SCIENCE PLAN AND PROGRESS REPORT FOR THE TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA
(TES SFA)

Environmental Sciences Division
Oak Ridge National Laboratory

Sumitted to the
Terrestrial Ecosystem Science Program, Biological and Environmental Research
DOE Office of Science
January 23, 2012

Principal Investigators:

Paul J. Hanson
Environmental Sciences Division
Oak Ridge National Laboratory
Building 2040, Rm. E216
One Bethel Valley Road
Oak Ridge, TN 37831-6301
Phone: 1-865-574-5361
E-mail: hansonpj@ornl.gov

Peter E. Thornton
Environmental Sciences Division
Oak Ridge National Laboratory
Building 2040, Rm. E210
One Bethel Valley Road
Oak Ridge, TN 37831-6301
Phone: 1-865-241-3742
E-mail: thorntonpe@ornl.gov

Co-Principal Investigators	E-mail	Primary Task
Robert J. Andres	andresrj@ornl.gov	Task F5
Lianhong Gu	lianhong-gu@ornl.gov	Task F4
Paul J. Hanson	hansonpj@ornl.gov	Task R1, F3a
Leslie A. Hook	hookla@ornl.gov	Data Management
Melanie A. Mayes	mayesma@ornl.gov	Task F3c
W. Mac Post	postwmiii@ornl.gov	Task F1
Peter E. Thornton	thorntonpe@ornl.gov	Task F1
Jeffrey M. Warren	warrenjm@ornl.gov	Task F2

ABSTRACT

Understanding responses of ecosystem carbon cycles to climatic and atmospheric change is the focus of the ORNL Terrestrial Ecosystem Science Scientific Focus Area (TES SFA). Overarching science questions include: (1) How will interactions among the physical climate, biogeochemical cycles, ecological processes, fossil fuel emissions and land use evolve and influence one another over decades and centuries? (2) How do terrestrial ecosystem processes, interactions and feedbacks control the magnitude and rate of change of greenhouse gases? and (3) How will the magnitude and rate of atmospheric and climatic change alter the structure and function of terrestrial ecosystems and their capacity to provide goods and services to society? The proposed science includes large-scale manipulations, carbon cycle observations, process-level studies, and an integrating suite of modeling efforts. ORNL's climate change manipulations are organized around a single climate change experiment focusing on the combined response of multiple levels of warming at ambient or elevated CO_2 in a black spruce - *Sphagnum* ecosystem in northern Minnesota. The experiment allows the evaluation of mechanisms controlling vulnerability of organisms and ecosystem processes to climate change variables. The TES SFA addresses fundamental processes controlling terrestrial vegetation function and change to improve mechanistic representation of ecosystem processes within terrestrial carbon (C) cycles and Earth system models. Integration of biophysical, biochemical, physiological, and ecological processes in ecosystem models is optimally constrained by historical and contemporary observations. The TES SFA plan is structured to eliminate artificial distinctions between experimental or observational studies and model building, parameter estimation, evaluation, and projection.

This page left blank for double-sided printing.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The TES SFA supports research to understand and predict the global terrestrial ecosystem forcing of the earth's climate, and to assess vulnerability of terrestrial ecological systems to projected changes in climate and atmospheric composition. 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. Targeted experiments are conducted for the quantification of climate change responses to improve prediction of the effects of atmospheric and climatic change on ecosystems' capacities to deliver goods and services, and on feedbacks from ecosystems to the atmosphere and climate. Other process research is targeted at accurately quantifying the exchange of CO_2 between the atmosphere and land ecosystems through photosynthesis, net production and storage pools, autotrophic and heterotrophic respiration, disturbance, and land management practices. TES SFA research also 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. Fundamental processes controlling terrestrial vegetation function and change discovered by TES SFA tasks are used to improve mechanistic representation of ecosystem processes within terrestrial carbon (C) cycle and Earth system models.

The TES SFA is developing capabilities for quantitative projection of future atmospheric greenhouse gas concentrations and ecological effects from environmental change that incorporate complex feedbacks and responses among terrestrial ecosystems, human activities, and Earth's climate system. Spatial and temporal analyses of terrestrial ecosystem responses will provide robust and fundamental scientific results, syntheses and analyses to advance fundamental understanding. The breadth and complexity of this undertaking requires the scientific and technical expertise of scientists across the DOE complex, and is focused on delivering timely answers to questions of national importance. Quantitative, transparent and accessible science products produced by the TES SFA can be used by decision-makers and stakeholders to evaluate and address climate change consequences. The TES SFA team's unique strengths in measurement, experimentation, and modeling will be synergistically combined to answer pressing global change science questions. ORNL's powerful computation and informatics capabilities are available to support this vision of Earth system analysis. The TES SFA group focuses on interactions among the climate system, terrestrial ecosystem dynamics, biogeochemical dynamics, and land use change that are most suited to the team's current strengths and potential for development.

Overarching Science Questions

The following overarching science questions are driving TES SFA activities and each is supported by hypotheses about likely terrestrial responses to environmental and atmospheric change:

1. How will interactions among the physical climate, biogeochemical cycles, ecological processes, fossil fuel emissions and land use evolve and influence one another over decades and centuries to come?
2. What terrestrial ecosystem processes, interactions and feedbacks control the magnitude and rate of change of atmospheric CO_2 and other greenhouse gases?
3. How will the magnitude and rate of atmospheric and climatic change alter the structure and function of terrestrial ecosystems and their capacity to provide goods and services to society?

Goals and Milestones

The TES SFA Science Plan addresses the following five research goals and associated long-term (5 to 10 year) milestones. Progress on recent (3-year) milestones is summarized later in this report.

1. *Resolve uncertainty in the sign and magnitude of global climate-terrestrial C cycle feedbacks under future climatic warming and rising CO_2.* Current terrestrial C cycle models used in coupled C cycle-climate simulations show a range of responses so large that we cannot determine the sign of the terrestrial C cycle feedback with climate with any real confidence.

- Long-term goal: Provide an operational system to analyze C sources and sinks that integrates global C measurements, data assimilation and experimental results to quantify the sign (net uptake or loss of C from terrestrial ecosystems) and more tightly constrain the magnitude of global climate-terrestrial C cycle feedbacks.

2. *Understand and quantify organismal and ecosystem vulnerability to warming and how the response to warming is modified by CO_2.* Projected magnitudes and rates of future climatic and atmospheric change exceed conditions associated with current interannual variations or extreme events. It follows that a suite of processes will be impacted to a degree and in ways that we have insufficient information to predict from observations alone: experimental manipulations are required.
   - Long-term goal: Conduct and complete experimental manipulations and synthesize results including the development of algorithms for characterizing changes in net plant production and relative species composition and associated changes in water balance and biogeochemistry under climatic change.
3. *Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in Earth system models as a function of time, space, soil type, and climate*. Soil C is the largest terrestrial C pool, and the dynamics are difficult to quantify due to the myriad of biological, environmental, and edaphic factors present at all scales of space and time. Current understanding of mechanisms governing soil C dynamics is inadequate for projecting the potential for storage and release of soil C as a function of changing edaphic and climatic factors.
   - Long-term goal: Provide a flexible model of soil C storage based on microbial processing of soil C for incorporation in fully coupled Earth system models.
4. *Incorporate new findings on interannual and seasonal dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and Earth system models emphasizing the importance of the decadal time scale.* Landscape-level measures of C, water and energy flux provide essential data for the evaluation of land-atmosphere exchanges in order to validate and improve terrestrial C and Earth system models.
   - Long-term goal: Achieve predictive capacity to simulate interannual to decadal dynamics important to water balance, biogeochemical cycling and vegetation response to climatic change across ecosystems.
5. *Search out key uncertainties within global land-atmosphere-climate models and future Earth system diagnosis models as the basis for proposing new measurements and experiments as new knowledge is gained.*
   - Long-term: Resolve major components of terrestrial feedback uncertainty for the entire Earth system. New model capabilities will include improved process-based representation of soil organic matter dynamics and new representation of ecosystem climate change response mechanisms derived from experiments.

Research to accomplish these broad goals and objectives is organized as a series of tasks focused on terrestrial ecosystem responses to environmental and atmospheric change and to climate change forcing modifications driven by terrestrial C cycle processes or structural features. Tasks included in TES SFA efforts to date are listed below with parenthetical identification of the goals that each addresses.

Climate Change Response Tasks

Task R1: Spruce and peatland responses under climatic and environmental change (SPRUCE; Goals 1 and 2).

Task R2: Walker Branch Watershed long-term monitoring (Goal 4).

Climate Change Forcing Tasks

Task F1abc: Mechanistic C cycle modeling (Goals 1, 2, 3, 4, & 5).

Task F2: Partitioning in trees and soils (PiTS; Goals 4 and 5).

Task F3: Representing soil C in terrestrial C cycle models (Goal 3).

Task F4ab: Terrestrial impacts and feedbacks of climate variability, events, and disturbances (Goal 4).

Task F5: Fossil C emissions (Goals 1 and 5).

TES SFA activities interact with global modeling activities at ORNL to improve the representation of terrestrial C cycle processes and climate-vegetation-C cycle feedbacks required to reduce uncertainty in predictions by global climate and Earth system models of future climate and terrestrial response.

Data systems and informatics are not a separate focus area, but an integral part of the TES SFA. ORNL is developing and deploying data and information management, and integration capabilities needed for the collection, storage, processing, discovery, access, and delivery of data. Systems will also be developed for assimilation of available measurements, synthetic analysis results, model forcing and boundary condition data sets, and the archiving of model outputs. Such an information system facilitates model-data integration and provides accessibility to model output and benchmark data for analysis, visualization, and synthesis activities.

Approach

Developing robust parameter estimation procedures and reducing uncertainty through identifying and improving structural deficiencies in global terrestrial C cycle models are accomplished through organized interactions among data collection, experimental manipulation, and model development at all scales. Experiments and field observations are employed to better understand organismal responses to environmental and atmospheric changes from molecular through whole-plant responses to the integrated function of entire ecosystems. Our efforts are focused on understudied ecosystem processes and ecosystems subject to greater rates of change under projected climate futures. We use model-data assimilation and multivariate model benchmark evaluation in all aspects of the TES SFA's research program. The SFA uses 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 is the dominant forcing factor, we include research to quantify fossil fuel emissions, including their spatial and temporal distributions and associated uncertainties. Products of the TES SFA include primary research publications, synthesis activities (e.g., critical review papers, model-data intercomparisons, and international workshops), newly archived data, and a multi-scale model-data assimilation system delivering analyses of climate change forcings and terrestrial organism responses appropriate for local-to-global analyses.

Highlights for the period October 2009 through December 2011

- Published 84 papers with 16 additional manuscripts progressing towards final acceptance (see Appendix A)
- Developed the theoretical approach and a web-based tool for the extraction of key photosynthetic data from foliar CO_2 response curves (Gu et al. 2010 and http://leafweb.ornl.gov)
- Developed a new experimental method for conducting field experimental warming studies (Hanson et al. 2011), and engaged in community dialog on appropriate warming methods for future use (Amthor et al. 2009).
- Published a highly visible *Scientific American* article on environmental change experiments (Wullschleger and Strahl 2010).
- As a result of field experiments with transplanted ^{14}C labeled leaf litter, we developed new soil C cycle (Parton et al. 2010; Tipping et al. 2011) and root growth (Riley et al. 2009) model improvements to enhance the capacity of C cycle models to capture the fate and turnover of C.
- Proposed and demonstrated the importance of an improvement to the conventional eddy covariance theory with measurements from the MOFLUX site (Gu et al. 2011) made possible by detailed profile measurements within that forest canopy. All flux sites in the world should reprocess their previous measurements in order to avoid bias errors in C and water fluxes and budgets. MOFLUX reprocessing has been completed.
- Demonstrated for the first time with a fully-coupled Earth System Model (CESM) that C-nutrient interactions can have a fundamental influence on atmospheric CO_2 concentrations and global-scale ecosystem-climate feedbacks (Thornton et al. 2009).
- Applied the land component of the CESM modeling framework to show the influence of rising CO_2, increasing mineral nitrogen (N) deposition, and human-caused land use and land cover change on global-scale river flow, one of our most reliable and integrative evaluation metrics for the global models (Shi et al. 2011).

Terrestrial Ecosystem Science SFA Participants (1 January 2012)

Robert J. Andres, ORNL Environmental Data Researcher
Deanne J. Brice, ORNL Technical Staff
Joanne Childs, ORNL Technical Staff
Natalie A. Griffiths, ORNL postdoctoral researcher
Lianhong Gu, ORNL Senior Research Staff Member
Paul J. Hanson, ORNL Distinguished Research Staff Member
Daniel J. Hayes, ORNL Associate Research Staff Member
Leslie A. Hook, ORNL Associate Research Staff Member
Kevin Hosman, Technical Staff – University of Missouri – Columbia
Colleen M. Iversen, ORNL Associate Research Staff Member
Anthony W. King, ORNL Senior Research Staff Member
Randall K. Kolka, USDA Forest Service Researcher
Jiafu Mao, ORNL Associate Research Staff Member
Melanie A. Mayes, ORNL Research Staff Member
Karis J. McFarlane, Lawrence Livermore National Laboratory
Richard J. Norby, ORNL Corporate Fellow
Brian Palik, USDA Forest Service Researcher
Stephen G. Pallardy, Professor – University of Missouri – Columbia
Jana R. Phillips ORNL Technical Staff
Wilfred M. Post, ORNL Distinguished Research Staff Member
Daniel M. Ricciuto, ORNL Associate Research Staff Member
Christopher W. Schadt, ORNL Research Staff Member
Stephen D. Sebestyen, ORNL USDA Forest Service Researcher
Xiaoying Shi, ORNL Associate Research Staff Member
Jessica M. Steinweg, ORNL postdoctoral researcher
Peter E. Thornton, ORNL Senior Research Staff Member
Dali Wang, ORNL Associate Research Staff Member
Jeffrey M. Warren, ORNL Associate Research Staff Member
David J. Weston, ORNL Research Staff Member
Stan D. Wullschleger, ORNL Distinguished Research Staff Member
Xiaojuan Yang, ORNL postdoctoral researcher

Key individuals' roles and responsibilities are further defined in Section 5.

NARRATIVE (SECTIONS 1 THROUGH 6)

1. BACKGROUND AND PROGRAM OVERVIEW

The Earth's environment is changing on all scales, from local to global. Global change predictions made by the present generation of coupled climate-C cycle models are hampered by uncertainty surrounding fundamental climate-ecosystem feedbacks and by climate change impacts on ecosystem structure and function. Current understanding of these feedbacks and impacts is not adequately represented in today's state-of-the-science analyses of Earth system dynamics. The TES SFA's approach to Earth system analysis combines the development and improvement of terrestrial land surface models with the deployment of new measurements and experiments. This is done in coordination with complementary ORNL efforts in global climate and coupled climate-C model development and simulation. Improved understanding of terrestrial land surface responses and feedbacks to climate and atmospheric change will be integrated in global-scale Earth system models for future climate change research and applications. Our paradigm is to identify and target critical uncertainties in coupled climate and terrestrial ecosystem processes and feedbacks, prioritized by their influence over global change predictions on decadal and century timescales. New measurements and experiments are employed to obtain new knowledge required to reduce these uncertainties, identifying and filling gaps in the representation and parameterization of fundamental processes within existing Earth system models. Major uncertainties and critical knowledge gaps under current consideration are outlined in the science plans attached to this document.

The TES SFA research includes large-scale manipulative experiments, C cycle observations, process-level studies, and an integrating suite of modeling and prediction efforts. C cycle modeling and research involve the integration of biophysical, biochemical, physiological, and ecological processes into terrestrial ecosystem models that are optimally constrained in structure and function by historical and contemporary observations and experimentation. The models include process-level results of manipulative experiments to enable projections of future responses and feedbacks to climate forcing. ORNL's environmental change manipulations are organized around a single experiment (SPRUCE) focusing on the combined response of multiple levels of warming at ambient or elevated CO_2 (eCO_2) levels in a *Picea mariana - Sphagnum* peat bog in northern Minnesota. The experiment provides a platform for testing mechanisms controlling vulnerability of organisms and ecosystem processes to important climate change variables (e.g., thresholds for species decline or mortality, limitations to regeneration, biogeochemical regulation of productivity, C evolution). The TES SFA also currently supports smaller-scale manipulations to quantify C partitioning in trees and soil (PiTS) to inform model parameterization and process, as well as limited support for core, long-term tracking of the hydrologic, biogeochemical and biological response of the Walker Branch Watershed to inter-annual climatic variations, and sustained support for the characterization of global C emissions. ORNL's SFA research plans and philosophy effectively eliminate an artificial distinction between experimental or observational studies and modeling (including model construction, parameter estimation, evaluation, and prediction).

1.1 TES SFA PERFORMANCE TIMELINE AND ORGANIZATIONAL UPDATES

Work summarized in this document was initiated in October 2009 as a part of the Oak Ridge National Laboratory (ORNL) Climate Change Program Plan (http://tes-sfa.ornl.gov). That plan included Scientific Focus Areas (SFAs) on Climate Change Response, Forcing, and Mitigation. In July 2010, at the direction of DOE-BER, we were asked to combine the Response and Forcing SFAs into the Terrestrial Ecosystem Science Climate Change Scientific Focus Area (i.e., the TES SFA). This document includes progress-to-date reporting through December 2011 for all tasks of the Response and Forcing SFAs initiated October 2009. We then describe future planned research under the TES SFA and provide specific budgets for the 2013, 2014, and 2015 fiscal years.

1.2 TES SFA PHILOSOPHY, RESEARCH, GOALS, AND MILESTONES

TES SFA research is exercising an iterative modeling process (Figure 1) in which observational and experimental studies and modeling activities at different spatial and temporal scales are integrated and used to estimate and mechanistically explain current C sources and sinks and forecast their future behavior and influence on atmospheric CO_2 concentration and climate. The TES SFA's focus on terrestrial land processes and function is complementary to broader ORNL Climate Change Science Institute (CCSI) efforts in global climate and coupled climate-C model development and simulation.

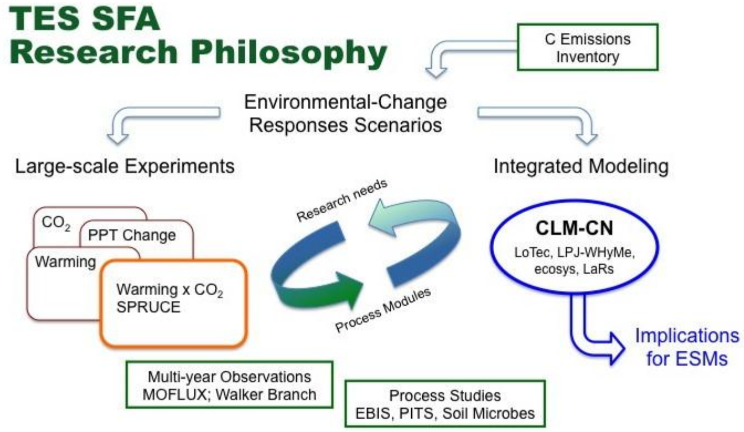

Figure 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

Carbon cycle modeling and research involve the integration of biophysical, biochemical, physiological, and ecological processes into terrestrial ecosystem models. Terrestrial C-cycle models, which represent our best scientific understanding from experiments, are validated and constrained by historical and contemporary observations and further informed by experimental manipulations that enable projections of future ecosystem response and feedbacks to climate forcing.

Accurate model representations of soil C cycling processes, particularly responses to short- and long-term environmental changes, are needed to improve predictions of regional- to global-scale climate models. Given recent process-level advances in our understanding of the chemistry of soil C storage and susceptibility to warming-induced decomposition, the accuracy of current models in predicting soil C response to environmental change is uncertain. The TES SFA is generating mechanistically based rate data to resolve recent questions regarding the nature of stabilized soil C, and to develop process-level models describing soil C response to environmental change.

