land-atmosphere carbon exchange over the period 1980-2009) activity. This study tests the ability of Dynamic Global Vegetation Models (DGVMs), forced with observed climatology and atmospheric CO2, to model the contemporary global carbon cycle.

Milestone/Deliverable for FY2010:

F1-O1: March 2010. Make any needed corrections in forward model North America regional estimates; contribute results to NACP synthesis activities.

Several manuscripts have been submitted (Caias et al., Schwalm et al.), several others are prepared and undergoing internal review (Barr et al., Huntzinger et al.) several others prepared and undergoing internal review, and more are under development from these activities. These papers will contribute immediately to the international REgional Carbon Cycle Assessment and Processes (RECCAP) project, and to the IPCC AR5 reports.

2. Physiological processes:

Progress has been made in the following areas:

1. Improved approach to estimating parameters of the Farquhar-von Caemmerer-Berry (FvCB) model of photosynthesis from leaf gas exchange measurements
2. Improved global acquisition capability of photosynthetic process parameters through automated web services for key data analyses
3. Representation of internal (mesophyll) conductance of CO2 and improving stomatal conductance modeling in ecosystem process models

We have identified theoretical and procedural difficulties in estimating FvCB parameters from leaf gas exchange measurements. Most importantly we have developed a new approach that can overcome these difficulties. Our progress is reported in one paper in press (Gu et al. 2010a) and one paper near completion (Gu et al. 2010b).

We have developed and implemented the LeafWeb (hppt://leafweb.ornl.gov) to develop a global database of biochemical, physiological, and biophysical properties of single leaves to support studies of plant functions and terrestrial carbon cycle modeling. LeafWeb has been developed in collaboration with CDIAC and provides automated numerical analyses of leaf gas exchange measurements. LeafWeb provides only analysis for C3 photosynthesis. Analysis capabilities for C4 plants are being developed.

We have found that in the middle of the growing season, internal conductance can be more limiting than the stomatal conductance for carbon assimilation resulting in overestimation of the net carbon assimilation and transpiration. The influence of internal conductance on transpiration is through the coupling between the photosynthesis and transpiration processes. After further testing of the internal conductance algorithm in FAPIS, we plan to implement it in CLM.

Point CLM, Data Assimilation, and Regionalization:

Milestone/Deliverable for FY2010:

F1-02: September 2010. Use data assimilation methods to produce new plant functional type (PFT) parameter in CLM-CN. Involves extension of data assimilation method to optimize multiple parameters simultaneously over multiple sites within the same PFT.

In Ricciuto et al. (submitted) we estimate parametric and associated predictive uncertainty at eddy flux sites. Parameters in the Local Terrestrial Ecosystem Carbon (LoTEC) are estimated using both synthetic and actual observations. These model parameters and uncertainties are then used to make predictions of carbon flux for up to 20 years. We find a strong dependence of both parametric and prediction uncertainty on the length of the data record used in the model-data fusion. In this model framework, this dependence is strongly reduced as the data record length increases beyond 5 years. If synthetic observations of initial biomass pools with realistic uncertainties are included with flux data in the model-data fusion, prediction uncertainty is reduced by more than 25% when flux data records are less than three years. If synthetic annual observations of above ground woody biomass increment are also included, uncertainty is similarly reduced by an additional 25%. When actual observed eddy covariance data instead of synthetic data are used, there is still a strong dependence on data record length, but the results are harder to interpret because of the confounding effects of model structural error.

A regional application of the Local Terrestrial Ecosystem Carbon (LoTEC) model with optimized parameters (see section below of point simulations and data assimilation) was used to simulate carbon fluxes over North America using the North American Regional Reanalysis (NARR) as input meteorology. Carbon flux estimates were produced from 1979-2008 using model parameters from 1) literature and 2) an optimization study that used net ecosystem exchange observations from 6 deciduous eddy covariance towers. The optimized parameters resulted in a 10% increase in simulated deciduous forest GPP with a similar pattern of interannual variability. There was also a greater sensitivity of NEE and GPP to the long-term temperature increase between 1979 and 2008. The results are complicated by large discrepancies between the observed meteorology at the sites and the meteorology from the corresponding NARR gridcell, especially regarding incoming shortwave radiation. We are currently performing LoTEC model simulations to test the sensitivity of carbon fluxes to different forcing datasets, and the applicability of parameters optimized using site observed forcing to regional simulations using reanalysis forcing.