Manipulative experimental work under the TES SFA focuses on the identification of critical response functions for terrestrial organisms, communities, and ecosystems to environmental changes. Both direct and indirect effects of these experimental perturbations are analyzed to develop and refine models needed for full Earth system analyses.

Research summarized for the TES SFA is ambitious in its scope, effort, and fiscal requirements. It represents a challenge that is fully utilizing, testing and extending the broad interdisciplinary facilities of the DOE National Laboratories. Proposed and ongoing experiments, simulations, and measurements are conducted to enhance our understanding of the quantitative mechanisms of terrestrial biological responses of important ecosystems to environmental and atmospheric changes and physical and ecological feedbacks between Earth and its climate.

Overarching Questions and Relevant Science

The following overarching science questions and the subsequent description of key goals and milestones acknowledge significant uncertainties in climate change prediction regarding terrestrial ecosystem response.

1. How will interactions among the physical climate, biogeochemical cycles, ecological processes, fossil fuel emissions and land use evolve and influence one another over decades and centuries to come?
2. What terrestrial ecosystem processes, interactions and feedbacks control the magnitude and rate of change of atmospheric CO_2 and other greenhouse gases?
3. How will the magnitude and rate of atmospheric and climatic change alter the structure and function of terrestrial ecosystems and their capacity to provide goods and services to society?

2. PROGRESS SINCE OCTOBER 2009

Research goals and all milestones for near-, mid-, and long-term deliverables for the TES SFA were described and justified in the original SFA plans. In the context of a 3-year review cycle initiated in October 2009, the following goals and their near-term deliverables are summarized. Details are documented in the following sections.

1. *Understand and quantify organismal and ecosystem vulnerability to the interactive effects of atmospheric and climatic change through the use of new experimental manipulations employing multi-level warming with appropriate CO_2 exposures and measures of water and nutrient limitations.*

- Select a target ecosystem or ecosystems on which to focus experimental studies of response to warming and CO_2 increases based on feasibility, projected vulnerability, societal and scientific importance [*completed in 2010*].
- Complete the design [*completed in 2011*] and construction of new experimental manipulations, and initiate treatments [*ongoing infrastructure development through spring 2013*].

2. *Resolve uncertainty in the sign and magnitude of global climate-terrestrial C cycle feedbacks under future climatic warming and rising CO_2.*

- Deliver a functional C cycle model including element feedback constraints and CO_2 response [*completed in 2010*] incorporating conclusions from completed experiments [*ongoing through 2012*] capable of quantifying global patterns of terrestrial C sources and sinks.
- Develop plans for new measurement and experimental needs, highlighted by forcing uncertainties [*ongoing through 2012*].

3. *Improve model representation of belowground C partitioning to better predict the fate of C under future climate warming, rising CO_2 and other climate perturbations.*

- Short-term manipulative field measurements to quantify internal plant C partitioning (especially into belowground sinks) and subsequent impacts on soil N cycling and autotrophic/heterotrophic CO_2 release will be conducted in different tree species based on specific needs for model parameterization [*completed loblolly pine measurements 2011, efforts for other tree species and data-model integration are ongoing*].

4. *Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in Earth system models and to inform mitigation strategies through ecosystem management.*

- Complete and synthesize TES SFA experiments and measurements on the forms, fate and transport of soil C based on isotopic tracer and other studies in natural and managed ecosystems.
  - Landscape gradient analyses [*completed in FY2011*].
  - EBIS-AmeriFlux Efforts [*on schedule for completion in FY2012*].

5. *Incorporate new findings on interannual and seasonal C and water dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and Earth system models emphasizing the importance of the decadal time scale.*

- Synthesize existing land-atmosphere C, water and energy measurements and experimental results to constrain interannual and seasonal dynamics in terrestrial land surface and C models [*completed each year*].
  - MOFlux observations [*completed, archived and summarized for 2005 through 2010*].
  - Develop extreme events backbone database for exteme events [*data for drought and freeze events have been completed*].

2.1 PROGRESS BY TES SFA TASKS

Section 2.1 expands our progress-to-date reporting through December 2011 for all tasks of the TES SFA including Response and Forcing SFAs initiated October 2009. For context on our progress over the initial years of TES SFA activities, full descriptions of the initial plans for all tasks can be found in the June 2009 ORNL Climate Change Program plan available on line at http://tes-sfa.ornl.gov. Page limits preclude a comprehensive discussion of all progress-to-date under the TES SFA, but a full listing of TES SFA peer-reviewed publications since October 2009 is provided in Appendix A to supplement this text.

Appendix B provides additional details for several key publications from ORNL climate change studies that predate the TES SFA, but that represent a logical extension of our overall efforts in climate change science.

CLIMATE CHANGE RESPONSE TASKS

2.1.1 TASK R1 – SPRUCE AND PEATLAND RESPONSES UNDER CLIMATIC AND ENVIRONMENTAL CHANGE [THE SPRUCE EXPERIMENT]

Experimental efforts of the TES SFA are critical to future projections of ecosystem structural and functional responses to climatic and atmospheric change because they provide measured observations of responses to environmental conditions that are not duplicated within current or historical measurements conducted through time or across space. Experiments provide the comprehensive data sets needed to generate response curves or multidimensional surfaces. Such data are needed within models to drive projections beyond the data sets available from current and historical observations.

The SPRUCE experiment is a climate change manipulation focusing on the combined response of multiple levels of warming at both ambient and elevated CO_2 (eCO_2). The experiment is being set up to provide a one-of-a-kind platform for testing mechanisms that control vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for species decline or mortality, limitations to regeneration, biogeochemical regulations of productivity). SPRUCE is being established in a *Picea mariana* [black spruce] – *Sphagnum* spp. forested peatland in northern Minnesota. This ecosystem, located at the southern extent of the spatially expansive boreal peatland forests, is considered to be especially vulnerable to climate change and to have important feedbacks on the atmosphere and climate.

Since October 2009, progress has been made on all planned SPRUCE activities including the design and development of experimental infrastructure, the installation of environmental monitoring on the S1 Bog of the Marcell Experimental Forest, testing and evaluation of measurement methods, and the planning for and execution of *a priori* model simulations to guide plans for pre- and post-treatment observations. The following summary briefly describes progress in these areas and Section 3.1 lays out the timeline and deliverables for SPRUCE in FY2013, 2014, and 2015 that will include the initiation of a decade of experimental treatments. Additional SPRUCE details can be found at http://mnspruce.ornl.gov. The SPRUCE website provides project documents, images, and presentations that are available to participants and the public. The site was implemented using the Drupal web site application/content management system.

2.1.1a Project Agreements and Environmental Review

Memorandum of Understanding – A memorandum of understanding (MOU) between UT-Battelle and the USDA Forest Service was developed to define the roles and responsibilities of each institution in the long-term operation of the SPRUCE experiment (http://mnspruce.ornl.gov/content/spruce-project-documents).

National Environmental Policy Act Approval – DOE procedures for approving experimental activities both on and off of the Oak Ridge Reservation led to the decision that an Environmental Assessment (EA) of the SPRUCE activity was needed. A draft EA was completed in November 2010 and was submitted for public comment during March 2011. Final NEPA approvals were granted 10 June 2011 allowing infrastructure development to take place on the S1 Bog in Minnesota. The published Environmental Assessment documents can be found on the SPRUCE project web site: http://mnspruce.ornl.gov/content/spruce-project-documents.

2.1.1b SPRUCE Project Structure

The SPRUCE experiment comprises the research tasks and a combination of both ORNL and USDA Forest Service staff identified in Figure 2. The key task leads and supporting personnel are indicated in the figure. The coordinating panel is made up of the Response SFA research manager (Paul J. Hanson), the Minnesota USDA Forest Service contact (Randall K. Kolka), the Technical Task leads, and a group of external science advisors. This coordinating panel serves as the decision-making body for major

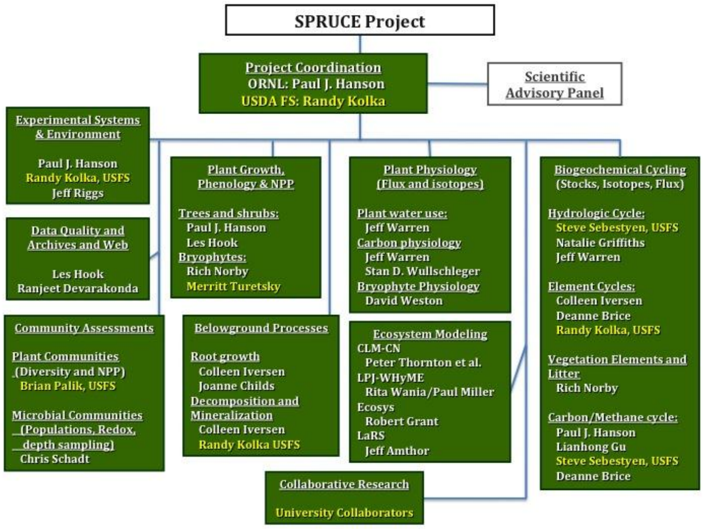

Figure 2. Organization of the SPRUCE experiment showing tasks and personnel

operational considerations throughout the duration of the experimental activity and it will be the panel for vetting requests for new research initiatives to be added to the experiment when it becomes operational.

2.1.1c Infrastructure

We succeeded in bringing our vision of a next-generation warming and CO_2 exposure enclosure to reality. In October 2009 we had a conceptual idea for an enclosure that would provide both above- and belowground warming treatments to a complex ecosystem including trees, shrubs and a high-C soil. Hanson et al. (2011) demonstrated the capacity of our new approach to produce logical temperature differentials both above- and belowground to depths of at least 2 meters, and further indicated that the new method may produce disproportionately high CO_2 emissions from deep soil storage pools or enhanced root activity that have not been previously observed in warming studies. We constructed and tested a full 12-m diameter version of the above- and belowground warming concept at ORNL. Since the initiation of the SFA, scientists and engineers produced full construction plans for the concept by February 2010, established subcontracts for its construction in March 2010, and in June 2010 we took ownership of a full-scale prototype of the enclosure for instrumentation ahead of testing (Figure 3). The enclosure was populated with a variety of sensors including temperature sensors (air and soil), relative humidity sensors, an array of radiation sensors to evaluate its actual energy use, and CO_2 sampling ports in order to evaluate the homogeneity of temperature and atmospheric conditions within the enclosure and the energy demands needed to attain target warming temperatures.

While planning and constructing the warming enclosure, we engaged ORNL expertise in complex fluid dynamics modeling in various exercises to estimate the turbulence dynamics and energy use needs of the enclosure. We completed testing of the field performance of this all-electric prototype for air warming, deep belowground warming and the production of elevated CO_2 atmospheres between January and November 2011. Results from testing the electrically heated prototype (Figure 4) show that temperature differentials of as much as +7 °C can be achieved for variable energy inputs. Propane-based heating will be needed in Minnesota to achieve target warming levels of +9 °C because local electrical supplies are not available at those demand levels.

ORNL engineers simulated and designed the addition of a frustum to the initial aboveground enclosure, which had straight sides for simplicity to further deflect external winds and limit energy losses. Following installation of the frustum the turnover time of warmed air within the enclosure was increased and energy use went down. At target temperatures of +3 and +6 °C the enclosure yielded a mean differential per energy input value of approximately 0.17 and 0.09 °C per kW of energy input.

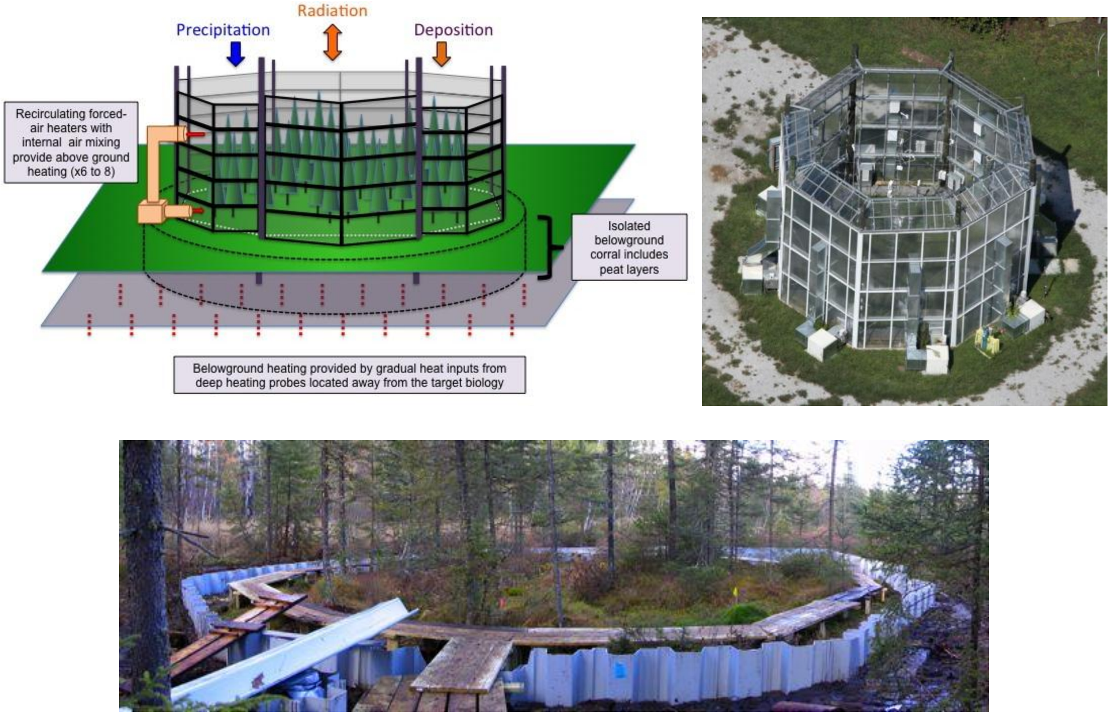

Figure 3. SPRUCE ecosystem warming enclosure concept (left photograph) and the final fully instrumented prototype (right photograph). The warming enclosure has instrumentation for measuring turbulence, air temperature, and relative humidity at multiple heights, and soil temperatures to depths as much as – 2m. Sampling tubes for [CO$_2$] measurements are also installed. The lower photograph shows a full-scale prototype corral installed in the S1 Bog in Minnesota. Interlinked sheet piles between 3 and 4 meters long were driven through the peat to the underlying ancient lake bottom to seal a hydrologic basin for testing.

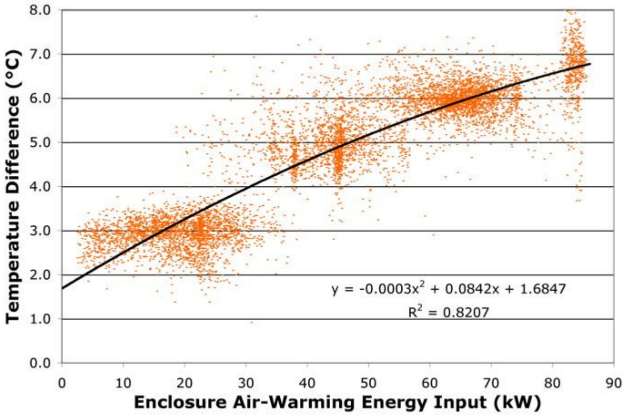

Figure 4. Temperatures achieved in the warming prototype in the absence of solar radiation inputs. Variation along the *x*-axis is predominantly driven by wind.

In addition to constructing the warming prototype in Oak Ridge, TN we completed a full-scale prototype of our belowground corral on the S1 Bog of the Marcell Experimental Forest in October 2011 (Figure 3 lower photograph). This flow barrier will serve two purposes: (1) prevention of flow into the plots if snowmelt desynchronizes between the chamber and the surrounding peatland, or if water table gradients develop between inside and outside of the experimental plots due to changes in water use inside the chamber, and (2) a means to collect and measure the volume and chemical composition of surface runoff from each plot. Design documents were prepared and a prototype constructed under subcontract with Minnesota vendors to allow testing of the system in 2012. If proven to be an effective barrier, the corral will allow us to better characterize the hydrologic budget of the manipulated peatlands and more appropriately capture the full influence of warming on integrated ecosystem processes and functions.

Site Engineering – Detailed construction diagrams and site plans necessary to supply power to the experiment, clear roadways and open areas, and to characterize subcontract details for building the boardwalks for the S1 Bog were completed in 2010 (Figure 5 center). Land clearing near the S1 Bog as indicated in the figure and the clearing of a corridor along which electrical service can be brought to the S1 Bog was completed in November 2011.

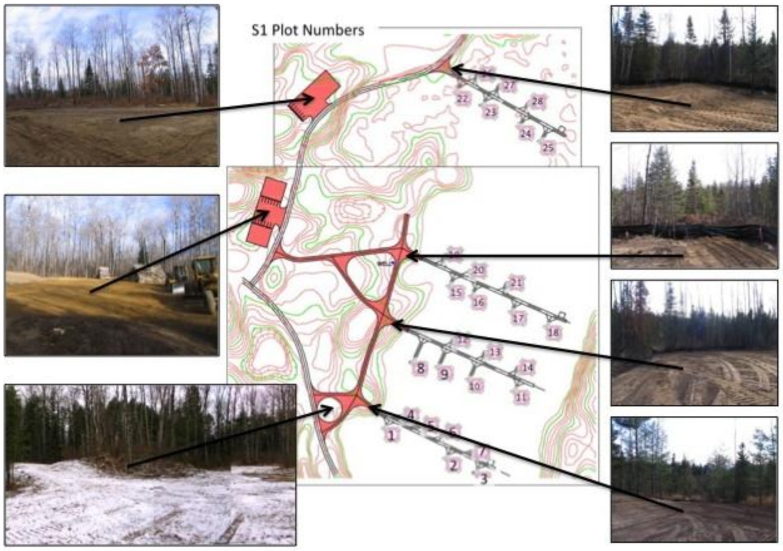

Figure 5. SPRUCE engineering site plan for the S1 Bog showing the access roads, parking, parking areas including locations for temporary office buildings in upland areas to the west side of the bog, and the extensive network of boardwalks that must be added to the bog itself to allow repeated access to up to 28 experimental units. Photographs show land clearing completed November 2011.

Experimental Design – The SPRUCE experiment is being developed to determine the integrated response of the spruce bog ecosystem and its component processes and parts (trees, shrubs, bryophytes, and microbial communities) to a broad range of above- and belowground temperature increases, and to test how those responses to increased temperature will be altered by elevated atmospheric CO_2 concentration. Experimental temperature treatments will range from ambient to a +9 °C differential from ambient for both air and deep soil (Hanson et al. 2011). Those treatments will be repeated in combination with ambient or elevated CO_2 atmospheres approaching 800 to 900 ppm. The treatment levels and their allocation to the available experimental units on the S1 Bog are being configured to provide optimal data for characterizing a range of temperature response curves for plant- or ecosystem-level phenomenon.

The original SFA plan proposed an incomplete factorial using 28 experimental units that included four replicates of each of the following seven treatments: unchambered ambient plots, control plots at +0 °C, warmed plots at +3, +6, and +9 °C and warmed plots exposed to elevated CO_2 atmospheres at +3 °C and +9 °C. Although this approach is viable, project participants realized that the incomplete factorial design was statistically weak, open for criticism, and not the best approach for addressing our priority science questions surrounding responses to warming. Through quantitative analysis of different possible experimental designs, we concluded that a more flexible regression-based experimental design including a broad range of temperature levels would yield more statistical power and better long-term data to characterize response curves for application within ecosystem and earth system models.

Such a modification of the experimental design provides the flexibility to choose the number of treatment levels from 28 surveyed experimental plots (Figure 5) allowing us to accommodate the costs of constructing, operating, and adding instruments to the warming enclosures. A regression-based experimental design appropriate for detecting the shape of the temperature or other environmental response curves will be pursued as an experimental design with more flexibility than traditional analysis of variance (ANOVA). This approach will allow us to evaluate and parameterize response curves for the shape of previously unmeasured phenomenon (Cottingham et al. 2005). If necessary, this combination of treatment plots occupying perhaps 20 experimental units might still be justifiably binned into low, medium and high temperature treatments for ANOVA based assessments for some variables.

A minimum of six experimental units for each level of CO_2 (ambient and ~900 ppm) deployed over the range of temperatures from 0 to +9 °C is needed to provide redundancy to protect against infrastructure failure while still allowing the flexibility to evaluate a range of forms for response curves.

An important assumption underlying this choice is that there are no strong gradients across the experimental area that would mandate a block design. Preliminary survey data from the site justify making this assumption.

Application of the treatments – The SPRUCE research group has been discussing the manner in which temperature treatments would be applied. Initial assumptions were that the treatments would be set to their target level from the start of the experiment and held there for the duration of the 10-year study. However, concerns about instantaneous changes to high temperature differentials have led us to consider ramping temperatures over 1 to 5 years to target treatment temperature differentials when they would be held constant for the remaining years. This approach would allow us to evaluate the effects of rate of change on acclimation by a range of organism functional types. The subsequent constant differential period would then allow us to monitor the influence of intra- and interannual variations on the imposed treatments. The decision on ramping will be made with the benefit of further external input.

2.1.1d   Modeling: *a priori* approximations of experimental results

We engaged two modeling groups to produce *a priori* model projections of the experimental treatment conditions to rationalize magnitudes of responses and to help drive measurement plans and investments for both pre-treatment and post-treatment activities within the SPRUCE experiment. Paul Miller (Lund University) with input from Rita Wania (University of Victoria) completed *a priori* model projections for SPRUCE experimental treatments using the LPJ-WHyMe digital vegetation model (Wania et al. 2009a, 2009b, 2010; Miller et al. in prep.). Their model was initialized for application of ambient simulations to *Picea-Sphagnum* bog ecosystems and included an intermediate detailed model for methane flux. Robert Grant (University of Alberta) conducted model runs with the *ecosys* model (Dimitrov et al. 2010ab), which had been previously configured for applications to mature boreal black spruce ecosystems. The *ecosys* model also includes a detailed characterization of methane cycle mechanisms.

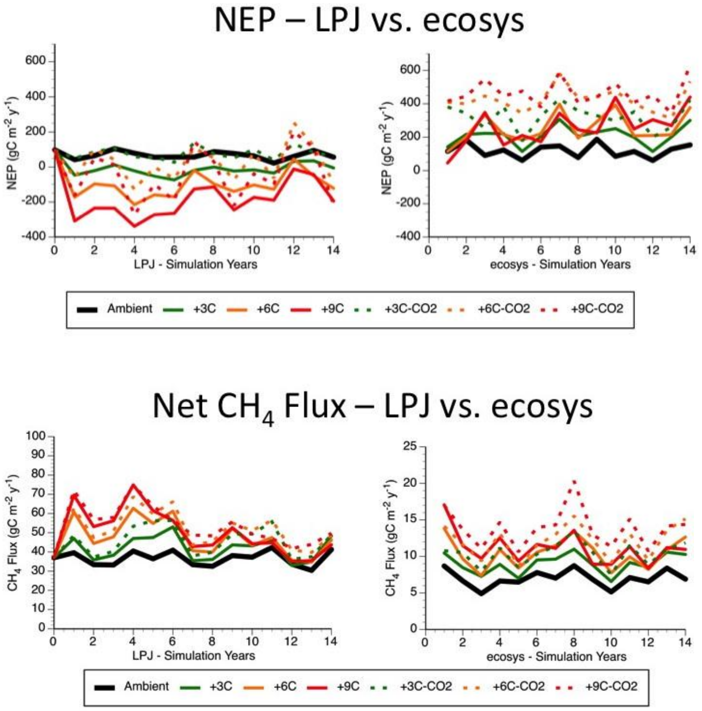

Figure 6. Simulated net ecosystem production (NEP) of CO_2-C (upper graphs) and CH_4-C (lower graphs) from the LPJ-WHyMe and ecosys models. Disagreements in flux magnitude stem from different starting assumptions imposed by each model, and the inverse relationship for NEP is the result of a N feedback present within ecosys that is not represented in LPJ-WHyMe. Positive NEP values represent C uptake by the land surface.

Figure 6 shows contrasting results from the two completed *a priori* model runs. Initial model runs were parameterized with little input from the SPRUCE site, and the results reflect each model's characteristics. Different magnitudes of CO_2 and CH_4 fluxes projected by the models were driven by different assumptions of the age of forest stands (LPJ – developing; *ecosys* – mature). More interesting are the opposite projections for net ecosystem production from the two models with LPJ projecting C loss and *ecosys* projecting C gain. The *ecosys* model contains a full N budget absent from this version of LPJ, which explains the difference in model projections. Warming treatments in the bog are hypothesized to enhance decomposition and nutrient mineralization, leading to enhanced C uptake by higher plants. In the *ecosys* model this response is very dominant and leads to enhanced C gain. These *a priori* model runs give us glimpses of what may happen with future warming and elevated CO_2 conditions. The variation the magnitude and direction of responses is justification for the execution of the SPRUCE experiment. We will pursue further simulations to better define expectations.

Peter Thornton, Daniel Ricciuto, and Gautam Bisht at ORNL are in the process of converting a point version of the CLM-CN land surface model (Thornton et al. 2007) for application to the SPRUCE high C bog ecosystem. Initial efforts with CLM-CN have focused on model modifications needed to represent the isolated hydrologic cycle of the bog environment, as well as the observed patterning of the bog interior into raised hummocks and sunken hollows having distinct hydrologic dynamics and vegetation communities. Initial runs with the original CLM-CN hydrology configuration generally agree with the LPJ-WHyMe results, showing strong warming-induced C losses for target treatment levels and compensatory responses (through enhanced primary production) in the presence of elevated atmospheric CO_2. Next steps for *a priori* CLM-CN modeling are to couple the new hydrology treatment with vertically structured soil organic matter pools, and then to introduce components of a methane model recently developed for CLM (Riley et al. 2011). We are also considering funding of *a priori* model runs with the TEM model that has been applied to high latitude ecosystems with similar characteristics (Euskirchen et al. 2009; Zhuang et al. 2004)

2.1.1e Observations and Measurement Evaluations for SPRUCE

Data management and SPRUCE Web site – The SPRUCE Project initiated its data management program with the development and release of a comprehensive Data Policy. The Policy is a clear statement of the importance of the data collection effort and the control of the flow of data from field collection through archiving and to its fair use by the scientific community. Data will be archived at the CDIAC Data Archive (http://cdiac.ornl.gov/). The components of the Data Policy are expanded upon in the Data Management Plan. The plan provides a structured framework to capture the project-defined requirements for maintaining data quality and consistency, and for controlling data processing. Data management guidance and best practices are included for implementation by the research group. Data Collection Guides have also been created to provide step-by-step instructions for implementing specific data collection and reporting activities.

The TES SFA also recognizes the need to develop the capability to track samples in projects like SPRUCE beyond their initial use and/or samples collected specifically for long-term archiving, future use, and data reporting. The TES SFA will coordinate with other BER funded projects and other leaders in environmental sample archiving (e.g., LTER and NEON) as applicable to enable this capability. The Policy, Plan, and Guides are available on the SPRUCE web site: http://mnspruce.ornl.gov/content/spruce-data-policies.

Environmental monitoring – Environmental monitoring stations with numerous sensors were established on the S1 Bog at the Marcell Experimental Forest over the summer and fall of 2010 with further enhancements added in 2011. Data are retrieved by USDA Forest Service staff and transferred to SPRUCE data management where the files are archived and processed, basic quality control checks are performed and time-series plots are produced for review. These data are posted on the web site for project use and public dissemination at http://mnspruce.ornl.gov/webfm.

Surveys of the S1-bog experimental site – An initial survey of above- and belowground characteristics of the S1 Bog needed to clarify the final experimental design was conducted in late September 2009. We subcontracted with a research group at Rutgers University to conduct ground-penetrating radar estimates of peat depth distribution across the S1 Bog to further clarify the best locations for future experimental blocks. A manuscript describing this process and its future application for assessing stocks of peatland carbon has been accepted pending revisions in Soil Science Society of America Journal (Parsekian et al.).

Tree and Shrub Measurements – During FY2010 and FY2011, preparations for long-term pre- and post-treatment observations of tree and woody shrub responses were initiated. We collected initial biomass data and developed allometric relationships for application to annual biomass and C increment estimates for SPRUCE trees, shrubs and understory plants. Plot centers on the S1 Bog for up to 28 experimental units were established for application to the assessment of tree (*Picea and Larix*) responses to the warming and CO_2 treatments. The numbers and distributions of each tree species within these 28 plots were assessed during a field campaign in February 2011. Tree diameters at 1.3 m (i.e., DBH) were measured and tree positions were mapped. These observations were done in the presence of snow cover and frozen conditions to protect the underlying shrubs and *Sphagnum* microtopography. These data will be used together with other vegetation and peat characteristic data to choose homogeneous plots for random application to experimental treatments. Automatic dendrometers were installed on *Picea* trees to enable correlations between above- and belowground phenology. Basal area growth was shown to begin in mid-June and was completed by mid-August. Automated dendrometers will be deployed on a subset of trees in all plots to provide intra-annual growth data and phenological indications of changing allocation patterns.

Fine-root assessments – Minirhizotrons were installed on the S1 Bog in July 2010, in two areas accessible by boardwalks but away from the future location of experimental plots. Twelve tubes were installed in each of the two areas and initial measurements were done to verify the efficacy of the approach. Experience installing, anchoring, and imaging minirhizotrons in the bog was also used to inform a review paper on minirhizotron use in wetlands (Iversen et al. in press). The minirhizotron tubes were monitored throughout 2011 to provide data on fine-root production and standing crop in relation to a gradient of spruce density and in hummock compared with hollow topography, and they will provide guidance for tube placement and appropriate imaging interval in the experimental plots. Preliminary data indicate that: (1) root production increased with increasing *Picea* density but decreased at highest *Picea* density levels, (2) root production and standing crop were greatest in the hummocks, and (3) few roots were present in deeper peat (> 90% of root standing crop was shallower than ~10 cm, which was the average summer water-table depth).

Roots are currently being separated from a subsample of peat cores collected in June 2011 in order to characterize root morphology, chemistry, and root mass per unit soil depth. Preliminary analysis indicates differences in morphology between *Picea*, *Larix* and ericaceous shrubs, and that the majority of root length is shrub roots of < 0.2 mm diameter.

Sphagnum community assessments –The moss community, particularly *Sphagnum* species, plays a central role in the structure and function of the S1 Bog, and the response of that community will most likely be central to the overall response of the ecosystem to our imposed treatments. Substantial initial effort in FY2010 and FY2011 was dedicated to becoming familiar with the species, and to develop experience with measurement techniques appropriate for characterization of *Sphagnum* productivity.

Sphagnum Species Identification – Two dominant and several lesser species of *Sphagnum* have been identified on the S1 Bog. *S. angustifolium* is prominent and dominant in hollows and on the sides of hummocks, covering 68% of the bog area. *S. magellanicum* is also present throughout the bog (19% cover) but it dominates on hummocks and often mixed with *S. angustifolium*. *S. fuscum*, *S. capillifolium*, and *S. rubellum* are also present, but comprise 1% or less cover. *Polytrichum* (8% cover) and several feather mosses are scattered throughout the bog, occasionally forming large patches in drier sites and will need to be considered in measures of annual production and changing species composition within experimental treatments.

Sphagnum Growth measurements – *Sphagnum* growth was determined by measuring length increment and translating that to dry mass increment using standard methods (Clymo 1970). The standing crop estimate (~ 140 g C m^{-2}) compares well with estimates of Weishampel et al. (2009); it is similar to the estimated standing crop of spruce needles. Annual production of *Sphagnum* is estimated to be ~ 100 g C m^{-2}. Nitrogen concentrations are consistent with literature values.

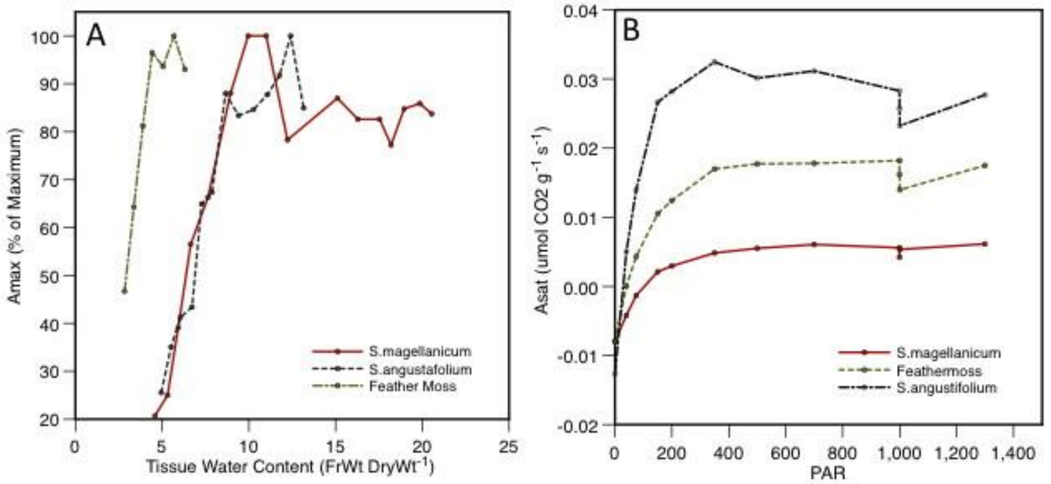

Figure 7. Photosynthetic characteristics of *Sphagnum* and feather moss as a function of tissue water content (left graph) and photosynthetically active radiation (PAR; right graph).

<u>Sphagnum Physiology</u> – Samples of the two dominant *Sphagnum* species and a feather moss were collected across hummock-to-hollow transects as part of a survey assessment to assign physiological attributes to specific species. Samples are being analyzed for N, protein, Rubisco and light saturated photosynthesis (A_{sat}) in response to PAR, tissue water content and ambient CO_2 concentrations. The three moss species varied considerably in their A_{sat} response to tissue water content and PAR (Figure 7). A research plan has been developed for using molecular and physiological tools to measure the responses of major components of the bryophyte community to increased temperature, CO_2 and altered seasonal hydrology. These data will be used to predict whether differential physiological responses will lead to changes in bryophyte community composition and function that can influence whole-ecosystem C and nutrient cycling in a bog system experiencing warming, elevated CO_2, and altered hydrology.

<u>Microbiology</u> – A preliminary characterization of depth-specific profiles of microbiological, physical and biogeochemical properties of the S1 peat material was begun in December 2010 (Figure 8). These investigations are being carried out seasonally (e.g., under the snow, snowmelt, and summer/snow free) to understand how changes in peat temperature profiles affect these properties. Cores are being sampled to depths of 1.5 to 2 m and sectioned into 10-cm increments for microbial population and activity estimates. The abundance of bacteria, *Archaea* and fungi were measured with 16SrRNA QPCR (Castro et al. 2010) and microbial enzyme potentials/activity measurements are being made for a suite of reactions related to the C and N cycles (Sinsabaugh 1994). The pH, %C, %N, and %fiber content were also measured as described in other tasks. Temperature and Eh, are being measured continuously in the field using a HYPNOS data logger (Vorenhout et al 2004).

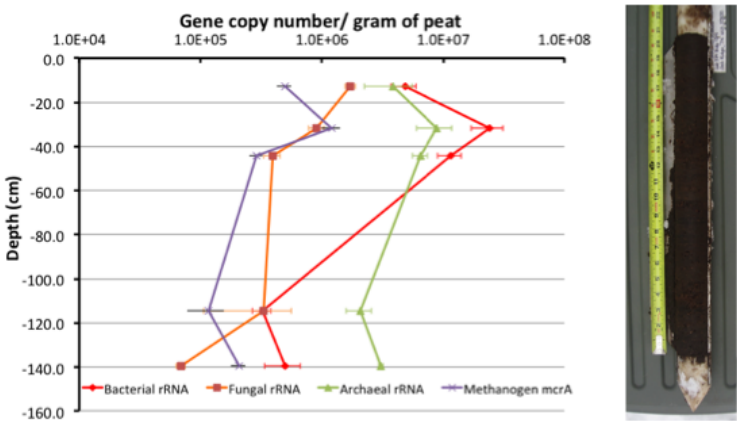

Figure 8. QPCR profiles of bacterial, fungal- Archeael and methanogen abundance (left) from under snow cores collected December 2010.

While Eh was slightly positive in the upper depths of the peat profile indicating that aerobic processes will likely predominate (e.g. nitrification, methane consumption), it is driven substantially negative at depths below 50 cm, which indicates that anaerobic processes (e.g. methanogenesis) will predominate. This trend is inversely related with pH, which becomes less acidic with depth, and corresponds well with patterns observed in the gross composition of the microbial community. Our optimized QPCR assays demonstrate that while bacterial and fungal abundance decreases with depth, *Archaea* (including methanogen) abundance remains high, resulting in dramatic shifts in the ratios of these three groups that could shift during warming, driving further biogeochemical feedbacks.

Biogeochemical Cycling – Planned element cycling measurements in response to warming and elevated CO_2 include: 1) plant nutrient concentrations, stocks, and fluxes, 2) peat nutrient availability, 3) in situ, whole system indicators of changing N biogeochemistry, and 4) peat physicochemical characteristics. We have initiated investigations of the pretreatment characteristics of plant nutrient concentrations, stable C and N isotope ratios, and peat properties in the S1 Bog at Marcell Experimental Forest.

Plant nutrient concentrations – Plants were collected in July 2010. Different plant tissues from common S1 Bog species were analyzed for C and N. A comparison of the two dominant tree species indicated that *Larix* had higher foliar N concentrations and lower foliar C/N ratios than *Picea*. The herb *Smilacina* had the highest foliar N concentration and the lowest foliar C/N ratio among six sampled herbs and shrubs. The preliminary data will be used for planning pre-treatment sampling protocols for herbs, shrubs, and trees during the 2011 and 2012 growing seasons. Ion-exchange resins were installed in summer, 2011 at three depths to test their efficacy and develop appropriate methodology for nutrient analysis, and peat incubations under aerobic and anaerobic conditions in the laboratory are being conducted to examine net N and phosphorus mineralization at multiple peat depths.

Foliar samples from *Picea* and *Ledum* across a transect of the S1 Bog were analyzed for N and P concentration to determine if there are any gradients that would influence location of experimental plots. N and P concentrations were highest at the northern end (where *Alnus* is present) and in the mid-section, where the peat depth is least, but these areas are not where experimental plots will be located. There was a weak relationship suggesting lower %N and %P in *Picea* (but not *Ledum*) with increasing peat depth (excluding peat > 8 m), but no other relationships with site variables were detected. Nitrogen concentrations were greater in *Ledum* than in *Picea*, but P concentrations were similar. The N/P ratio was greater than 16 in *Ledum*, which can be indicative of a P deficiency, and less than 14 in *Picea*, which can be indicative of N deficiency. Variability across the site was not large.

Whole system indicators of N cycling – Building on results from studies in other ecosystems, measurements of natural ^{15}N abundance have been proposed as a measure of whole system changes in N cycling under warming and elevated CO_2. This indicator will be used in conjunction with other measurements of nutrient availability (i.e., buried ion exchange resins, changing water chemistry and peat incubations) to study changes in ecosystem N cycling in SPRUCE. Measurements of changing N availability and biogeochemistry are not trivial in a system where the substrate is either waterlogged or frozen for a significant part of the year.