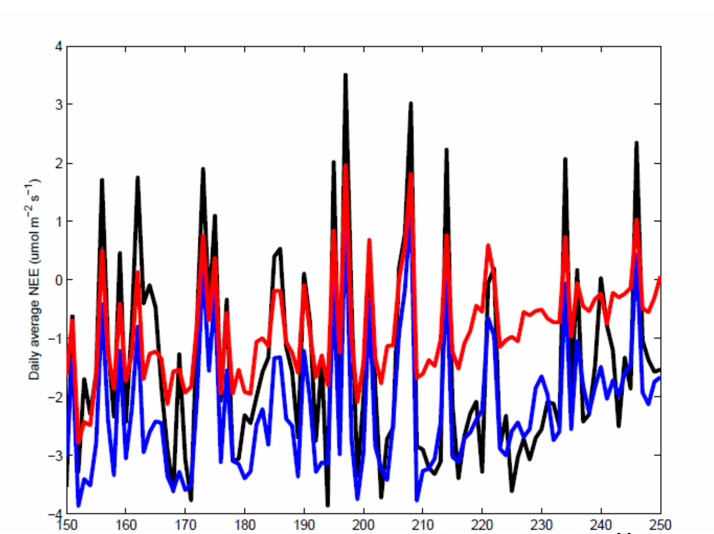

Figure 2. Simulated daily net ecosystem exchange at Howland Forest during the summer months of 1996 using default CLM-CN parameters (red) and optimized parameters (blue). The optimized model is in better agreement with observations (black), especially on days with higher uptake of CO_2.

While the data assimilation framework is made computationally efficient by using LoTEC, it lacks prognostic capability as part of a fully coupled earth system model. The ability to parameterize the land component of an earth system model through data assimilation will allow for more accurate re-analyses and predictions of terrestrial fluxes and feedbacks. To this end, we have implemented a point version of CLM-CN, allowing us to perform forwards runs of this model at individual observation sites using site-specific information as driver data when available. Our new version streamlines the previous CLM-CN multistep process into a single script and adds new functionality to use site data. This point version of CLM-CN is also being utilized in a new data assimilation framework currently under development (see initial results in Figure 2). The increased complexity of CLM-CN requires the use of more computationally efficient and parallel data assimilation methods that can take advantage of high-end computing resources. The preliminary CLM-CN data assimilation package is currently undergoing code profiling to analyze timing and performance in a supercomputing environment that will help us identify areas for improvement.

Task F2. Partitioning in Trees and Soil (PiTS) -- *A field research facility for developing dynamic carbon partitioning representations for global models*

Our objective is to improve the carbon (C) partitioning routines in existing ecosystem models based on the concepts gathered from plant partitioning models and tested against field observations and manipulations. We will use short-term, comprehensive field measurements of processes related to C partitioning from leaves to roots and roots to soil and generate general response functions based on measureable environmental attributes. We will develop and test a dynamic carbon-partitioning module that will be integrated into the Common Land Model (CLM) in Task F1. It is important to find out what processes are essential and how to represent them efficiently for use in CLM-CN. We plan to start from a dynamic, individual tree based carbon-partitioning model and then progressively simplify its structure to reach a balance between computational demand and process representation. We will test the simplified scheme with sugar measurements and allometric relationships from the PiTS experimental manipulation.

Milestone/Deliverable for FY2010:

F2-01: September 2010. Locate first set of plots; excavate trenches and install instrumentation, canopy access, and exposure chamber; conduct first labeling and allocation experiment.

Eight replicate loblolly pine trees will first be labeled with a pulse of ^{13}C-enriched CO_2, applied by enclosing the trees in a temporary plastic chamber. This will be followed by a manipulation of the C balance of the canopy of one-half of the trees during a 15-day experimental period: (1) 5 days baseline data, (2) 5 days C starvation of four trees using shade cloth, and (3) 5 days of post-treatment monitoring. GPP will be calculated based on continuous sap flow data. Carbohydrates in leaf, stem, and root tissue will be measured daily. 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. Periods of fine-root production will be determined through minirhizotron observations.

This year, we will conduct the experimental manipulation at peak summer in order to test the experimental design and concept. Next year, 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.

Figure 3. (left) The array of eight loblolly pine in the UT FRREC. (right) A pit was excavated to 1 m deep.

PiTS Experiment Construction: Activity to-date

- The research site was chosen on the University of Tennessee Forest Resources Research and Education Center (FRREC) (http://forestry.tennessee.edu/ORForest.html) adjacent to the Oak Ridge Reservation and has a small grove of 6-m tall, 5-year-old planted loblolly pine (*Pinus taeda* L.) (Figure 3).
- A NEPA compliance screening of the project through a NEPA Action Review was completed, and a categorical exclusion was obtained.
- Electrical service to the site was established through the City of Oak Ridge.
- A temporary office and air conditioned instrument shelter (Mobile Mini) was rented and delivered to the site.
- In mid-April, a 2-m wide × 1-m deep soil pit was dug using a compact track loader (Bobcat) adjacent to eight loblolly pine trees (Figure 3). The pit allows us to unambiguously associate root and soil dynamics with specific trees, and also allows greater access to soil at depth.
- In mid-May, the pit was instrumented with a series of tools for tracking C partitioning within the tree and soil.
  - Root observation windows were installed at the base of each tree to maintain soil structure, moisture and root integrity, as well as allow access to roots of a known age. Preliminary soil cores indicated that 95% of root biomass in this stand was in the top 50 cm of the soil; therefore, the windows were installed to 50 cm depth.
  - Two minirhizotron tubes were inserted horizontally into the pit face approximately 50 cm (horizontally) from each tree to track the timing and vertical distribution of root growth; one was installed at a shallow soil depth (5 cm) and one was installed deeper in the soil profile (30 cm).
  - Soil water probes were inserted adjacent to each tree vertically into the soil to a depth of 80 cm to track soil water dynamics.
  - Variable length heat dissipation sap flow probes were inserted into the north side of each tree at 1 m height in order to facilitate modeling of gross primary production.
  - Each tree was fitted with a digital dendrometer to track small-scale temporal changes in tree growth and water use.
  - Soil respiration chambers were installed adjacent to each tree to track soil carbon efflux. Preliminary data collection is ongoing, providing guidance for optimal chamber placement. The respiration chambers will be connected to a Picarro $^{13}CO_2$ analyzer in order to differentiate between root-associated carbon fluxes (after ^{13}C labeling) and heterotrophic soil carbon fluxes.

- A JLG 26-foot rough-terrain scissor lift (United Rentals, Knoxville, Tennessee) was delivered to the site, and three project personnel have been trained to operate it. The lift will provide access to tree canopies from the pit to facilitate photosynthesis measurements.

Progress is on track to complete facility construction and conduct an intensive labeling and allocation experiment in July-August, 2010. Evaluation of preliminary data sets will be provided by September 2010, as well as an evaluation of the second phase for the facility and development and testing of modeling code.

Task F3. Representing soil C in terrestrial C cycle models

1. EBIS-AmeriFlux (Lead: Hanson)

We are executing an experimental plan designed to use ^{14}C-enriched leaf and root litter and humus at multiple AmeriFlux sites for the direct characterization of leaf litter, organic layer humus, and fine root litter C transfers to mineral-soil sinks over a range of climatic and biological conditions. The experimental data generated by the EBIS-AmeriFlux effort together with conclusions from the preceding EBIS-Oak Ridge study will provide a key contribution to databases on soil carbon cycling processes for use in evaluating the next generation of terrestrial carbon models. Those models are needed in the ongoing evaluation of terrestrial ecosystem's role in the global carbon cycle. This proposed research provides data for addressing DOE's goal of understanding mechanisms controlling C flux, and for the improvement of models to be applied to policy discussions regarding the safe levels of greenhouse gases for the earth's system.

Milestone/Deliverable for FY2010:

F3-01: September 2010. EBIS-AmeriFlux (Hanson): Complete annual site visits to MI, MA, NH and MO for year-3 sampling; complete all post-sampling processing of soils and litter; complete CN analysis of samples from all four sites.

The annual sampling trips were completed and all bulk C and ^{14}C samples for analysis were transferred to our cooperators at Lawrence Livermore and Lawrence Berkeley National laboratories on schedule. Analytical procedures are underway and on schedule for completion in September of 2010.