Carbon pools and processes – Planned studies of C pools and processes include measurements of C stocks and fluxes. Physical and chemical properties of peat have a direct bearing on the vulnerability of organic matter to microbial attack, decomposition, and nutrient release in response to warming and elevated CO_2 at the S1 Bog. Because 97% or more of the C in ombrotrophic bogs at Marcell is tied up in peat (Weishampel et al. 2009), our preliminary work on C pools and processes has been centered on the properties of peat at the S1 Bog.

Based on peat samples collected in the summer of 2010 and early 2011, vertical profiles were constructed for peat C and N stocks at S1 Bog. Estimated C stocks totaled 132.5 kg C m^{-2} in the top 2.5 m of peat. The estimate was in agreement with prior calculated peat stocks (Weishampel et al. 2009) when scaled to equivalent depths. Most of the estimated peat C stock resides at depths below 90 cm, and there are high uncertainties about the deep peat C content that will be resolved by future sampling.

Peat physicochemical characteristics – Peat samples were obtained in March and July 2010 and June 2011, and optimum sampling methods for accessing hummock, shallow and deep peat were determined. Ideal sampling equipment must be able to penetrate fibric surface peat horizons, minimize compaction, retain sample integrity, and yield sufficient dry matter for analysis. Large-diameter cores (7 cm) were needed to meet these requirements.

Using a WaterMark® Universal Core Head Sediment Sampler, we distinguished a 10 to 12 cm surface layer of dead *Sphagnum* from deeper, decomposed peat in the S1 Bog in July 2010. Samples of dead *Sphagnum* and decomposed peat were processed using a 5-part laboratory protocol that included: 1) elemental and isotopic analysis, 2) analysis of fiber content, 3) sequential chemical extractions, 4) decomposition measurements, and 5) sample archival (approximately 25% of the initial fresh sample).

Elemental and isotopic analysis – Peat samples were analyzed for C and N and also analyzed for stable C and N isotope ratios. Samples will be analyzed for ^{14}C at a later time to determine the age of peat at different depths in the S1 Bog. Vertical profiles of stable N and C isotope ratios at S1 Bog were constructed on the basis of plant and peat samples collected in July 2010. Tissue samples from *Picea* and *Larix* and dominant ericaceous shrubs were strongly depleted in natural abundance ^{15}N, with the exception of two species (*Eriophorum* and *Smilacina*). Measurements of ^{15}N aboveground were indicative of a tightly closed N cycle and limited ecosystem N availability. Belowground vertical peat profiles of $\delta^{15}N$ and $\delta^{13}C$ were relatively flat but showed some slight enrichment in ^{15}N and ^{13}C consistent with older, more decomposed organic matter at depth.

Peat chemistry – Using published methods (Wieder and Starr, 1998), we analyzed the chemical characteristics of fibric peat samples collected in March 2010 from the S1 Bog. Initial analyses were performed for the purpose of testing laboratory methods in addition to preliminary chemical characterization of surface, fibric peat samples. Additional analyses are planned for both fibric and hemic peat samples obtained during the July 2011 field campaign.

Chemical extractions provide a detailed, quantitative characterization of the amount of C in nine different organic matter fractions (soluble fats, oils, and waxes; soluble carbohydrates, soluble phenolics; hot-water solubles, holocellulose, alpha-cellulose, hemicellulose, lignin; and acid-soluble carbohydrates).

Holocellulose (including alpha-cellulose and hemicellulose), lignin, and acid-soluble carbohydrates are regarded as more resistant to decomposition than soluble nonpolars and water-soluble fractions. Refractory forms of C dominate fibric surface peat in the S1 Bog. The predominance of refractory constituents in fibric peat from S1 Bog may be caused by rapid decomposition of the more easily degraded components or the natural chemistry of litter inputs (especially from mosses and shrubs). Fiber content of peat is also being evaluated as a baseline data set with the presumption that such characteristics might change with warming.

Peat decomposition – Laboratory incubations are being used to determine the potential lability of different types of peat to decomposition under aerobic (drained) and anaerobic (saturated) conditions. Decomposition of fibric and hemic peat from the July 2010 field campaign was studied using an Oxymax-ER soil respirometer. Peat samples were incubated for 9 days in the dark at room temperature and at moisture conditions obtained in the field (saturated). Under saturated conditions, measurements of CO_2 efflux indicated significantly greater decomposition rates for surface fibric peat (dead *Sphagnum*) than more decomposed, hemic peat. Decomposition rates increase dramatically when free water is drained from samples of surface fibric peat (dead *Sphagnum*). The preliminary measurements indicate that surface water levels in the S1 Bog will play an important role in determining peat CO_2 efflux under different treatments in SPRUCE. We are continuing the incubation studies to determine optimum incubation times and conditions for in vitro quantification of potential decomposition rates of different peat types and will couple measurements of C and N mineralization under different temperature regimes, and aerobic/anaerobic conditions to inform biogeochemical cycling in models.

Land surface and landscape CO_2 and CH_4 flux – Open-path CO_2 and CH_4 sensors have been acquired for use in the measurement of (1) plot-scale head space accumulation measurements of CO_2 and CH_4 diffusion from the bog surface, and the evaluation of the efficacy of enclosure level assessments of CO_2 and CH_4 flux. Large collars (1.3-m diameter) have been obtained and an enclosure “dome” has been constructed for the plot scale observations (Figure 9).

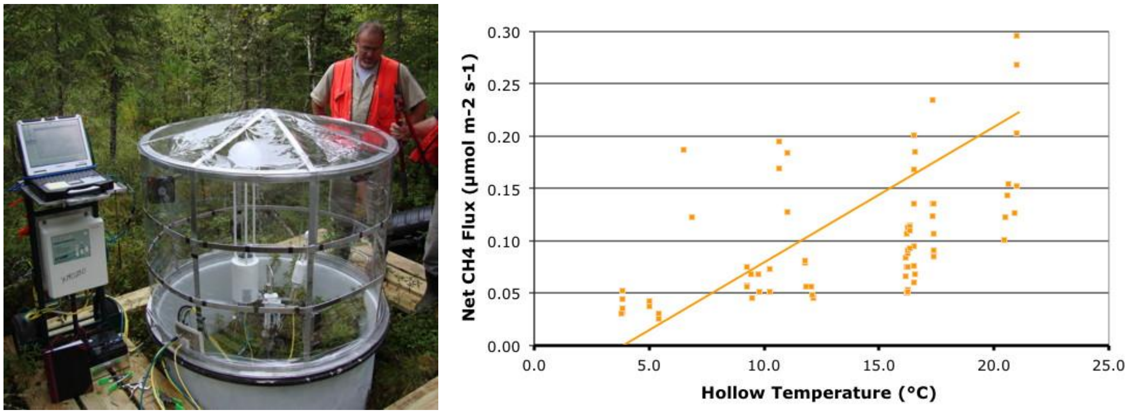

Figure 9. Open-path CH_4 and CO_2 sensors (photo) deployed for measurements of flux from hummock-hollow complexes on the S1 Bog. Seasonal data from mid-June through early-November (right graph).

Large eddy simulations, bubble and smoke tests conducted inside the prototype enclosure in Oak Ridge showed that the mixing time scale of air is on the order of minutes and the flow is horizontally homogeneous except for a very short distance (< 1 m) near the inlets and outlets of the blowers. These flow characteristics indicate that it may be possible to apply the eddy covariance technique to measure fluxes within the enclosure. We are currently testing the efficacy of quantifying whole plot gas exchange for CO_2, CH_4 and water vapor within the warming enclosures.

Plant physiology – The overarching focus on physiological processes is to understand the rates and seasonal dynamics of water use and C exchange by the higher plant species of the bog. Linkages between climate conditions and moisture availability for vascular vegetation above the Sphagnum layer dictate gross primary production and respiratory contributions to site C balance and impact the surface energy balance. Measurements to date have characterized key processes that must be monitored and modeled to interpret instantaneous to long-term term ecosystem processes with warming and elevated CO_2 treatments.

Foliar and whole-plant physiology were examined for S1 Bog species in 2010 and 2011 through laboratory and field-based research. In late summer, the maximum ranges of predawn to midday ψ for shrubs, spruce and larch were -1 to -10, -1 to -15 and -3 to -20 bars, respectively. Plant water use as sap flow was investigated in *Ledum, Chamaedaphne* and *Vaccinium* shrubs, *Larix* and young (<1 m) or mature *Picea* trees using energy balance (EB) and thermal dissipation (TD) techniques. The EB technique was found to apply to all species regardless of size; however, EB required high maintenance and was very sensitive to thermal disturbance. The TD technique was more robust and was best applied to trees with sapwood depth > 1 cm (*i.e*., trees with a diameter > 5 cm).

Foliar gas exchange measurements included: (1) light and CO_2 response curves on detached plant material under semi-controlled conditions, and (2) *in situ* diel measurements at prevailing light, in conjunction with determination of leaf water potential. Gas exchange was assessed for S1 Bog species in 2010 and 2011 through multiple field campaigns, and supplemented with growth chamber observations. Field gas exchange was measured at prevailing temperatures for all species, with particular focus on the most recent cohorts of *Picea* (the S1 trees have up to seven annual cohorts) from lower, mid and upper canopy positions. Other branch samples were collected from *Picea* trees cut for sap flow calibration, immediately put in coolers on ice and shipped overnight to ORNL to assess temperature response curves (ranging from 8 to 43 °C) in growth chambers. Growth chamber observations of cut branches of *Picea* revealed that the optimal temperature for net photosynthesis (A) was < 30 °C for the current-year (2011) foliar cohort. A increased with temperature, peaking between 22 and 30 °C for individual samples, then declined steeply by 30-35 °C, and approached $A = 0$ by 40 °C.

Species differences in light response were apparent. Net photosynthetic CO_2 assimilation (A) in shrub and herbaceous species was 90% light-saturated at ≤ 500 µmol m^{-2} s^{-1} PAR, whereas in the tree species (*Picea* and *Larix*), A saturated at or above 1500 µmol m^{-2} s^{-1} PAR. Responses of A to varying intercellular $[CO_2]$ (C_i) were relatively consistent within species. The major difference across species was in CO_2-

saturated *A*, which varied from 13 to 20 μmol m^{-2} s^{-1}. In mid-summer, mean light saturated *A* was ~6 μmol m^{-2} s^{-1} for *Picea* (the dominant tree species) with no difference between canopy positions (upper, mid or lower) or foliar cohorts (2008, 2009, 2010, 2011). This suggests that foliar display limited shade-dependent reductions in *A*. *Picea* leaf mass per area increased with age, while leaf N concentration declined with age from 0.85% to 0.65% N between 2011 and 2006 cohorts. There was little difference in leaf N concentration with canopy position.

In FY 2012, an expanded field campaign will be conducted using thermal dissipation sensors to assess seasonal patterns of water use in *Picea* and *Larix* species. Specific effort will be focused on assessing the potential for seasonal water stress during drier periods as the water table depth declines. Photosynthetic response to temperature will also be further explored on the tree and shrub species by conducting measurements in situ and on detached branch material in the lab.

Hydrology and water chemistry – Depth-specific water samplers were installed in July 2011 to measure hydrological response variables (water flowpaths, runoff dynamics, and chemistry). Water level and chemistry data show when organic soils are saturated and allow measurement of chemical and isotopic composition of those waters to provide baseline information prior to deployment of operational chambers.

2.1.1f SPRUCE Publications, Presentations and Meetings

Task R1 has produced two new publications related to warming methods. Amthor et al. (2009) provide commentary on the appropriateness of experimental warming methods for experiments designed to inform future climatic changes, and Hanson et al. (2011) describe a new method for deep belowground warming combined with air warming that allows ecosystems to experience the 'correct' bottom to top temperature regime for an end-of-the-century climate. The enclosure being developed for application to SPRUCE is a much larger version of this concept for application in the Minnesota peatland.

Colleen Iversen organized and hosted a workshop at ORNL on October 7-8, 2010 entitled "Advancing minirhizotron use to examine ephemeral root dynamics in peatland and high C ecosystems". The workshop was funded by the New Phytologist Trust and the US DOE Office of Science. A manuscript on this effort has been accepted (Iversen et al. in press). SPRUCE project participants have also been contributing summary talks and posters at a variety of regional and national meetings to gather feedback from interested persons and solicit the interest of collaborators with skills and interests that go beyond that of the SPRUCE core group.

Table 2.1 Progress on Task R1 Deliverables (expressed in abbreviated form)

Date	Deliverable	Status
Oct 2009	Finalize the ORNL/USFS Interagency Agreement	Completed
Nov 2009	Initiated National Environmental Policy Act (NEPA) Process	Completed
May 2010	Establish and test operational aboveground 12-m prototype at ORNL	Completed
Summer 2010	Evaluate pre-treatment bog species characteristics	Completed
April 2010	NEPA Process Initiated October 2009, but was finally completed in June 2011	Approval: 10 June 2011
Summer 2010/2011	Collection of baseline understory plant data for the experimental locations on the S1 Bog	Completed
July 2010 to date	Initiate continuous environmental monitoring on ambient plots	Completed & continuing
Oct 2010	Finish boardwalk experimental engineering plans and diagrams	Completed
Jan 2011	Lease SPRUCE office and light laboratory space in Grand Rapids, MN	Completed
Apr to Oct 2011	Collect pretreatment biological observations	Completed & Ongoing
Summer 2010/11	Conduct allometric evaluations for *Picea*, *Larix* and ericaceous shrubs	Completed
Fall 2011	Install a full-scale belowground corral prototype	Completed
Summer/Fall 2011	Initiate CH_4/CO_2 flux measurements from the bog	Completed
Spring Summer 2012	Notwithstanding NEPA delays that slowed down infrastructure installations, site preparations including land clearing and road additions were completed in November 2011, and other plans are falling into place.	Underway

2.1.2 TASK R2 – WALKER BRANCH WATERSHED LONG-TERM MONITORING

Walker Branch Watershed (WBW) is a long-term forested watershed research site on the Oak Ridge Reservation. Hydrological, biogeochemical, and ecological studies in WBW have made important contributions to our understanding of effects of changes in atmospheric deposition and climate variability and change in this region. Objectives of the WBW long-term observations have been to:

1. Quantify responses of an eastern upland oak forest ecosystem to inter-annual and long-term variations in climate and atmospheric deposition of sulfur and N, and
2. Provide integrated, long-term data on climate, forest vegetation, soil chemistry, and hydrologic and chemical fluxes at the catchment scale to support other focused research projects on the Oak Ridge Reservation and elsewhere in the region.

A number of major deliverables associated with long-term observations of vegetation and hydrology of WBW been produced since October 2009. Kardol et al. (2010) reported on the importance of species, succession, and climate on forest composition and biomass accumulation using the long-term data set (1967–2006) of tree diameter growth and survival. Over the period of study, forest communities underwent successional change and substantially increased in biomass. Summer temperatures and drought were found to affect biomass accumulation in some species, and *Pinus echinata*, the dominant species in pine stands, decreased over time due to periodic outbreaks of pine bark beetle (*Dendroctonus frontalis*). The results of this study indicated that the direct effects of climate variability on eastern hardwood forests biomass accumulation and composition were small in comparison to changes resulting from natural succession or insect outbreaks.

Progress on the long-term measurements of climate and catchment-scale hydrology, atmospheric chemical deposition, and stream chemical outputs in Walker Branch Watershed is proceeding as planned. The 40-year record of hydrology and 20-year record of weekly stream water chemistry has been analyzed, and a manuscript summarizing these results is currently in revision at *Biogeochemistry*. Briefly, the hydrologic record demonstrated that Walker Branch Watershed has experienced a 20% decline in precipitation and a 34% decline in runoff over the past 20 years. The different flowpaths contributing to stream flow and runoff have also changed through time, as reflected by changes in the concentrations of geochemical solutes (Ca^{+2}, Mg^{+2}, and SO_4^{-2}) in stream water. Inter-annual variation in stream water NO_3^- concentrations were driven by antecedent hydrologic conditions (e.g., multi-year droughts), suggesting that climatic patterns can influence nitrate concentrations at shorter time scales in Walker Branch. Overall, this research highlights how climate change may alter both hydrologic and biogeochemical processes at a watershed scale, and emphasizes the necessity of long-term monitoring programs to quantify these changes.

Table 2.2 Progress on Task R2 Deliverables (expressed in abbreviated form):

Date	Deliverable	Status
April 2009 & 2010	Annual hydrology, atmospheric deposition, stream chemistry, and input-output budgets for calendar years 2009 and 2010	Completed
FY2010 Deliverable	Publication on the long-term trends in stream chemistry, input-output budgets and climatic variability.	Completed
Sep 2011	Publication on response of stream metabolism to climatic variability and projected changes based on a 6-year continuous record.	In progress

CLIMATE CHANGE FORCING TASKS

The TES SFA includes five tasks (F1-F5) related to climate change forcing. These tasks employ models, experiments, and landscape C measurements to advance our understanding of terrestrial C cycle processes. Task F1 provides an integrative analysis framework through modeling and model-data integration. Tasks F2-F5 address key research priorities necessary to resolve process 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. Task F5 resolves uncertainties in CO_2 fossil fuel emissions that will improve our ability to analyze terrestrial CO_2 forcing on climate.

2.1.3 TASK F1 – MECHANISTIC C CYCLE MODELING

This task focuses on the synthesis and integration of new experimental and observational knowledge to inform and improve terrestrial land surface and biogeochemistry models, with a particular emphasis on migration of knowledge into the Community Land Model (CLM) component of the Community Earth System Model (CESM). This integration effort has two primary goals: first, to improve the predictive skill of climate system models through improved fidelity of process representation in their land surface biophysics and biogeochemistry components; and second, to generate and test new hypotheses which address critical uncertainties in the terrestrial ecosystem components of climate system prediction.

This integration framework is designed and implemented to answer the research question: *What are the sign and magnitude of the global climate-C cycle forcing from land, and what are the process contributions to that overall forcing across a range of spatial and temporal scales?* We are pursuing answers to this question through investigations at multiple spatial scales: site scale model-data integration (Task F1a), regional and global land ecosystem modeling (Task F1b), and coupled Earth System Modeling (Task F1c).

2.1.3a Task F1a: Improve ecosystem process models with site-level observations and experimental data

Model Parameter Estimation – The Local Terrestrial Ecosystem Carbon (LoTEC) model has the same temporal resolution as CLM but lacks additional components of a land-surface model beyond C cycle dynamics, which makes it more efficient for use in optimization studies. Model-data fusion was performed using LoTEC for 10 sites with hourly data constraints of net ecosystem exchange (NEE) and latent heat flux (LE) in order to optimize 20 model parameters. We employed a genetic algorithm (GA) analysis to find the global optimum parameter set, and Markov Chain Monte Carlo (MCMC) analysis to explore parameter uncertainty when desired. In the NACP site synthesis project (http://nacp.ornl.gov/mast-dc/int_synth_site.shtml), LoTEC was consistently among the top performers among 22 participating models in this exercise (Schwalm et al. 2010; Dietze et al., in review) which demonstrates the utility of model-data fusion and suggests that errors or uncertainty in model parameters are at least as important as differences in model structure. We also used LoTEC to demonstrate the utility of different observation types and lengths to reduce uncertainty about key C cycle variables (Ricciuto et al. 2011).

CLM requires about 50 times more processing time per model year than LoTEC, presenting a new set of challenges for model-data fusion. MCMC, which requires on the order of 10^5 simulations, is prohibitively expensive; however we have applied the GA method successfully on a computer cluster to optimize with small numbers of parameters. Scaling up the model-data fusion algorithms in a way that is consistent with the CESM framework is challenging from a computer science standpoint, and we are currently collaborating with the National Center for Atmospheric Research (NCAR) and testing several candidate code designs.