Task F3a Progress-to-date (FY2010 Annual Summary)

Paul Hanson organized and Margaret Torn hosted the annual EBIS-AmeriFlux annual meeting at LBNL in Berkeley, California on 26 February 2010. Progress to date and plans for FY2010 were discussed. The goal of completing all project manipulations, measurements and syntheses by the end of FY2012 was also emphasized, as was the incorporation of EBIS-AmeriFlux efforts in broader Science Focus Area activities at each of the participating national laboratories. The following bullets provide a general summary of progress on EBIS-AmeriFlux to date.

- EBIS-AmeriFlux experimental plots were established at each of the four sites (MI, NH, MA, and MO) in the early winter of 2007 and 2008. At that time five replicate plots were established and continuous environmental monitoring was initiated for surface litter and soil temperature and surface soil moisture at each plot.
- Cohorts of enriched leaf litter were added all replicate 2 x 2 m plots at each site in 2007, 2008, and 2009 to establish the pulses of ^{14}C-enriched carbon for tracking leaf-litter-to soil C transfer and accumulation rates.
- In 2007, a single cohort of enriched humus was added to 1x1 m plots at all sites for tracking humus-to-soil C transfer and accumulation rates.

- In 2008, Enriched root material was also used to establish root-to-soil decomposition bags for the assessment of root-to-soil C transfer and accumulation rates. To date, four replicated samples have been collected and processed for roots and soils.
- Prior to the addition of enriched plant materials at each site, time-zero samples of organic and mineral soil layers were collected to a depth of 90 cm. Analysis of the carbon content, baseline ^{14}C-signatures, and associated soil physical characteristics were conducted and provided the basis for an assessment of the nature and turnover of long-term C pools for each of the study sites.
- The Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory processed approximately 1100 ^{14}C-samples in support of the EBIS-AmeriFlux research project during the first 2 to 3 years of the study.
- EBIS project staff continue to synthesize material from the EBIS-Oak Ridge effort. Four new research articles were published in 2009, with one in press and another in review. A full summary of EBIS research publications and published abstracts is attached to this report.
- PDF versions of the power point presentations given at the Berkeley workshop are available under EBIS-AmeriFlux headings on the project web page at: http://ebis.ornl.gov.

2. Soil carbon modeling (Lead: Garten)

Milestone/Deliverable for FY2010:

F3-02: Aug 2010. Complete comparative analysis of soil C dynamics at 5 sites (MI, MO, NH, MA, TN) using Stella-based prototyping model. Submit manuscript.

We used a two-compartment soil carbon model to examine relationships between the turnover times of labile soil carbon and mean annual temperature at five AmeriFlux sites (University of Michigan Biological Station, Harvard Forest, Bartlett Experimental Forest, University of Missouri's Baskett Wildlife Research and Education Area, and the Oak Ridge Reservation). Interpretation of the latitudinal differences indicated that labile soil carbon stocks and turnover times are related primarily to mean annual temperature and secondarily to soil texture.

Soil carbon at each site was partitioned into two pools (labile and stable) on the basis of carbon measured in the forest floor and POM and MOM fractions from the mineral soil. A two-compartment steady-state model, with randomly varying parameter values, was used in probabilistic calculations to estimate the turnover time of labile soil organic carbon (MRT_U) and the annual transfer of labile carbon to stable carbon (k_2) at each site in two different years. Based on empirical data, the turnover time of stable soil carbon (MRT_S) was determined by mean annual temperature and increased from 30 to 100 years from south to north. Moving from south to north, MRT_U increased from approximately 5 to 14 years. In a comparison of northern study sites, both the amount and turnover time of labile carbon were significantly less at site UMB than at HAR and BEF. These sites also had strongly different vertical soil profiles of whole soil carbon stocks. In addition to the absence of a humus (Oa) layer, site UMB had significantly less forest floor and mineral soil carbon than other northern sites. Soil texture was also markedly different at UMB where there was more than 90% sand and less than 10% silt-clay. Consistent with its role in stabilization of soil organic carbon, silt-clay content along the gradient was positively correlated ($r = 0.91$; $P \leq 0.001$) with parameter k_2. Mean annual temperature was indicated as the environmental factor most strongly associated with south to north differences in the storage and turnover of labile soil carbon.

Depending on unknown temperature sensitivities, large labile pools of forest soil carbon are potentially at risk of depletion by decomposition in a warming climate, and losses could be disproportionately higher from coarse textured forest soils. A draft manuscript describing this work as been completed and, in June 2010, was circulated to AmeriFlux site investigators for review (Garten, 2011).

Task F4. Landscape-scale carbon dynamics, extreme events, and disturbance (Lead: L. Gu)
Since the start of FY 2010, major progress has been made in the following areas:

1. Ecosystem water use efficiency under water stress
2. Global analysis of vegetation photosynthesis phenology
3. Use of chlorophyll fluorescence measurements to validate estimation of photosynthetic parameters
4. Impacts of ice storms on forest ecosystem structures and functions
5. Operations of Missouri Ozark AmeriFlux site

1. Ecosystem water use efficiency under water stress
Milestone/Deliverable for FY2010:
F4-01: September 2010. Completion of an eddy flux paper on interannual variability of terrestrial carbon flux from forests near the prairie-forest border to the continental US.

Midwest ecosystems are prone to water stress and drought frequencies are expected to increase with climate change in this region. Since its establishment in 2004, the Missouri Ozark AmeriFlux (MOFLUX) site has experienced alternate dry and relatively wet years. Taking advantage of this sequence of contrasting environmental conditions, we have investigated the direct and indirect influences of environmental controls and biological processes on ecosystem water use efficiency. We have found that at the ecosystem level, water use efficiency exhibits behaviors that have been observed at leaf levels. Specifically, we observed that the stomatal optimization theory appeared to be applicable to the whole forest ecosystem. However, complexities may arise from interactions between different environmental and biological factors; for example, the relationship between ecosystem water use efficiency and a controlling factor may depend on variations of other controlling factors (indirect influence). Also the variation of water use efficiency depends on temporal scales. We reported our findings in Global Change Biology (Yang et al. 2010).

2. Global analysis of vegetation photosynthesis phenology
The seasonal cycle of plant community photosynthesis is one of the most important biotic oscillations to mankind. Our previous efforts have led to the development of a comprehensive framework to studying this cycle. We proposed a new function to represent the cycle and generalized a set of phenological indices to quantify its dynamic characteristics (Gu et al. 2009). We have applied this analytical framework to the Fluxnet dataset. We are now at the initial stage of analyzing the results that have been obtained. But some potentially important findings have been already made. For example, we found that the peak recovery rate of vegetation photosynthesis in spring, when normalized by the peak photosynthetic capacity in the growing season, is primarily determined by the rate of temperature rise during the same period. The relationship between the normalized peak recovery rate and the rate of temperature rise shows divergence between and convergence within vegetation types with the largest slope found for grassland and smallest slope found for evergreen needle leaf forest. This finding shows that the rate of temperature change within a year has important ecological and biological functions.

3. Chlorophyll fluorescence measurements to validate photosynthetic parameters
It is difficult to directly verify the values of photosynthetic parameters estimated from leaf gas exchange measurements because the true values of these parameters cannot be known. This has been one of major sources of uncertainty for terrestrial carbon cycle modeling. We proposed an

idea of using chlorophyll fluorescence measurements to indirectly validate the values of photosynthetic parameters estimated from leaf gas exchange measurements. The foundation of photosynthetic parameter estimation based on analysis of leaf gas exchange measurements is the correct identification of the limitation state distribution of each point in the dataset. Chlorophyll fluorescence as a function of intercellular CO_2 partial pressure contains information about limitation states. We are using this measurement to evaluate the new photosynthetic parameter estimation approach of Gu et al. (2010) with measurements from the MOFLUX site operated by this project.

4. Impacts of ice storms on forest ecosystem structures and functions
In 2007, an ice storm occurred at the MOFLUX site. Coarse woody debris observations showed a large increase after the ice storm. Further, Leaf Area Index was reduced in the following year. We are now analyzing how this ice storm might have influenced flux exchanges. In the meantime, we have been conducting a literature survey to determine the impacts of ice storms, which are a common winter phenomenon in the eastern US, on the structures and functions of eastern US forests. We have also collaborated with scientists from the Chinese Academy of Forestry in an effort that resulted in a comprehensive analysis of the socioeconomic and ecological impacts of the massive 2008 Chinese ice storm. This included the devastating impacts on forests, which will be helpful to our analysis on impacts of ice storms on US forests. This study has been accepted by Bulletin of the American Meteorological Society (Zhou, Gu, et al. 2010).