Direct estimation of model parameters from physiological/leaf scale measurements is a complementary approach to whole ecosystem model-data optimization. For estimating parameters used within the Farquhar-von Caemmerer-Berry (FvCB) model, we developed a new approach that overcomes previous limitations and tested it with simulations, leaf gas exchange data, and chlorophyll fluorescence measurements of multiple species at the Missouri Ozark AmeriFlux site (Gu et al. 2011). We expanded this approach by developing and deploying LeafWeb, a SErvice-in-Exchange-for-Data-Sharing (SEEDS) web tool. This web tool allows investigators with leaf gas exchange data to contribute to a global database of biochemical, physiological, and biophysical properties of single leaves (Gu et al. 2011). This provides new information in support studies of plant function and is valuable new information for developing terrestrial C cycle model parameters.

Model Structural Enhancements – We used the methodology developed by Gu et al. (2003) and Gu et al. (2009) combined with the global Fluxnet data set (http://www.fluxdata.org) to identify biotic and abiotic controls on canopy photosynthetic phenology across biome and climate zones that can be used to improve the representation of seasonal C uptake dynamics (Figure 10).

CLM is currently integrated in the CESM, which has been designed and optimized to run global simulations. We developed PTCLM (PointCLM), a special single-point version of CLM that can be run quickly and efficiently, and is consistent with the version of CLM in CESM. This code was successfully migrated to the main code trunk of CLM and was released to the wider community in June 2011. PTCLM is a key technical component of the TES SFA, connecting experimental and site-level observations to the global Earth system. Versions of PTCLM are being used to address science questions in the SPRUCE and PiTS projects (see Sections 2.1.1 and 2.1.4, respectively). Additional details of these site-level modeling activities appear in those sections of the document.

We applied PTCLM at 15 flux tower sites, in coordination with the NACP site-level synthesis activity. Initial simulations showed significant bias in the model predictions of the diurnal cycle of photosynthesis, and this was traced to the model representation of plant N uptake and allocation to new growth, low-productivity bias at fire prone sites, and overestimation of photosynthesis at cold sites in the fall and spring, when temperatures are at or below freezing. A description of the model improvements from site-level investigations is currently in preparation, with a manuscript to be submitted in March 2012.

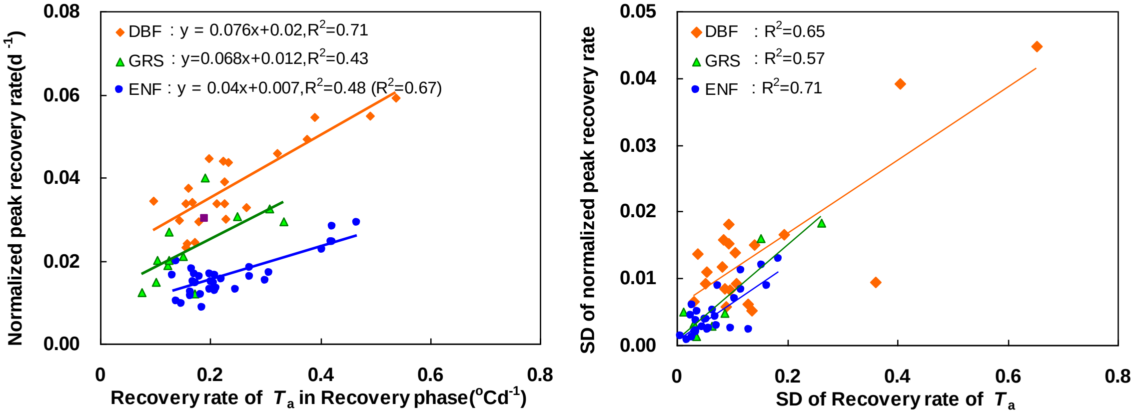

Figure 10. Relationship of the normalized peak recovery rate (PRR) of canopy photosynthesis (left panel) and its standard deviation (SD, right panel) with the rate of increase in daily mean air temperature (Ta) in spring and its standard deviation. DBF: deciduous broad-leaf forest; ENF: evergreen needle-leaf forest; GRS: Grassland.

2.1.3b Task F1b: Regional and Global Land Ecosystem Modeling

We developed and applied methods to compare the results from the Terrestrial Biosphere Models (TBMs) collected as part of the North American Carbon Program (NACP) regional and continental interim-synthesis activities (Huntzinger et al., accepted; http://nacp.ornl.gov/mast-dc/int_synth_contreg.shtml). This project synthesizes and compares simulations of 19 TBMs, including CLM, to assess current understanding of the terrestrial C cycle in North America. Significant disagreement among the models is driven by a combination of factors. This disagreement highlights the need for further analysis through the use of formal model runs and a detailed model simulation protocol in order to isolate the influences of model formulation, structure, and assumptions on flux estimations. We are involved with the NACP Multi-scale Terrestrial Model-data Intercomparison Project (MsTMIP) that addresses these issues.

We carried out an inventory-based analysis of the North American C budget (Hayes et al., accepted). The strongest sinks for atmospheric CO_2 were associated with agriculture in the Midwest region and with areas of commercial forestry in the Northwest and Southeast US. The effect of the lateral transfer of harvested forest and crop products was manifest as source areas in US states with high populations of humans and/or livestock. An additional source was contributed by the tropical forest areas of Mexico, which have been experiencing significant rates of land cover change in recent decades. The inventory-based total NEE estimate of -327 TgC yr^{-1} for North America is smaller than the mean estimate of the forward models included here and much smaller that the mean of seven recent inversion analyses. Progress in refining the continental scale NEE will come in part from better integration across the approaches such that inventory data is used in calibration and validation of forward models, which will provide the initial surface flux estimates for inversions analyses.

We compared monthly gross primary production (GPP) simulated by the latest half-degree resolution CLM model simulations with satellite estimates of GPP from the MODIS GPP data set on a 10-yr period, January 2000–December 2009 (Mao et al., submitted). For the long-term annual and seasonal means, major GPP patterns are clearly demonstrated by both products, but there are systematic overestimates or underestimates of GPP for CLM for some regions. Comparisons of the phase of the averaged seasonal cycle show that CLM4 (Mao et al. 2012) has longer C absorption period than MODIS for most plant functional types. We have also derived model-predicted values for the Normalized Difference Vegetation Index (NDVI) for CLM, and compared to remote sensing observations from the MODIS instrument (Mao et al., in press).

Despite the importance of phosphorus (P) as a limiting nutrient in terrestrial ecosystems, our understanding of terrestrial P dynamics and ability to model P cycling are hampered by the lack of consistent measurements of soil P. We developed a database of over 180 sites to investigate the relationship between distributions of different forms of P and the stages of soil development (Yang and Post, 2011). Our analysis of the database showed that organic P (Po) is decoupled from C and N in highly weathered soils with larger variations of N:Po ratio and higher mean value of N:Po ratio, compared to slightly weathered and intermediately weathered soils. We combined this database with several global spatial databases (e.g. lithology, rock P content, soil orders) and insights on soil P processes to develop a map of total soil P and the distribution among mineral bound, labile, organic, occluded, and secondary P forms in soils globally (Yang et al., submitted). This global soil P map will be used in a CLM-CNP model under development that includes P as a limiting element.

2.1.3c Task F1c: Coupled Earth System Modeling

We are able to estimate the effects of single forcing factors and the interactions among multiple forcing factors through carefully constructed suites of CLM simulations. Global-scale simulations are conducted using CLM forced by surface weather data sets (offline simulations), and also by using CLM as a component of the fully coupled CESM. In 2011 we completed our first full set of offline simulations, and are now using the results in a series of model-data investigations. As a first step, we investigated how climate, rising atmospheric CO_2 concentration, increasing anthropogenic N deposition and land use change influenced continental river flow over the period 1948–2004 using CLM coupled to RTM, a global river routing scheme (Shi et al. 2011). Our simulations suggest that to better understand the trends of river flow, it is not only necessary to take into account the climate, but also to consider atmospheric CO_2, C-N interactions, and land use change.

We have also performed a series of fully coupled climate-biogeochemistry simulations using CESM1, following the simulation protocols established for contributions to the upcoming IPCC Fifth Assessment Report. These simulations explore the influence of historical and potential future fossil fuel emissions, anthropogenic N deposition, and land use and land cover change on the evolution of greenhouse gas concentrations and associated climate change over the period 1850-2100. A manuscript describing these results is in preparation for submission in April 2012. We will use these simulations as a baseline against which to evaluate the influence of new process representations emerging from the TES SFA. Our particular focus will be on quantifying the effects of new terrestrial ecosystem process representations on global scale climate-ecosystem feedbacks.

Table 2.3 Progress on Task F1 Deliverables (expressed in abbreviated form):

Date	Deliverable	Status
F1a – Site		
Oct 2009	Gap-filled input forcing data sets for conducting simulations at AmeriFlux and FLUXNET sites completed and archived with ORNL DAAC.	Completed
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.	Completed with LoTEC, underway with CLM
Sep 2010	Documentation of site-scale data assimilation framework for continual	Completed

	updating and analysis.	
Mar 2011	Quantify parameter uncertainty when considering various data streams and constraints with eddy covariance data (CO_2, H_2O, sensible heat) and biometric data. Submit manuscript and archive model simulations with ORNL DAAC.	Completed
Sep 2011	Evaluation of CLM performance across NACP site-level synthesis flux tower sites completed, submit manuscript and archive model simulations with ORNL DAAC.	Completed
F1b – Regional		
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.	Completed
Mar 2010	Spatially uniform ecosystem initial conditions for use in future projections with forward ecosystem models.	Completed
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.	Completed
Dec 2010	Submit manuscript comparing CLM model simulations to observation-based measurements including Carbon Tracker and other inversion model estimates of net terrestrial C exchange.	Completed
Mar 2011	Submit manuscript employing fingerprint analysis of factors influencing historical C fluxes using ITCM and CLM-CN with MODIS based observations.	Completed
Mar 2012	Implement standard procedure for archival of regional and global LoTEC and CLM-CN simulations and model forcing data.	Underway
F1c – Coupled		
Oct 2009	Operational capacity to carry out offline and coupled sequence of simulations with CCSM.	Completed
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-C cycle feedbacks, using the existing structure, process representations, and parameterizations of CLM-CN.	Completed
Mar 2012	Submit manuscript investigating the influence on regional and global scale climate-C cycle feedbacks of new parameterizations emerging from site-level data assimilation of eddy covariance observations.	Underway
Sep 2012	Submit manuscript investigating the influence on climate-C cycle feedbacks of new parameterizations emerging from regional-scale data assimilation and fingerprint analyses.	Underway

2.1.4 TASK F2 – PARTITIONING IN TREES AND SOIL (PITS)

The Partitioning in Trees and Soil (PiTS) task was established with the objective of improving the C partitioning routines in existing ecosystem models by exploring mechanistic model representations of partitioning tested against field observations and manipulations. The approach we are pursuing is to employ relatively short-term field manipulations to reveal specific responses that can lead to improvements in model representation of C partitioning processes. A key feature of this task is the close interaction between modelers and empiricists in the planning of the manipulations and the analysis of results. Our objective has been to measure how C partitioning and flux within plants and into soil varies with short-term changes in gross primary production (GPP), and to use results to test and potentially modify partitioning routines in ecosystem models. Three research sites were selected for this task (PiTS-1, -2, -3), and projects are in various stages of completion. Fieldwork and data collection at PiTS-1 has been completed and a manuscript describing results has been published (Warren et al. in press); fieldwork at PiTS-2 and -3 will continue through FY12. Concurrent modeling activities utilizing data collected from the field studies are ongoing.

The first of three research sites (PiTS-1 – shading in loblolly pine) was located on the University of Tennessee Forest Resources Research and Education Center (FRREC) in Oak Ridge, TN. The FRREC maintains a website highlighting the PiTS project (http://forestry.tennessee.edu/pitsresearch.htm). The PiTS-1 trees were enclosed in a temporary plastic chamber and labeled with a pulse of ^{13}C-enriched CO_2

on September 1, 2010 over a 2-h period. Subsequently, trees were enclosed in shade cloth to produce light shade (LS) and heavy shade (HS) treatments in order to alter GPP and the C balance of the canopy. The impacts of shading on photosynthesis, plant water potential, sap flow, basal area growth, root growth, and soil CO_2 efflux rate were assessed for each tree over a 3-week period. The progression of the ^{13}C label was concurrently tracked from the atmosphere through foliage, phloem, roots, and surface soil CO_2 efflux. The HS treatment significantly reduced C uptake, sap flow, stem growth and fine root standing crop, and resulted in greater residual soil water content to 1 m depth. Although there were apparent reductions in new C flux belowground, the heavy shade treatment did not noticeably reduce the magnitude of belowground autotrophic and heterotrophic respiration based on surface soil CO_2 efflux rate (CER), which was overwhelmingly driven by soil temperature and moisture. The ^{13}C label was immediately detected in foliage on the day the label was applied (half-life = 0.5 d), progressed through phloem by day 2 (half-life = 4.7 d), roots by day 2-4, and subsequently was evident as respiratory release from soil, which peaked between days 3-6. The $\delta^{13}C$ of soil CO_2 efflux was strongly correlated with phloem $\delta^{13}C$ on the previous day, or two days earlier (Figure 11). We succeeded in reducing C uptake with the shading treatment, which also reduced sap flow, stem growth, and resulted in enhanced root mortality. We also succeeded in incorporating the ^{13}C label into the trees, which allowed us to track C movement from the canopy to the bole to the roots, and finally to soil CO_2 efflux. A manuscript describing the results has been published online by *Tree Physiology* for an upcoming special issue on C allocation. The data collected are currently being used to test a point version of the Community Land Model (CLM-CN), a land surface biogeochemical model that incorporates autotrophic and heterotrophic C-N interactions. The model will be parameterized to the existing pine stand based on measured or estimated values of biomass pools, foliar physiology, soil characteristics, and site environmental conditions. The model will then be modified by inclusion of a ^{13}C-partitioning module that will make use of our labeling results. Solar radiation will be reduced in the model to simulate shade treatments manipulations and resultant changes in soil moisture, sap flow, C uptake and growth will be validated against our measured data, and provide feedback for assessment of structural performance of the model.

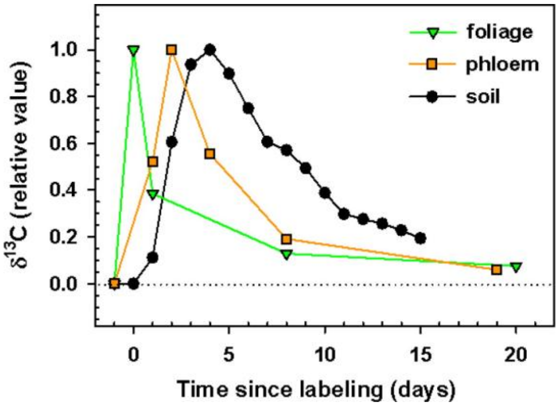

Figure 11. Mean relative concentration of ^{13}C label in loblolly pine foliage, phloem tissue and soil CO_2 efflux in the PiTS 1 experiment. Results were valuable for providing information about the timing of C transport through the plant-soil system. The shading treatment reduced GPP, but not the timing of C flow through the system.

A second research site (PiTS-2 – sweetgum girdling) has been established that takes advantage of the residual ^{13}C label in soils within previously CO_2-enriched plots (ECO_2) of the legacy ORNL FACE experiment. The $\delta^{13}C$ signal will be used to facilitate measurement and modeling of the impact that variation in belowground C partitioning has on decomposition of soil organic matter (SOM). Plant and soil samples from ECO_2 plots confirm that the soil remains relatively ^{13}C depleted after canopy fumigation with a depleted source of CO_2, but new leaves (and therefore new plant inputs) have little remaining ^{13}C signal from the FACE exposure. In July 2011 belowground C partitioning was manipulated by girdling the stems within one half of each 25-m diameter, historical FACE plot (n = 2 ECO_2 and 2 ambient CO_2 plots) and separating them by a plastic-lined trench backfilled with soil. Girdling physically blocks phloem partitioning of new C into the root system, which enables us to (1) quantify the effect of new C inputs from roots on nutrient cycling and SOM decomposition, and (2) quantify the size of belowground C storage pools used for root production. Root production is being monitored with the existing minirhizotron tubes (which have equilibrated with the surrounding soil over a period of 15 years), in-growth cores are used to assess the ^{13}C of newly produced roots, soil cores are extracted periodically to assess the ^{13}C of roots and SOM, and nutrient availability is sampled with ion-exchange resins. Soil CO_2 efflux is monitored manually or with an automated IRGA system, and the $^{13}CO_2$ label in soil efflux is monitored in ECO_2 plots by Cavity Ring-Down Spectroscopy. We are also sampling the soil for microbial community composition, and monitoring soil water content and site meteorological conditions. These data will be used to inform belowground processes in a point version of CLM-CN that has already been parameterized for the ORNL FACE site.

The final research site (PiTS-3 – dogwood shading) is currently being established at the FRREC in a dogwood stand planted in 1996. This stand has previously supported various genetics and cultivation studies by the University of Tennessee; the trees are mature (~ 5 m) and well spaced (3.7 m × 3.7 m). This study improves upon PiTS-1 by physically isolating the belowground system using trenches, and spatially isolating treatments by distance. In this study, we are interested in soil C turnover rates, storage, roots and mycorrhizae. As such, we are heavily instrumenting this site, with minirhizotron tubes, soil respiration chambers, soil moisture sensors and sap flow sensors. In addition, cylindrical mesh chambers (20 cm d × 40 cm h) that exclude hyphae or roots (with aperture of 0 or 61 μm, respectively), and controls were installed near each tree to separate partitioning of new C among belowground components. We will subsequently manipulate GPP by shading and monitor changes in C flux through the system using seasonal ^{13}C labeling events. Plant C uptake, water use, growth and respiration will be quantified. The fate of new C as plant biomass, litter, mycorrhizal transfer or respiratory release will be assessed and the results used in a modeling framework.

Table 2.4 Progress on Task F2 Deliverables and Deliverables continuing through FY2013.

Date	Deliverable	Status
Mar 2010	Construct and instrument the first phase of the PiTS Facility	Completed
Sep 2010	Conduct labeling event and field observations for PiTS-1 (loblolly shading).	Completed
Jun 2011	Construct and instrument PiTS-2 (sweetgum girdling).	Completed
Aug 2011	Complete data analysis and manuscript preparation for PiTS-1.	Completed
Oct 2011	Initial simulations of PiTS-1 to add capability in CLM-CN to specify atmospheric ^{13}C and radiation reduction routine. PiTS-1 manuscript submission.	Completed
June 2012	Submit data to CDIAC data archive for public release concurrent with publication of paper.	Planned
Apr 2012	Construct and instrument PiTS-3 (dogwood shading).	Planned
May 2012	Simulations of PiTS-1 site using CLM-CN completed using observed driver meteorology and ^{13}C data. Construct model framework for simulating girdling in PiTS 2.	Planned
June 2012	Hire postdoctoral associate to lead partitioning modeling activities	Ongoing
Dec 2012	Finalize data analysis and manuscript preparation for the PiTS field studies. Complete manuscript detailing CLM-CN modeling for PiTS 1. Complete PiTS 2 simulations and begin PiTS 3 simulations.	Planned
Sep 2013	Final manuscripts from all PiTS studies submitted for publication.	Planned
Dec 2012 & 2013	Submit data to CDIAC data archive for public release concurrent with publication of paper.	Planned

With the completion of the PITS activities in FY2013 we plan to transition mechanistic process work to another understudied area of potential model sensitivity – root functional dynamics in context of environmental, physical and chemical conditions. Those plans are described below in Section 3.4.

2.1.5 TASK F3 – REPRESENTING SOIL C IN TERRESTRIAL C CYCLE MODELS

2.1.5a 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 (EBIS-AmeriFlux)

Task F3a 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.

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. Experimental changes in ^{14}C signatures from litter additions were obvious in the surface horizons after 2 years of manipulation, but we have completed 4 applications of enriched litter) to provide us with the strongest possible signal for quantifying transfer rates to the mineral soils.