5. Operation of the Missouri Ozark AmeriFlux (MOFLUX) site
Data collected in 2009 at the MOFLUX site has been cleaned and submitted to AmeriFlux data center. FY2010 has seen continuous growth in the use of MOFLUX data by national and international users (see the publication list). Additionally, the MOFLUX site has attracted independent research projects. A partial list of funded projects includes:

- Hanson et al., ORNL and others, EBIS-AmeriFlux, Characterizing Organic Carbon Flux from Litter Sources to Mineral-Soil Sinks: Establishment of a Distributed Enriched Background Isotope Study for AmeriFlux Hardwood Forests
- Ken Davis, Penn St. U, High Accuracy CO_2 Measurements since 2006
- Dan Obrist, University of Nevada, Desert Research Institute, Understanding Sugar Maple Range Limits: Climate and Competition
- Michael Dietze, University of Illinois, Linking Carbon Reserves to Sugar Maple Demography across the eastern United States
- Peter Reich et al., University of Minnesota, Understanding Sugar Maple Range Limits: Climate and Competition

Task F5. Fossil-fuel CO_2 emissions for synthesis activities (Lead: G. Marland)
Under Task 5 we have (1) contributed to an annual global carbon balance exercise, (2) investigated the uncertainty in CO_2 emissions estimates, (3) developed a database of the monthly pattern of CO_2 emissions from fossil-fuel use, and (4) lead the effort to update the US research plan on the global carbon cycle.

1. Role fossil fuel emissions in global carbon balance.

An update, through 2008, of the global balance of the carbon cycle was coordinated through the Global Carbon Project, with ORNL participation, and published as Le Quéré et al. in November 2009 (Le Quéré et al., 2009). This much-quoted, widely influential publication involved contributions from 31 scientists around the world. Our research contributed a key component of this report - the most up-to-date estimates of emissions from fossil-fuel combustion. A notable contribution of this 2008 collaboration was an attempt to estimate all major components of the global carbon cycle (e.g. oceans, terrestrial biosphere, atmosphere, etc.) independently so that we could illustrate the general amplitude of the uncertainty in balancing the carbon cycle, and the importance of trying to match top-down and bottom-up estimates of the different components in order to maximize understanding of the full cycle. Work is well underway on constructing another annual update for 2009. Where we used to talk of a "missing sink" for carbon, the effort to estimate carbon cycle components independently now emphasizes that there is uncertainty in every component but that, at the mean, the sink estimates exceed the source terms.

2. Estimation of uncertainty in fossil fuel emissions.
Milestone/Deliverable for FY2011.
F5-01: March 2011. Complete an analysis of the global and spatial distribution, and the evolution of global uncertainty with time.

ORNL's recent updates in emissions estimates and emissions inventories have been included in a major report on emissions uncertainty and treaty verification from the National Research Council (NRC, 2010). We have also attended multiple meetings and participated in many discussions on this topic led by the IPCC, NASA, the CIA, the European Union, WWF, the JASON group in the US, and those who aspire to create a global Greenhouse Gas Information System. Working with European colleagues we have published a short paper on the uncertainty of emissions estimates (Marland et al., 2009).

3. Database of monthly fossil fuel emissions.
Milestone/Deliverable for FY2010.
F5-01: September 2010. Develop database of emissions inventories at the scale of states and months at a global scale for use in Task F1 analyses.

In trying to understand the details of the global carbon cycle and in consideration of international discussion of treaty verification, it is becoming increasingly apparent that there is a need for CO_2 emissions inventories at finer temporal and spatial scale than countries and years. Recent analyses suggest that it is particularly important to have a good indication of the nature of the annual cycle of emissions. A long term effort, involving ORNL, to collect data on energy consumption at monthly time steps and to develop from this a global and national data set on emissions per month has yielded a data product in time for use in the IPCC Fifth Assessment Report and elsewhere, plus a manuscript has been completed for publication in a peer-reviewed journal (Andres et al., 2010). Working from the monthly emissions data we have also estimated monthly emissions on a grid of 1 degree latitude by 1 degree longitude and the monthly stable-isotope signature of emissions. The effort focused on finding whatever data were available at monthly resolution for the 21 countries that emit 80% of global, fossil-fuel related CO_2. The result pushes very hard on data processing and extrapolation and it is clear that emissions inventories with smaller temporal and spatial resolution will have to rely on statistical and modeling exercises.

C. Forcing SFA FY2010 publication list

Andres, R.J., J.S. Gregg, L. Losey, G. Marland, and T.A. Boden, 2010. Monthly, global emissions of carbon dioxide from fossil fuel consumption, submitted.