As was the case in EBIS-Oak Ridge, litter C is easily transferred to the organic horizons. Litter to mineral soil transport does take place (Fröberg et al. 2009), but little C remains after an annual cycle due to microbial consumption of the new labile C forms. Coarse texture soils at the University of Michigan Biological Station (UMBS) appear to allow deeper transport and net retention of C than at the other sites. Cold conditions enhance the accumulation of C within horizons, but extensive earthworm populations in Missouri may disrupt this pattern. Humus to soil C transfer is not as obvious, but humus decomposes more slowly than fresh leaf litter and our capacity to observe this transfer is limited by the lower level of ^{14}C enrichment of this material.

McFarlane et al. (accepted) interpreted bulk and soil fraction C turnover times from the time-zero ^{14}C data in the context of changing atmospheric through time for all EBIS-AmeriFlux plots located across the eastern United States. Total soil C stocks ranged from 55 ± 4 to 229 ± 42 Mg C ha-1 and were lowest at MI-Coarse and MO-OZ and highest at MI-Fine and NH-BF. Differences in climate only partly explained differences in SOM ^{14}C and turnover times, which and were 75 to 260 yr for free-light fractions, 70 to 625 yr for occluded-light fractions, and 90 to 480 yr for dense fractions. The shortest turnover times were observed at the warmest site, but the longest turnover times were found at the northeastern sites (NH-BF and MA-HF), rather than the coldest sites (MI-Coarse and MI-Fine). It appears that localized soil factors within eastern US temperate broadleaf forests may be at least as important in determining soil C stock and turnover as climate.

New EBIS Publications from Oak Ridge Efforts – Using EBIS-Oak Ridge manipulation data Kramer et al. (2010) demonstrated that forms of C leached from fresh forest leaf litterfall were not a detectable C source for the underlying mineral soil microbes. Recent leaf-litter C was determined to have no measurable effect on microbial respiration and biomarkers in the underlying mineral soil. After 4 years, less than ~6% of the microbial C was estimated to be derived from the added 1 to 4 year old surface litter. The results of this study provided quantitative evidence that root-derived C is the major (>60%) source of C for microbes in temperate deciduous forest soils.

Data from the Enriched Background Isotope Study (EBIS) were also used to improve functional mechanisms within the classic C cycling model – DayCent (Parton et al. 2010). EBIS field studies quantified the fate and transport of uniquely enriched C isotopes in experimentally manipulated leaf litterfall for soils of an upland oak forest of eastern Tennessee. The experiment revealed important process not currently included in forest C cycle models. Major revisions to the DayCent model included (1) adding a surface organic pool, (2) incorporating a detailed root growth model, and (3) the inclusion of plant phenological growth patterns. The next-generation model is named ForCent. Comparisons of EBIS data to ForCent model outputs demonstrated the utility of the enhanced model. Application of ForCent improvements should enhance soil C cycle models for forests within land surface models may provide better global C cycle projections.

Tipping et al. (in press) used the DyDOC model to simulate the soil C cycle of a deciduous forest at the Oak Ridge Reservation using extensive data from the Enriched Background Isotope Study (EBIS), The model was first fitted to hydrological data, then observed pools and fluxes of C and ^{14}C data were used to fit parameters describing metabolic transformations of soil organic matter (SOM) components and the transport and sorption of dissolved organic matter (DOM). According to the parameterized model, SOM turnover within the thin O-horizon rapidly produces DOM (46 gC m^{-2} y^{-1}), which is predominantly hydrophobic. This DOM is nearly all adsorbed in the A- and B-horizons, and while most is mineralized relatively quickly, 11 gC m^{-2} y^{-1} undergoes a “maturing” reaction, producing mineral-associated stable SOM pools with mean residence times of 100-200 years. Only a small flux (~ 1 gC m^{-2} y^{-1}) of hydrophilic DOM leaves the B-horizon. The SOM not associated with mineral matter is assumed to be derived from root litter, and turns over quite quickly (mean residence time 20-30 years).

2.1.5b Task F3b: Modeling soil C turnover in eastern forests

Garten et al. (2011) reported on a study designed to compare the turnover time of labile soil C (C), in relation to temperature and soil texture, in several forest ecosystems that are representative of large areas of North America. Carbon and N (N) stocks, and C: N ratios, were measured in the forest floor, mineral soil, and two mineral soil fractions (particulate and mineral-associated organic matter, POM and MOM, respectively) at five AmeriFlux sites along a latitudinal gradient in the eastern United States. The five sites were: University of Michigan Biological Station, MI; Harvard Forest, MA; University of Missouri’s Baskett Wildlife Research and Education Area, MO; US Department of Energy’s Oak Ridge Reservation, TN; US Forest Service’s Bartlett Experimental Forest, NH. Sampling at four sites was replicated over two consecutive years.

With one exception, forest floor and mineral soil C stocks increased from warm, southern sites (with fine-textured soils) to cool, northern sites (with more coarse-textured soils). The exception was a northern site, with less than 10% silt-clay content, that had a soil organic C stock similar to the southern sites. A two-compartment model was used to calculate the turnover time of labile soil organic C (MRTU) and the annual transfer of labile C to stable C (k2) at each site. Moving from south to north, MRTU increased from approximately 5 to 14 years. ^{13}C enrichment factors (ε), that described the rate of change in δ^{13}C through the soil profile, were associated with soil C turnover times. Consistent with its role in stabilization of soil organic C, silt-clay content was positively correlated ($r = 0.91$; $P \leq 0.001$) with parameter k2. Mean annual temperature (MAT, °C) was related to latitudinal differences in the storage and turnover of soil C, but soil texture superseded temperature when there was too little silt and clay to stabilize labile soil C and protect it from decomposition. Each site had a relatively high proportion of labile soil C (nearly 50% to a depth of 20 cm). Depending on unknown temperature sensitivities, large labile pools of forest soil C are at risk of decomposition in a warming climate, and losses could be disproportionately higher from coarse textured forest soils.

Table 2.5 Progress on Task F3 Deliverables (expressed in abbreviated form):

Date	Deliverable	Status
Oct 2009	Element and isotopic analysis of FY2009 data	Completed
Nov/Dec 2010	2-year sampling of C pools for the Task F3a leaf and humus litter manipulations	Completed
Mar 2010	Post-sample processing of all field collected sample.	Completed
Apr 2010	Manuscript: comparative soil C dynamics at five AmeriFlux study sites including estimation of soil C turnover times.	Completed/ Accepted
Jun 2010	Bulk-^{14}C analyses for all sites, plots, and soil pools.	Completed
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.	Completed
Sep 2010	Manuscript: soil C cycling and vertical mixing by worms.	Combined with McFarlane et al.
Nov/Dec 2010	3-year sampling of C pools for the Task F3a leaf and humus litter manipulations.	Completed
Mar 2011	Complete post-sample processing of all field collected samples.	Completed
Jun 2011	Complete bulk-^{14}C analyses for all sites, plots, and soil pools.	Completed
Dec 2011	Complete final sampling of all EBIS-AmeriFlux plots	Completed
As accomplished	Submit data to CDIAC data archive for public release concurrent with publication of paper.	Ongoing

Field and laboratory activities associated with Task F3a will be completed in FY2012 and will only require manuscript preparation and handling time in the next 3-year cycle. Task F3b is complete and requires no further support.

2.1.6 TASK F4 – TERRESTRIAL IMPACTS AND FEEDBACKS OF CLIMATE VARIABILITY, EVENTS AND DISTURBANCES

Task F4 focuses on climate variability and episodic events as related to ecosystem C and water cycles, energy balance and vegetation dynamics. It has the view that the variances (climate variability) and tails (extreme events) of the probability density functions of climate variables are as important as the means for ecosystem responses to climate change. Its goal is to enable mechanistic representation of impacts and feedbacks of a broad spectrum of climate conditions in Earth system diagnosis and prediction. The original plan for Task F4 contained three subtasks: (a) strategic flux measurements at the Missouri Ozark Flux (MOFLUX) site, (b) network synthesis and extreme event case studies, and (c) rapid, collaborative response to developing extreme events.

During the initial 3-year TES SFA performance period, Task F4 contributed 15 peer-reviewed papers and 2 book chapters with 1 manuscript currently in review.

2.1.6a Task F4a.1: MOFLUX site operations

The MOFLUX data acquisition systems include EC instrumentation, meteorological and radiation sensors, vertical profiles of CO_2, H_2O, temperature and humidity, soil respiration systems, and vertical profiles of soil temperature and water content. These measurements are processed and quality-checked daily with the MOFLUX Automated Daily Data Processing and Reporting System (MADDPRS). The continuous data streams are complemented by scheduled measurements of leaf biochemistry and physiology, predawn leaf water potential, litter collection/weighing, dendrometer band measurements, and coarse woody debris collection/weighing. Two major unforeseen climate events and the ORNL cyber attack have influenced activities.

During the winter of 2009-2010 freezing of accumulated water in one of the flux tower legs burst the aluminum tube structure, suspending activities that required tower ascent until repair was completed by early June. Subsequently, in winter tower leg bases are now heated with wrapped, thermostatically-controlled heat tape covered with fiberglass insulation. In late July 2010, an unusually strong lightning strike destroyed a sonic anemometer and some temperature and humidity probes. The impact of this incident on flux data streams was minimized by the presence of a parallel EC system that was not affected by the strike. A new boom-mounted EC flux system (Campbell Scientific CSAT sonic anemometer and LI-COR LI-7200 closed path CO_2/H_2O analyzer) was installed before the growing season of 2011. A new ground station also was installed with soil moisture, temperature and heat flux instrumentation. After parallel operation of the older and new EC flux systems for some time for comparison, the older system will be moved to the ground station. The April 2011 ORNL cyber attack and new policies subsequently taken by ORNL for cyber security disrupted MADDPRS, forcing manual data processing until MADDPRS was restored in mid-June.

2.1.6b Task F4a.2 – MOFLUX Science

Interannual variability in MOFLUX C and water budgets – A comprehensive analysis on the interannual variability and climate controls of MOFLUX forest ecosystem C and water budgets is now under way. Preliminary results indicated that the MOFLUX forest ecosystem is a consistent C sink (Table 2.6). However, the interannual variability is large and mostly controlled by water availability. The mean growing season predawn leaf water potential at the site is found to be an excellent predictor of annual C budget and in particular, the summer C budget and the C and water budgets are closely coupled.

A word of caution, a new advance in the EC theory made at the MOFLUX site (see the next section) indicates that previous flux measurements of trace gases and water vapor need to be re-processed by nearly all flux sites to avoid substantial biases in estimated C and water budgets. At the MOFLUX site, we have already completed the reprocessing of flux data obtained since its establishment in 2004 using the new theory. However, we have not had time to re-compute the annual budget numbers that we expect will be quite different from those in Table 2.6.

Table 2.6 Preliminary estimates of annual NEE of CO_2 (negative uptake) and evapotranspiration at MOFLUX.

Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**Mean**
Annual NEE of CO_2 (gC)	-541	-347	-462	-608	-603	-482	-507±40
Annual ET (mm)	699	654	586	735	713	801	698±30

Advances in the eddy covariance theory for flux measurements – At the MOFLUX site, we have periodically reexamined the foundation of the EC theory, taking advantage of unique measurements available at the site, to ensure the assumptions of the EC technique are valid and the obtained fluxes and budgets of C and water are accurate. We have recently investigated the bias errors caused by applying the steady-state theory of Webb, Pearman and Leuning (WPL 1980), theory that is widely used to calculate the eddy fluxes of water vapor, CO_2 and other trace gases. This investigation led to several potentially very significant advances in the eddy covariance theory and its application in flux measurements of trace gases (Gu et al. 2012). We reformulated the eddy covariance concept to provide a general and internally consistent theory for application to both open- and closed-path technologies. The conventional eddy covariance theory was a special case of the reformulated theory. The reformulated theory suggests a new direction for next generation of eddy covariance technologies that would employ N_2 or Ar gas as a tracer to better resolve flux processes over target surfaces. The following specific recommendations were made to the global flux community: 1) Flux sites should stop assuming no vertical flux of dry air and make corrections due to this assumption, 2) Past data sets should be reprocessed and 3) an adequate system for measuring vertical changes in storage must be an integral part of the eddy covariance instrumentation at flux sites.

Canopy physiology and phenology studies – Canopy physiology and phenology studies are an integral part of the MOFLUX research agenda. The integration of process-level physiology and landscape flux measurements at a biome ecotone with diverse climate conditions (e.g. droughts of different intensities, late season freezes) enables MOFLUX to inform large scale land surface models such as CLM effectively. The measurements so far have yielded some of the most important ancillary data sets for interpreting observed ecosystem-level fluxes and for applications in modeling and data assimilation. A/Ci measurements at MOFLUX were crucial in the development of an improved methodology for estimating fundamental photosynthetic parameters for C cycle models (Gu et al. 2011) and for the launch of the automated leaf analysis website leafweb.ornl.gov. LeafWeb has been serving users from different countries since 2010. Additionally, these leaf level measurements have allowed the estimation of mesophyll conductance for multiple species at different depth of the canopy. A model of mesophyll conductance has been developed. We are now evaluating the performance of the mesophyll conductance model in FAPIS with the intention of transferring the mesophyll conductance model to CLM-CN once it is tested.

In 2010, abundant growing season precipitation kept predawn leaf water potentials sufficiently high that canopy function was not subjected to appreciable drought influence. Daily PAR flux averaged on a weekly basis was quite variable, but did not show any directed trend toward decline until early September. Leaf necrotic fraction increased gradually during growing season, before spiking upward in September. Loss of leaf area to necrosis, especially late in the season, was greatest in the better-illuminated, upper-crown position. Seasonal analysis of the light response of photosynthesis (Figure 12) indicated peak efficiency in utilization of high light levels in early summer and declines thereafter.

These data support the existence of an early-summer peak in photosynthetic capacity as indicated by V_{cmax} and J_{max} data obtained concurrently (data not shown). Individual leaf images and WinFOLIA imagery analysis illustrate the relationship between leaf necrosis and photosynthetic rate at high light. Leaf photosynthetic capacity derived from analysis of A-Ci curves peaked in mid- to late-May and declined gradually thereafter. By late August, V_{cmax25} and J_{max25} had declined to about 50% of peak levels. CO_2 flux rates peaked in late May and early June, thereafter declining steadily through late September. Based on parameter dynamics, it appeared that there was co-limitation of CO_2 flux rates by multiple sources. Observed reductions in CO_2 flux rates were most closely associated with declining biochemically-based photosynthetic capacity through late August. Subsequently, steep declines in CO_2 flux rates appeared to be strongly co-limited by leaf biochemistry, leaf necrosis associated with seasonal senescence, declining photosynthetic energy supply and reduced LAI.

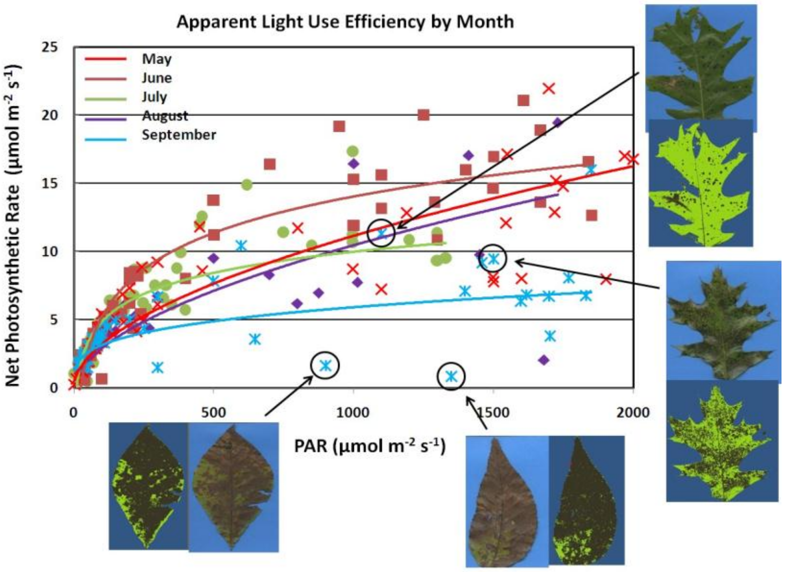

Figure 12. Response of net photosynthesis to PAR at monthly intervals during the 2010-growing season. Data fitted by exponential curve functions. Circled data points illustrate the association of particular net photosynthetic rates with level of leaf necrosis as illustrated by scanned leaves. Adjacent image emphasizes the necrotic area as determined by win Folia Pro software. Side leaves are black oak; bottom leaflets are shagbark hickory.

Color analysis of digital images taken repeatedly from the flux tower captured summer 2010 dominance of the chlorophyll-related green color of the canopy as well as a red burst, declining greenness and increasing blue dominance as the canopy transitioned to a winter condition. This pattern was followed by reverses in these parameters in spring 2011, as well as an additional red burst, most likely associated with transient early accumulation of anthocyanins in developing shoots. As was expected, color analysis revealed a closer correspondence between green color channel values and MODIS 250 m-scale NDVI than EVI data, and a close relationship with LAI. Seasonal values of site-measured LAI appeared more closely related to NDVI than EVI, at least in proportional changes through time.

Dark respiration (DR) measurements were made on leaves covered overnight in opaque sleeves. Overall rates of DR average range from 0-10 percent of peak rates of net photosynthesis. DR increased across species in the order sugar maple<eastern red cedar<white oak<shagbark hickory<black oak. DR peaked in mid season (mid-July), declining thereafter. The trends in DR were related to trends in leaf temperature (not shown) through mid-season, but DR declined proportionally more from mid- to late-season than did leaf temperature (not shown). DR tended to increase with height in the canopy, as would be expected given the greater leaf mass per unit area in upper canopy leaves previous seen in MOFLUX work (not shown). As expected, DR tended to increase with leaf temperature.

MOFLUX support to network synthesis and other independent research projects – The MOFLUX site is strategically located in an ecologically important transitional zone between the central hardwood region and the central grassland region of the US. Because of its strategic location, the diverse data sets collected at the site have been used essentially in every major multi-site/regional synthesis efforts conducted by researchers in the flux community and in the North American Carbon Program (NACP) in the last couple of years. Since October 2009, we have actively contributed to at least eight multi-site/regional synthesis efforts that have already resulted in peer-reviewed publications (see also the list of papers for Task F4). These synthesis efforts covered a variety of topics, including continental-scale gross primary production (Xiao et al. 2010), net ecosystem exchange of CO_2 (Xiao et al. 2011), model-data intercomparisons (Schwalm et al. 2010), climate controls on net terrestrial C exchanges on global scales (Yi et al. 2010), network-wide nighttime ecosystem respiration (van Gorsel et al. 2009), land surface albedo products (Román et al. 2009) and their relationships to leaf N content (Hollinger et al. 2010), and effects of forests on land surface temperature (Lee et al. 2011). Over the years, multiple research teams have conducted complementary but separately funded studies at the MOFLUX site to take advantage of the facility and data sets we provide. Currently, three independent research projects are operating at the MOFLUX site: 1) high-precision CO_2 concentration measurements led by Dr. Ken Davis from Pennsylvania State University, 2) VOC measurements led by Dr. Alex Guenther of NCAR and Dr. Mark Potosnak of DePaul University, and 3) soil moisture measurements by the project of Cosmic-ray Soil Moisture Observing System (COSMOS, http://cosmos.hwr.arizona.edu. In addition, Dr. Andrew Richardson of Harvard University has committed to mounting one of his Phenocam Webcams on the MOFLUX tower in the immediate future.

Forest ecosystem water use efficiency – Growing-season droughts often occur at the MOFLUX site. We have used drought events that have occurred at the site to study how environmental controls affect ecosystem-scale water use efficiency (Yang et al. 2010). We found that in general, water use efficiency scaled with atmospheric saturation deficit in a nonlinear way as predicted by the stomatal optimization theory but was linearly related to soil water potential and diffuse radiation ratio. The variations in water use efficiency were explained more by atmospheric saturation deficit than by soil water potential or diffuse radiation ratio. The relationship between water use efficacy and any single controlling factor was subject to influence of the others. For example, we observed an opposite response of water use efficiency to soil water potential between low and high atmospheric saturation deficits, suggesting a breakdown of stomatal optimality under severe environmental stresses and a shift from optimal stomatal regulation to nonstomatal regulation at leaf scale.

2.1.6 Task F4b – Extreme event studies

JGR-Biogeosciences Special Section on Biogeosciences of Extreme Weather and Climate Events – 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 such as droughts, heat waves, hurricanes, ice storms, unseasonable freezes and wind storms and disturbance events such as fires and insect outbreaks. L. Gu, in collaboration with Altaf Arain of McMaster University, guest-edited a special section in *JGR-Biogeosciences* on the topic of Biogeosciences of Extreme Weather and Climate Events. The objective of the special section was to review the latest knowledge on biospheric responses and feedbacks to extreme events and help improve the sensitivity of physical, biological, societal, and ecological processes in the next generation of climate and integrated assessment models. The special section covered extreme events ranging from ice storms to droughts with spatial scales from local to regional and can be viewed in http://www.agu.org/journals/jg/special_sections.shtml.

Sudden C shifts between pools and vegetation recovery after large-scale extreme events – A massive 2008 China ice storm was used as a case study to investigate how large-scale extreme events in temperate regions affect terrestrial C cycles and vegetation recovery after extreme events. We provided guidance to Chinese colleagues on ground-based surveys while conducting remote sensing-based assessments of the ice storm damage on forests as well as post-storm vegetation recovery. The storm caused 20 million hectares of forests (10% of national forest cover) to lose at least 10% standing volume, which was about 3% of national forest standing volume (Zhou et al. 2011a). In a bamboo forest investigated (Zhou et al. 2011b), it was estimated that 8.21 (±3.55) Mg C per hectare was shifted from living biomass to dead by this single ice storm. Surprisingly, our remote sensing-based analysis (Sun et al. in review) indicated that most of the impacted forests recovered within a year, a recovery that was surprisingly fast considering the magnitude of destruction in forest structure. Ground surveys attributed this fast recovery to rapid understory/epiphytic growth under the broken canopies and widespread resprouting of physically damaged trees. We found that better pre-storm growth relative to normal years corresponded to longer recovery time, possibly a consequence of increased biomass debris production that hindered understory growth. Additionally, we found that more severely impacted forests recovered sooner. This unexpected relationship had no natural causes that we could ascertain but most likely resulted from poorly planned salvage logging preferentially targeting lightly to moderately impacted forests. These findings suggest that forest photosynthetic recovery in the aftermath of large natural disturbances may be dominated by species that normally contribute little to forest ecosystems and by life history strategies of trees that are often neglected in the study of forest succession. Careful planning of human intervention is needed to minimize disruption to such delicate ecosystem processes. Land surface and ecosystem models such as CLM will need to consider these processes for representing large natural disturbances.

Table 2.7 Progress on Task F4 Deliverables (expressed in abbreviated form). Deliverables have been revised from the original plan in response to unforeseen climate events and serendipitous research findings.

Date	Deliverable	Status
2010	Fix tower leg damaged by ice (unforeseen event)	Completed
2010	Submit flux and complementary biological data sets to AmeriFlux.	Completed
2010	Complete analysis on soil respiration, paper submitted.	Datasets harmonized. Rescheduled due to work on another paper
2010	Develop, test and implement a model of mesophyll conductance in FAPIS.	Completed
2010	Develop and test new eddy covariance theory, paper submitted (serendipitous findings)	Completed
2011	Submit 2010 fluxes and biological data to CDIAC	Completed
2011	Install new enclosed path (Li-7200) EC system to replace an existing system damaged by lightning strike (unforeseen event)	Completed
2011	Overhaul the MOFLUX Automated Daily Data Processing and Reporting System (MADDPRS) in response to new cyber security measures imposed by ORNL (unforeseen event)	Completed
2011	Reprocess 2004 - 2010 flux data according to the new theory	Completed
2011	Methodologies for computing annual C and water budgets at MOFLUX	Completed
2011	A quantitative framework for analyzing forest photosynthetic recovery after disturbance (newly added)	Completed
2011	Complete analysis on effects of contrasting drought regimes, FAPIS simulation of drought response	In progress
2011	Complete analysis on effects of frontal activities	In progress

2.1.7 TASK F5 – FOSSIL EMISSIONS

Task F5 centers on estimating CO_2 emissions from fossil fuel consumption as well as estimating the uncertainty associated with those estimates. Over the last two years, TES SFA funding has contributed to creating emission inventories at monthly temporal resolution the scale of individual states at a global scale for use in Task F1b analyses; examining the global and spatial distribution of emissions; and calculating the evolution of global uncertainty of those emissions with time. Progress towards the original deliverables is summarized in Table 2.8.

Table 2.8 Progress on Task F5 Deliverables (expressed in abbreviated form):

Date	Deliverable	Status
Sep 2010	Create preliminary emission inventories at the scale of states and months at a global scale for use in Task F1b analyses	Completed
Mar 2011	Complete an analysis of the global and spatial distribution, and the evolution of global uncertainty with time	Completed
Oct 2011	Submit manuscript on state scale fossil fuel emissions and associated global uncertainty with time	In progress

The calculation of emission inventories has progressed beyond preliminary estimates to operational processing of monthly data sets. Data are maintained by CDIAC and are made freely available to the public (as well as SFA Task F1b analysis). The analysis of global and spatial distributions of emissions has been applied to both annual and monthly data sets. Data are also maintained by CDIAC and are made freely available to the public. The manuscript in Table 2.8 could have been completed by October 2011; however, publication has been delayed as we continue to explore “best” methods to do these uncertainty calculations. Preliminary uncertainty estimates have been prepared and discussed with the C cycle emissions community. Workshops and publications (by us and others) have explored how to move forward on this uncertainty issue. The diversity of opinions arises because of the complexity of the input data to the fossil fuel CO_2 emission estimates. Input data are inherently uncertain due to issues related to dependent and independent data, missing and filled values, and expert judgment.

3. RESEARCH PLANS FOR FY2013, FY2014, AND FY2015

At this early stage in the TES SFA (2 years and 3 months of funded activity at the time this report was compiled), the iterative process among experiments, observations and the terrestrial C cycle modeling tasks has not yet dictated a new direction for the developing Task R1 SPRUCE study where research is just beginning, or Task F1 on C cycle modeling where key improvements continue. Major investments are underway to bring the SPRUCE experimental infrastructure to a fully operational state in FY2013. Associated pretreatment characterization of the Minnesota peatland will continue simultaneously with construction of experimental infrastructure. The pretreatment data and the experience that comes with its collection will put the research group and our collaborators on a solid footing for evaluating organism and ecosystem responses to the treatments when they are initiated. The existing CLM-CN terrestrial C cycle model will continue to be modified to allow it to fully capture the C cycle dynamics of wetland and peatland systems to allow fruitful interactions with SPRUCE, and to provide a solid generic framework for the simulation of wetland ecosystems after CLM-CN improvements are transferred to global scale modeling efforts.

The incorporation of robust C allocation mechanisms stemming from the results of Task F2 work will also be a key focus of upcoming modeling-experiment dialogs (Task F1) as the PiTS process studies come to fruition in FY2012. Fundamental uncertainties remain regarding the contribution of belowground productivity to the fate and storage of C within upland and peatland soils, and a new Task F2b is described below for the identification and characterization of root functions with respect to C exchange. Water extraction and nutrient uptake and cycling are the key areas of uncertainty for which process level studies are being proposed.

Process level studies focusing on mechanisms of soil C cycle transport to and accumulation rates within mineral soils (F3a and F3b) are or will be completed in FY2012 and a similar level of investment is being proposed for new emphasis on enzyme microbial decomposition dynamics for soil C (Task F3c described below).

For MOFLUX Task F4a, efforts will be shifted to include detailed analysis of foliar mesophyll controls on canopy GPP and to add a new focus on belowground production. New investments will be made to collect collaborative landscape level flux data for the ombrotrophic S1 Bog ecosystem (Task F4c) in areas analogous to those occupied by the SPRUCE manipulations.

Task F5 on fossil emissions will stay-the-course and provide high quality input to global C cycle analyses.

In the subsequent sections details are provide for new task whereas ongoing efforts are summarized succinctly with justification and measurement details provided in the original 2009 plans.

3.1 TASK R1: SPRUCE FUTURE PLANS AND DELIVERABLES

The motivation for SPRUCE (outlined in our original SFA plans provided with this document; http://tes-sfa.ornl.gov/node/17) is to develop quantitative information on ecosystem responses associated with climate change as a prerequisite for the development of ecological forecasting tools for policy makers to evaluate safe levels of greenhouse gases in the atmosphere. This objective complements the DOE’s mandate to understand both the consequences of atmospheric and climatic change for important ecosystems and the feedbacks between ecosystem response and climate through effects on C cycling (DOE 2009).

The SPRUCE experiment provides a platform for testing mechanisms controlling vulnerability of organisms and ecosystems to important climate change variables. This project addresses key science questions essential for informing higher-order models of vegetation change under projected future climates:

1. How vulnerable are terrestrial ecosystems and their component organisms to atmospheric and climatic change?

2. Will novel species assemblages or loss of species that result from species-specific responses to climatic and atmospheric change have unanticipated impacts on ecosystem processes? Do changes in ecosystem services precipitate a change in state (e.g., loss of a dominant plant functional type)?
3. What are the critical air and soil temperature response functions for ecosystem processes and their constituent organisms?
4. Will full belowground warming release unexpected amounts of CO_2 and CH_4 from high-C-content northern forests?
5. To what degree will changes in plant physiology under elevated CO_2 (eCO_2) impact a species' sensitivity to climate or competitive capacity within the community?
6. Will ecosystem services (e.g., biogeochemical, hydrological or societal) be compromised or enhanced by atmospheric and climatic change?

The SPRUCE project continues infrastructure development and pretreatment biological process observations in FY2012 with an anticipated transition to full-time experimental treatment applications spring 2013. The following deliverables outline major SPRUCE activities anticipated for the currently year (FY2012; our 3rd year) and the next 3-year funding cycle. SPRUCE treatments are expected to be operated and responses measured and interpreted over a full decade. Such a time period should allow time for interannual variation effects on treatments to be observed and for long-term nutrient cycle alterations to develop in response to the warming and CO_2 treatments.

Table 3.1 Future Task R1: SPRUCE Deliverables

Date	**Deliverable**	**Status**
FY2012 Deliverables		
Nov 2011	Complete site preparations for bog access and electrical service supplies	Completed
Mar/Apr 2012	Hire ORNL staff technologist to reside in Minnesota	Underway
May 2012	Complete specifications for data service to experimental plots, (2) scope specifications for data systems for data acquisition, storage, and transfer to ORNL, and (3) scope specification for site telecommunications.	Underway
May 2012	Complete engineering and drawings for field facilities including temporary office buildings, data system office space, storage, sample prep space, telecommunications.	Underway
May 2012	Complete construction of field facilities including temporary office buildings, data system office space, storage, sample prep space, telecommunications.	Underway
May 2012	Complete installation of boardwalks	Planned
May 2012	Submit a manuscript describing the influence of N on Sphagnum growth and photosynthesis at elevated temperature.	Underway
Apr to Oct 2012	Conduct pretreatment measurements and archiving of time-zero samples for the full range of disciplinary tasks at all defined experimental plots.	Planned
Jun 2012	Complete engineering and drawings for final aboveground warming chambers	Planned
Jul 2012	Complete the addition of electric, CO_2, propane and data service to all experimental plots.	Planned
Sep 2012	Complete the addition of environmental and observational monitoring systems to all planned treatment plots.	Planned
Sep 2012	Begin testing of data acquisition system.	Planned
Sep 2012	Submit manuscripts on full-scale warming prototype performance, and on seasonal CH_4/CO_2 flux observations using new methods.	Being prepared
FY 2013 Deliverables		
Oct 2012	Prepare pads for CO_2 tanks.	Planned
Mar 2013	Produce manuscripts on baseline plant water relations and woody plant foliar physiology for the S1 Bog.	Planned
Mar 2013	Data system fully operational.	Planned
April/May 2013	Complete construction of all above- and belowground infrastructures, and initiate treatments.	Planned

June 2013	Complete a manuscript on the influence of species and seasonal patterns on Sphagnum photosynthesis as a function of temperature, CO_2, relative water content, and PAR	Planned
2013	Conduct measurements for the full range of disciplinary SPRUCE tasks for all defined experimental plots employing any refined methods indicated by pretreatment studies.	Planned
July 2013	Submit manuscript on fine-root production in relation to topography and tree density	Planned
Sep 2013	Manuscript on seasonal and depth variation of microbial populations and activity in peat	Planned
FY 2014 Deliverables		
2014	Conduct measurements for the full range of disciplinary SPRUCE tasks for all defined experimental plots.	Planned
Sep 2014	Manuscript describing temperature sensitivity experiments of peat microbial communities in laboratory mesocosms	Planned
Sep 2014	Manuscript describing initial physiological response to treatments for the major vegetation types (trees, shrubs, Sphagnum)_	Planned
FY2015 Deliverables		
2015	Conduct measurements for the full range of disciplinary SPRUCE tasks for all defined experimental plots.	Planned
Sep 2015	Manuscript describing responses of microbial communities after first two years treatment	Planned

3.2 TASK R2: WALKER BRANCH FUTURE PLANS – A TRANSITION TO NEON

DOE-BER funded WBW research is being phased out. We are in a transition period over which the WBW footprint on the Oak Ridge Reservation will be developed as core wild-land site in the planned National Ecological Observatory Network (NEON) funded by the National Science Foundation. Anticipated deliverables during this transition periods are provided below:

Table 3.2 Future Task R2 Deliverables (expressed in abbreviated form):

Date	**Deliverable**	**Status**
April 2012	Analysis for annual hydrology and stream chemistry for calendar year 2011 is ongoing and will be completed by April 2012.	Planned
Summer 2012	Dual nutrient releases will be conducted again in the spring to characterize nutrient uptake during the period of high autochthonous (i.e., algal) production.	Planned
Sep 2012	Papers on the seasonal nutrient pulses to characterize uptake kinetics, and stream litter decomposition	Planned
FY2013	Papers on dual N and phosphorus uptake in streams and a paper on the controls on stream metabolism (determined using a structural equation model)	Planned

3.3 MECHANISTIC C CYCLE MODELING – FUTURE DIRECTIONS

This task incorporates model-data integration and model development across multiple spatial and temporal scales to identify process contributions to the global climate-C cycle forcing from terrestrial ecosystems. Although the ultimate goal of this task is to determine the global C-cycle forcing, the most comprehensive information about terrestrial processes exists over the much smaller scales of flux tower and experimental footprints where detailed observations are possible. The key challenge is how to convey information from local to global scales using a land surface model and how to estimate the uncertainties that result from this upscaling. A consistent modeling framework across scales is essential, and with this in mind we have adapted CLM-CN for multiscale model-data integration. In some cases outlined below, it is beneficial to employ more parsimonious models initially for algorithm development and use the resulting information to inform CLM-CN. Subtasks 3.3a, 3.3b, 3.3c and 3.3d outline future plans for model development and validation across site, regional, and the fully-coupled global scales.

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

An opportunity exists to capture mechanistic understanding and process knowledge gained in previous manipulative experiments within the current generation of land ecosystem process models. Based on experience gained through preliminary efforts in this direction over the past two years, we will use our new PTCLM framework to formalize a retrospective model-experiment synthesis, first bringing new process knowledge into CLM, and then testing the influence of this new knowledge on predicted climate-ecosystem feedbacks. We will leverage efforts already made in data set and modeling protocol development, for example under the FACE model-data intercomparison workshops supported by NCEAS and DOE-BER, and will make use of previous synthesis products that have not been applied to the global scale models, such as the Throughfall Displacement Experiment model-data intercomparison, and continuing use of the Enriched Background Isotope Study data set for model structural development and parameterization. We will also undertake new model-data syntheses, for example an evaluation of CLM using results from warming experiments.

In a similar vein, we have recently performed (with other DOE BER support) a literature synthesis of C, N, and phosphorus content of microbial biomass and soil organic matter, and we will apply this new data source to the development of an improved treatment of C:N:P stoichiometry in CLM. We will then characterize the effects of this change in model behavior on global-scale climate-ecosystem feedbacks. Specifically, we will continue our work with PTCLM to perform forward and inverse simulations at FACE, EBIS, SPRUCE, PiTS and an additional 30-40 AmeriFlux and FLUXNET sites, including three tundra and three tropical sites with the goal of model parameter optimization and uncertainty quantification. We have leveraged the Climate Science for a Sustainable Energy Future (CSSEF) project to develop a capability to perform large ensemble simulations of PTCLM efficiently in a high performance computing (HPC) environment. We will apply this ensemble framework to perform parameter sensitivity analyses at flux tower and experimental sites with about 1000 simulations per site. We will use these sensitivity analyses to select the 20-30 most important parameters at each site to be optimized.

We will continue to develop the parameter optimization framework. Through CSSEF we are also collaborating with the Sandia National Laboratory UQ team to develop a CLM-CN emulator. The emulator serves to interpolate model outputs at points for which the full model was not evaluated, and is much faster than the full model. Parameter optimization techniques such as MCMC may then be performed on the emulator with a minimal computational burden. Using this technique, we will produce joint posterior parameter probability density functions with less than 10^4 full model evaluations per site, which is computationally feasible. Unlike previous model-data fusion efforts, each CLM-CN ensemble run in the site optimizations will include a full model spin-up and will account for the site-specific disturbance histories. We expect this will constrain the long-term evolution of model C stocks and result in more accurate predictions. In addition to the site-level parameter PDFs, we will also generate joint PDFs for 12 CLM-CN plant functional types (PFTs) using at least two flux towers per PFT to be used in regional and global scale modeling. Estimating the uncertainty accurately will require further development of the cost function and assessment of observational uncertainties to account for spatial autocorrelation and natural variability in model parameters across sites. We will then evaluate the number of sites necessary to parameterize a PFT within an acceptable level of uncertainty.

Because of its speed and simplicity, the LoTEC model serves as an important test bed for optimization techniques. With LoTEC, PFT-level optimizations using the GA (without the full PDFs) have been already completed for temperate deciduous and coniferous ecosystems using 5 towers per PFT. This analysis will be expanded to include grassland, crop, tundra, and tropical ecosystems using available flux towers. We will use the approach outlined above to develop a LoTEC emulator and generate joint PDFs for all PFTs. Because LoTEC is computationally fast, we will also use MCMC directly (without the emulator) to estimate the joint PDFs. A comparison between the emulator approach and the direct approach will allow us to estimate the additional uncertainty that results from using the emulator.

In addition to parameter optimization, further model structural development is necessary to accurately represent ecosystems under observation or experiment. Further development of CLM-SPRUCE will include the addition of wetland hydrology, additional plant functional types representing wetland vegetation and sphagnum moss, and the ability of the model to simulate the proposed experimental manipulations. We are currently integrating a prognostic methane model, developed by Bill Riley and colleagues at LBNL (Riley et al. 2011), into our wetland-enabled version of CLM4, and we will exercise this model against observations of methane flux made within the SPRUCE experimental enclosures when the measurements are available. The methane model is responsive to hydrologic status, and so should couple in a meaningful way with our current modifications to CLM4 to include hummock and hollow wetland dynamics as observed at the SPRUCE S1 bog site. Similar model development is underway to incorporate ^{13}C-labeling experiments that took place as parts of PiTS (Sections 2.1.4 and 3.4), EBIS (Section 2.1.5a) and FACE (Norby and Zak 2011). We expect these improvements to be integrated into CLM-CN for use at other observations sites, and eventually, regional and global simulations.