Barr, A., D. Hollinger, A. Richardson, NACP Site-Level Synthesis Participants. CO2 flux measurement uncertainty estimates for the NACP site-level interim synthesis. JGR-Biogeosciences (submitted).

Bauerle, W.L., R. Oren, D.A. Way, S.S. Qian, P.E. Thornton, J.D. Bowden, R.F. Reynolds, P.S. Stoy, 2010. Photoperiod regulates seasonal carbon gain in forests : implications for carbon cycling under climate change. Nature (submitted).

Ciais, P., Josep G. Canadell, Sebastiaan Luyssaert, Frédéric Chevallier, Anatoly Shvidenko, Zegbeu. Poussi, Matthias Jonas, Philippe Peylin, Anthony Wayne King, Ernest-Detlef Schulze, Shilong Piao, Christian Rödenbeck, Wouter Peters and François-Marie Bréon. Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting? Nature Biogeosciences (submitted).

Garten Jr. CT (2011) Comparative analysis of forest soil carbon dynamics at five sites along a latitudinal gradient (in review).

Gu et al. (2009) Characterizing the seasonal dynamics of plant community photosynthesis. *In*: Phenology of Ecosystem Processes: Applications in Global Change Research, A. Noormets, Editor, Springer, New York, 275p.

Gu, L., S.G. Pallardy, K. Tu, B.E. Law, S.D. Wullschleger (2010) Reliable estimation of biochemical parameters from C3 leaf photosynthesis-intercellular carbon dioxide response curves. Plant, Cell and Environment (in press).

Gu, L., Assigning limitation transitions can distort key photosynthetic relationships in the analysis of leaf gas exchange measurements (manuscript completed, to be submitted to PCE).

Hollinger et al. (2009) Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. Global Change Biology16 (2): 696-710.

Huntzinger, D., W. Post, A. Michalak, Y. Wei, A. Jacobson, R. Cook, and co-authors. North American Carbon Project (NACP) Regional Interim Synthesis: Terrestrial biospheric model intercomparison. JGR-Biogeosciences (submitted).

Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7, 1877-1902, 10.5194/bg-7-1877-2010, 2010.

Kramer C, Trumbore S, Froberg M, Cisneros-Dozal LM, Zhang D, Xu X, Santos G, Hanson PJ (2010) Recent (<4 year old) leaf litter is not a major source of microbial carbon in a temperate forest mineral soil. *Soil Biology and Biochemistry* 42:1028-1037.

Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, et al., 2009. Trends in the sources and sinks of carbon dioxide, Nature Geoscience 2: 831-836.

Marland, G., K. Hamal, and M. Jonas, 2009. How uncertain are estimates of CO_2 emissions? J. Industrial Ecology 13(1): 4-7.

National Research Council, 2010. Verifying greenhouse gas emissions: methods to support international climate agreements. The National Academies Press, Washington D.C.

Noormets et al. (2009) The phenology of gross ecosystem productivity and ecosystem respiration in temperate hardwood and conifer chronosequences. *In*: Phenology of Ecosystem Processes: Applications in Global Change Research, A. Noormets, Editor, Springer, New York, 275p.

Parton WJ, Hanson PJ, Swanston C, Torn M, Trumbore SE, Riley W, Kelly R (2010) ForCent Model Development and Testing using the Enriched Background Isotope Study (EBIS) Experiment. *JGR-Biogeosciences* (in press)

Ricciuto, D.M., Anthony W. King, D. Dragoni, Wilfred M. Post. Parameter and prediction uncertainty in an optimized terrestrial carbon cycle model: Effects of constraining variables and data record length. JGR Biogeosciences (Submitted).

Román et al. (2009) The MODIS (Collection V005) BRDF/Albedo Product: Assessment of spatial representativeness over forested landscapes. *Remote Sensing of Environment* 113: 2476-2498.

Schwalm, C et al. (45 coauthors)A model-data intercomparison of CO2 exchange during a large scale drought event: Results from the NACP site synthesis. JGR-Biogeosciences (submitted).
Tipping E, Chamberlain PM, Fröberg M, Hanson PJ, Jardine PM (2010) Simulation of carbon cycling and Dissolved Organic Carbon transport in forest soil locally enriched with ^{14}C. *Biogeochemistry* (submitted).
van Gorsel et al. (2009) Estimating nocturnal ecosystem respiration from the vertical turbulent flux and change in storage of CO2. Agricultural and Forest Meteorology 149: 1919-1930.
Xiao et al. (2009). A continuous measure of gross primary production for the conterminous U.S. derived from MODIS and AmeriFlux data. Remote Sensing of Environment, 114(3): 576-591.
Yang et al .(2010) Environmental Controls on Water Use Efficiency during Severe Drought in an OzarkForest in Missouri, USA. Global Change Biology (in press).
Zhou, B, L Gu, Y Ding, L Shao, Z Wu, X Yang, C Li, Z Li, X Wang, Y Cao, B Zeng, M Yu, M Wang, S Wang, H Sun, A Duan, Y An, X Wang, W Kong (2010) The Great 2008 Chinese ice storm, its socioeconomic-ecological impact, and sustainability lessons learned. Bulletin of the American Meteorological Society (accepted).

5. Staffing and Budget Summary

A. Statement of funding allocated in FY2010

Effort by individual scientific and technical and support staff from October 2009 through 18 June 2010 is summarized for each major task of the Forcing SFA as follows:

New funding in the amount of $2,705K was provided in FY2010 to support Forcing SFA research. This was combined with $611K of carry over funds from FY2009 for a total operating budget of $3,316K in FY2010. New funds were allocated to Forcing SFA Tasks as described in the ORNL CCP Forcing SFA Science Plan, summarized as follows:

Task	$ (K)	% of new funds
F1	1,171	43.3
F2	287	10.6
F3	419	15.5
F4	467	17.3

Person	Org.	Task 1	Task 2	Task3	Task 4	Task 5	Totals
Andres, RJ	ESD					114	114
Brice, D	ESD			315.4			315.4
Childs, J	ESD		54				54
Garten, C	ESD			260			260
Gu, L	ESD	712			198		910
Hanson, PJ	ESD			219			219
Iversen, C	ESD		134				134
King, AW	ESD	345					345
Marland GH	ESD					632	632
Norby, RJ	ESD		101.5				101.5
Post, WM	ESD	512					512
Ricciuto, DM	ESD	616					616
Todd, DE	ESD			405			405
Thornton, P	ESD	490					490
Wang, D	ESD	661					661
Warren, J	ESD		56				56
Weston, DJ	BSD		6				6
Yang, B	ESD				304		304
Effort by Major Task	**---**	**3336**	**351.5**	**1199.4**	**502**	**746**	**6134.9**

F5	298	11.0
Reserve	63	2.3
Total	**2705**	**100.0**

A small reserve allocation (2.3%) was created to address unanticipated costs or to take advantage of new research opportunities, as determined by the Forcing SFA Lead and Task Leads.

B. Tabular summary of Forcing SFA subcontracts made with new FY2010 funds:

Subcontractor	$ (K)
ORISE	216.2
University of Missouri	211.5
University of Michigan	10.8
University of Tennessee	8.2
Harvard College	11.0
CompSci Consulting	11.0
Total	**468.7**

C. Personnel actions
New hires: Three new ORNL Research Staff Member positions are fully or partially funded under the Forcing SFA in FY2010: Dan Ricciuto, Daniel Hayes, and Dali Wang. In addition, one new post-doc position was created and filled with the recent hire of Xiaojuan Yang. Dan Ricciuto was previously an ORISE post-doc on the Forcing SFA.

D. Related National Laboratory investments (LDRD)
Peter Thornton received ORNL LDRD support in FY2010 for a project aimed at coupling the IMAGE integrated assessment model to CLM-CN to provide a capability for prognostic land cover and land use change within the context of the fully-coupled carbon-climate predictions of CCSM. LDRD Developments contribute directly to improved capability of CLM-CN, to be exercised under Task F1 of the Forcing SFA once they are operational (expected completion of LDRD project September 2010).

E. New Equipment Expenses
MOFLUX has been in operation since June, 2004. Many sensors have shown signs of degradation and the frequency of instrument breakdown is increasing, threatening data continuity and integrity. Thus we request funds to overhaul major sensor systems at the MOFLUX site for FY2011. The package will include the following components:
1. Purchasing a new set of eddy covariance flux system instruments ($40K)
2. Updating/repairing the soil respiration system ($50K)
3. A rotating shadowband radiation sensor to replace the 4-way radiation sensor ($20K)
4. Replacing soil heat flux, temperature and moisture sensors ($5K)