Table 3.3 Future Task F1a Deliverables

Date	Deliverable	Status
2012	Site-level emulator approach complete and documented. Submit manuscript on LoTEC PFT-level optimization. Submit manuscript on FACE model-data intercomparison.	Ongoing
2013	- Complete development of CLM-PiTS and CLM-SPRUCE and integrate structural changes into main CLM-CN code. - Submit manuscript detailing CLM-CN parameter sensitivity analysis for 20 tower sites. - Perform model-data comparison for PiTS experiments 1-3	Planned
2014	- Complete evaluation of CLM-CN at FACE, PiTS EBIS and other experiment sites using parameter optimization and comparison of multiple model structures - Evaluate CLM-SPRUCE with initial SPRUCE treatment data including evaluation of prognostic methane model against measurements..	Planned
2015	- Perform a full parameterization of all CLM-CN PFTs using the emulator-based method with all available flux tower and experimental data	Planned

3.3.2 Task F1b – Regional and Global Land Ecosystem Modeling

Our studies based on the NACP interim synthesis activities (Huntzinger et al. in press, Hayes et al. in press) have highlighted the differences in multiple constraints on the continental-scale C budget (inventory, forward and inverse modeling), and by comparing and evaluating their estimates key strengths and weaknesses of each scaling approach have emerged. Although there are benefits in retaining independence among approaches for estimating C fluxes, progress will be made by more formally integrating them. Ultimately, confidence in our ability to understand and predict the role of the North American C cycle in the global climate system will increase as the estimates from these different approaches begin to more closely converge and are combined in more fully integrated modeling systems.

Through full C budget accounting approaches to regional / continental-scale modeling, we have found some convergence toward an ‘answer’ for the contemporary North American C sink strength. However, given that our studies highlight the 1) uncertainties in component fluxes, 2) mismatches in spatial patterns, and 3) large spread in estimates across models, any convergence between the approaches would not necessarily occur for the ‘right’ reasons. Rather, our work draws attention to those components of the NA C budget that require more careful study through measurement and inventory methods. Regarding the modeling approaches, our work strongly suggests the need to better understand the causes underlying the large spread in estimates, most likely achieved through formal and controlled (i.e. common protocol) model inter-comparison studies informed by benchmarking frameworks based on reliable measurements and observational data sets.

TES SFA team members have recently been closely involved in participating in, as well as organizing, the NACP MultiScale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP). The goal of MsTMIP is to provide feedback to the terrestrial biospheric modeling (TBM) community in order to improve the diagnosis and attribution of C fluxes at regional and global scales. This project builds upon current and past synthesis activities by developing an integrative framework to isolate, interpret, and evaluate differences in how TBMs parameterize key physical and biological processes. As part of the MsTMIP activity, we have outlined a set of formal model simulations at the regional and global scale. In addition to organizing a comprehensive driver data framework on atmospheric chemistry, climate, and vegetation variables, we are leading the data and simulation protocol development for including an analysis of the impacts of disturbance and land use change on C cycling at the global and continental scales. TES SFA team members are contributing model results to this comparison activity from CLM-CN (Thornton et al. 2007), LoTEC (Ricciuto et al. 2011) and TEM (Hayes et al. 2011). We will continue to provide leadership on the analysis and synthesis of these model-data inter-comparison activities with the goal of improving the representation of key mechanisms in land surface models that will ultimately be coupled within Earth System Model frameworks that provide reliable projections of future climate change.

Specifically, new global (0.5 × 0.5 degree) and North American (0.25 × 0.25 degree) simulations will be performed for MsTMIP using both CLM-CN, LoTEC, and TEM including 4 forcing factor simulations in which various factors (e.g. CO_2, land use, N deposition) are turned on or off. A module will be developed for LoTEC to allow for harvesting and PFT transition to follow the land use data set prescribed by MsTMIP. We will also use the MsTMIP simulation and validation protocol to test CLM-CN with and without structural improvements such as the new multi-layer litter model and the addition of a plant N storage pool. We will also evaluate the default and optimized versions of both models, first for LoTEC and then for CLM-CN using the framework developed for the Carbon Land Model Intercomparison Project (C-LAMP) and, when they become available, products from the International Land Model Benchmarking Project (ILAMB).

For eventual data assimilation at the regional scale, ensemble versions of LoTEC and CLM-CN are being developed to allow multiple simultaneous regional and global simulations with varying parameters or forcings. This will support assimilation of gridded data sets such as MODIS LAI and forest inventory products. Current computational capabilities could support up to 200 simultaneous LoTEC simulations (0.5 × 0.5 degree for North America, 1×1 degree global) with full model spin up taking 1-2 weeks of walltime. Combined with the emulator approach developed in Task F1a, we expect to be able to estimate joint posterior PDFs of 10-15 LoTEC parameters using both flux towers and gridded data sets as constraints. Although our current computational resources do not yet support running a large ensemble of CLM-CN simulations for regional model-data fusion, we expect to be able to run ensembles of up to 20 simulations with full spin up taking about 1 month of walltime. We will use this capability to evaluate the regional and global sensitivity of CLM-CN to key parameters as determined in the site-level parameter sensitivity analyses.

We will also test the ability of CLM-CNDV (CLM-CN with dynamic vegetation) to assimilate Paleo data in support of the PaleoEcological Observatory Network (PalEON) for an 80x30 grid covering eastern North America from the years 0-2000 A.D. Data sources include proxies for past vegetation composition (fossil pollen), fire regime (sedimentary charcoal) and hydrological variability (lake levels and other indicators). Meteorological driver data and Paleo data are being provided by the PalEON team.

Table 3.4 Future Task F1b Deliverables

Date	**Deliverable**	**Status**
2012	- Global LoTEC, TEM and CLM-CN MsTMIP simulations completed - Submit manuscript on LoTEC North American simulations evaluating sensitivity of continental-scale flux to parameters	Underway
2013	- Document emulator approach for regional and global model-data assimilation - Perform LoTEC global simulations with assimilation of point and gridded observations, estimate global C flux and uncertainty - PalEON simulations and data assimilation framework complete	Planned
2014	- Complete CLM-CN global parameter sensitivity analysis - Document global data assimilation approach for CLM-CN and its integration with high-end computing resources	Planned
2015	- Perform CLM-CN global simulations with assimilation of point and gridded observations	Planned

3.3.3 Task F1c – Coupled Earth System Modeling

Our current results from single-forcing factor simulations demonstrate the importance of land use and land cover change (LULCC) as a major anthropogenic driver of greenhouse gas exchange. The current treatment of LULCC in CLM, while one of the more sophisticated among the global coupled models, does not take full advantage of the detail in historical or future scenario driving data sets. The most important deficiency in the current treatment is that is does not accommodate tracking of age classes, either in the secondary vegetation categories established following disturbance of primary vegetation, or in subsequent disturbances of secondary vegetation as occur for a rotational harvest management regime. Other modeling studies indicate that these effects play an important role in quantifying the C source-sink effects of LULCC (Shevliakova et al., 2009). We will evaluate the influence of age class distributions in CLM using a multi-age class binning approach, with explicit tracking of sub-class area distributions. This approach represents a compromise between accuracy and efficiency, since the potential number of age-class cohorts can be very large and computationally expensive. We target completion of new code structure by January 2013, with an evaluation of the influence on global climate-ecosystem feedbacks submitted for publication by January 2014.

Large-scale calibration of global ecosystem models is hindered by the lack of extensive observations at continental and global scales. Remote sensing techniques can provide long-term and large-scale products suitable for ecosystem model and earth system model constraints at fine spatiotemporal scales (Nemani et al. 2003; Running et al. 2004). We will focus on the systematic evaluation of CLM for C and water fluxes and state variables using the latest global satellite-derived data sets. We will investigate and update existing metrics of model performance using new remote sensing products (Randerson et al 2009). Also, we will extend our methods onto the up-coming Coupled Model Intercomparison Project Phase 5 (CMIP5) models and Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) outputs.

Table 3.5 Future Task F1c Deliverables

Date	Deliverable	Status
2012	Literature review on current evaluation metrics, satellite products, global offline ecosystem model outputs and earth system model simulations. Collect and re-map 30-year of NDVI, fPAR and LAI (1981-2010); GOSAT Chlorophyll Fluorescence (Frankenberg et al. 2011); The AMSR-E vegetation optical depth and soil moisture (Rebel et al. 2011); the forest C stocks in tropical regions (Sassan et al. 2011); MODIS GPP, NPP, fAPAR and ET (Zhao et al. 2010; Mu et al. 2011).	Underway
2013	Compare offline historical simulations of CLM4 with the standardized remotely sensed products at various spatial-temporal scales. Submission of related manuscripts.	Planned
2014	Evaluate transient simulations of fully coupled CMIP5 models and MsTMIP outputs against remotely sensed products at various spatial-temporal scales. Submission of related manuscripts.	Planned
2015	Set up and submit a standard observation database, metrics and diagnostic package for biogeochemical model and earth system model evaluation at global and continental.	Planned

3.3.4 New Task F1d – Integrating land-surface model constraints with inverse modeling

TES SFA team members have started to engage with The NOAA CarbonTracker research team. The terrestrial biosphere dynamics in CT is represented by the seasonal dynamics of the CASA model with monthly net fluxes estimated then scaled by ecoregion, to best match the atmospheric CO_2 concentration data sets. There is considerably more information about how terrestrial ecosystems constrain biosphere-atmosphere C exchanges that can be used to improve both CT CO_2 reanalysis and terrestrial C models. Increasing spatial and temporal resolution of atmospheric concentration measurements also provides additional information to allow direct land-surface model parameter estimation. Working in collaboration with CarbonTracker researchers, we will enhance the CarbonTracker framework with a more comprehensive C cycle representation from CLM-CN. By incorporating CLM-CN we will extend the powerful inversion modeling approach to determine whether or not the CLM-CN model simulations are consistent with the greatly expanding and increasingly important atmospheric CO_2 concentration data. In addition, this capability can be used to determine what land areas and gross fluxes are contributing to mismatches between model and atmospheric measurements that can lead to identification of model deficiencies that impact the atmospheric CO_2 concentration. This will provide a prediction capability currently absent in CarbonTracker and will serve as a test bed for science-based model development by identifying which formulations are most consistent with the full suite of C cycle observations, including site-level flux measurements, regional and global concentration observation networks, as well as future satellite with column total CO_2 measurements, aircraft profiles, and FTIR networks at high spatial and temporal resolution. The new regional, bi-directional ("top-down and bottom up") data-assimilation capability will further create new synergies with other DOE programs, such as the coherent AmeriFlux management network program, Next Generation Ecosystem Experiment (NGEE) initiative, and MsTMIP activities.

Table 3.6 Future Task F1d Deliverables

Date	**Deliverable**	**Status**
Spring 2012	Community engagement and on-site training at NOAA	Planned
FY2012	Develop capability, in collaboration with CT researchers, to run CT adapting the parallelization strategy to fully utilize high end computing at ORNL.	Underway
FY2013	Replace CASA with CLM-CN and/or LoTEC – develop capability to perform land-surface model parameter sensitivity and parameter optimization using the CT methodology.	Planned
FY2014	Incorporate transport model to advect fluxes from offline land model simulations to investigate the effective seasonal cycle at GLOBALVIEW sites	Planned
FY2015	Incorporate additional CO_2 concentration data streams into the CT/land-surface framework including regular aircraft profiles, FTIR networks, and satellite CO_2 measurements.	Planned

3.4 NEW TASK F2B – INTEGRATING ROOT FUNCTIONAL DYNAMICS INTO MODELS

Roots have high plasticity to changing environmental conditions thus exerting direct control on C uptake and cycling (Sperry et al. 1998, Hodge 2004, Aroca et al. 2012). Root functionality is expressed at various scales and is associated with both active and passive processes. Active processes include membrane control of aquaporin water channels and new root production. Passive processes include Michaelis-Menten enzyme kinetics related to nutrient uptake and loss of hydraulic conductivity due to embolism. These expressions of root function have direct and indirect impacts on plant water use and C uptake and partitioning to both short and long-lived pools (Hopmans and Bristow 2002, Bais et al. 2006, Davies 2007, Hodge et al. 2009, Maurel et al. 2010). Roots can respond quickly (within minutes) to changes such as a rainfall event through physiological mechanisms, or slowly (within days or weeks) to changes such as localized nutrient depletion through root attrition and radial or axial growth elsewhere.

Modeling nutrient and water uptake by roots has progressed in recent decades (Feddes et al. 2001, Hopmans and Bristow 2002, Feddes and Roats 2004, Simunek and Hopmans 2009), but most efforts have been focused at the point scale, and not extended to plot, landscape or regional scales. Root functional dynamics remain noticeably absent from the land component of global circulation models. The large-scale Community Land Model with coupled C and N cycles (CLM-CN) currently has no ability to represent the spatial or temporal resolution of root functional dynamics. Root function is relegated only to root distribution through a two-parameter exponential decay function – there is no distinction within that distribution of differential root functionality, although soil water potential controls do limit total plant water use.

Objective for new SFA Focus – As a proposed future direction for research within this SFA, we intend to improve representation of root functionality within CLM-CN through a stepwise program that will assess current knowledge, test model sensitivity, and modify or develop novel routines or modules to improve representation of root function as necessary. Model development work will be paired with an empirical research program to provide targeted data for validation and parameterization of the new elements within CLM-CN.

The characterization of root function with respect to C exchange, water extraction and nutrient uptake and cycling is a key area of model uncertainty for which new experimental or process level studies should be developed. We propose to conduct empirical studies that explore the dynamics of root function through linkages between *root distribution* (spatial location, temporal production), *morphology* (anatomy, size, age, order, mycorrhizal associations), and *physiology* (water and nutrient uptake kinetics) through the vertical soil profile. These studies are needed to parameterize novel model elements that will improve mechanistic representation of root function. CLM-CN, the main model currently employed in the TES SFA, does not have any explicit representation of root function based on distribution, morphology or physiological dynamics that is responsive to changing environmental conditions. In CLM, mean root distribution based on plant functional type, soil water potential and a plant-wilting factor do provide some feedback controls to photosynthesis (Oleson et al. 2010). However, unlike real ecosystems, root distribution in the model is static and root water potential is often uncoupled from soil water potential, both of which lead to a dichotomy between model and mechanism. Ten soil layers in CLM-CN are used for calculating thermal and hydrologic properties, but there are currently no depth-resolved C or nutrient (e.g., N, P, K, Ca, Mg) root or soil pools. Nitrogen is considered the key limiting nutrient in the model, and N uptake is calculated on a half-hourly time-step as a function of plant demand and soil mineral N availability. However, there is no indirect or explicit mechanistic regulation of nutrient uptake based on known root functional dynamics associated with root distribution, morphology, hydration, rhizosphere interactions or mycorrhizal associations. Simulations at North American eddy flux sites indicate that CLM-CN reproduces observed transpiration with relative accuracy, but it produces excessive N limitation of gross primary productivity, so improvements in the representation of belowground processes are clearly needed.

Ongoing model development efforts at other institutions (e.g., LBNL) are incorporating depth-resolved soil C and N pools into CLM-CN. Corollary efforts at ORNL within this SFA (3.5 New Task F3c) are focused on improving representation of soil organic matter turnover in CLM-CN, by novel development of an enzyme-based C and N mechanistic cycling module. Such improvements will allow for more realistic distributions of nutrient availability and C throughout the soil profile, linked specifically to environmental conditions (i.e., temperature). A logical continuation of this development pathway will be to improve fine root allocation schemes and resource extraction patterns so that roots can preferentially expand into or utilize soil areas with greater nutrient or water availability. Roots in nutrient-rich soil demonstrate increased hydraulic conductivity relative to similarly hydrated roots of the same plant in nutrient-poor soil, illustrating the plasticity of root function to nutrient availability. An allocation scheme that can address spatial or temporal functionality of roots could potentially reduce the known bias of excessive N-limitation in CLM-CN. Expressing root functionality within the model will build upon the explicit representation of fine-root distribution by requiring that nutrient uptake, water uptake, and root turnover are dependent on soil physical and chemical conditions, which vary temporally, and spatially through the soil profile. For relevance to CLM-CN, this new model structure would need to collapse the 3-dimensional (3D) spatial dynamics of root function into an integrated 1D or 2D spatial function built from the appropriate set of independent controlling factors. It would have a number of new parameters, and would require testing and validating with experimental data. The prior minirhizotron measurements and ^{13}C labeling results from the PiTS and ORNL FACE experiments will be valuable in determining the timescales related to fine-root allocation and turnover; *a priori* simulations at these sites indicate that additional model development will be necessary to reproduce the observed data.

New laboratory and field experiments that focus on root functional dynamics under changing environmental conditions are necessary to improve CLM-CN. The priority will be to isolate and quantify specific key mechanistic processes that drive root production and root-rhizosphere exchange of water, nutrients or C at short timescales. Novel techniques are available that might be employed to assess root distribution, root stress and water and nutrient uptake dynamics including stable isotopes, ion-selective electrodes, non-invasive imaging, sensor arrays, biosensors and micro-chambers (e.g., Pierret et al, 2005, Kim et al. 2007, Oswald et al. 2008, Vargas and Allen 2008, Herron et al. 2010, Rewald et al. 2011). These experiments will build upon the ORNL PiTS studies (2.1.4 Task F2a) that focused on C partitioning belowground, by investigating how C investment in roots relates to resource extraction under changing environmental conditions. The new research we propose will be built around the integrative premises that soil resource extraction is (a) directly linked to dynamic root functional response to resource availability and environmental conditions (soil characteristics, nutrition, water, temperature), and (b) is linked to root morphology and distribution, which in turn is linked to C partitioning and cycling. We hypothesize that the inclusion of dynamic root functionality based on these underlying premises within CLM-CN will improve model estimates of GPP due to enhanced sensitivity to spatial and temporal resource availability.

We propose three integrated tasks:

Assess the current representation of roots in models that vary in spatial and temporal resolution **-** We will consider: (a) mechanistic models that simulate water and nutrient transport within soil and uptake by individual roots (i.e., based on the Richards equation or Michaelis-Menten kinetics); (b) mid-scale models that include active and passive uptake balance (e.g., HYDRUS; Simunek et al. 1998, Simunek and Hopmans 2009) or rhizosphere and xylem regulation of water flux through the soil-plant-atmosphere continuum (e.g., Sperry et al. 1998); and (c) integrated land surface models that utilize macroscopic dynamics of site resources, root distribution, and relevant environmental driving forces (e.g., CLM-CM; Thornton et al. 2007, 2009). CLM-CN is of particular interest to us due to its current importance in broader global climate model simulations. Efforts will be focused on identifying aspects of root distribution and function that could affect nutrient uptake and limitations within CLM-CN. We will develop a comprehensive review manuscript on root nutrient and water uptake dynamics in context of C cycling in models in which we consider:

a. *How do models currently represent spatial and temporal variation in root functionality?*
b. *How does the current lack of detail regarding root function in macroscopic scale models contribute to model uncertainty?*
c. *What mechanisms associated with root function are most likely to be useful in future model improvement?*
d. *How is root morphology or distribution associated with uptake kinetics – what characteristics can we use to assess functionality?*
e. *What spatial and temporal scales are relevant, useful for modeling, and amenable to study?*

Conduct sensitivity analysis of CLM-CN **-** The sensitivity of CLM-CN to environmental conditions that affect net root production and function – specifically, temperature, water and nutrient availability – will be analyzed to determine how root presence, function and dynamics are linked to model behavior and output.

Develop of a new root function module for CLM-CN **-** The module will resolve root nutrient uptake dynamics temporally within the soil profile. This module will be developed and parameterized based on published data and new experiments. Directed laboratory and field-based experiments will be used to identify the necessary parameters and validate root functional response to environmental conditions. Current physical (e.g., soil texture, soil water potential) and biological (e.g., leaf area, stomatal conductance) components of the model have impacts on (and are impacted by) root function, such that an integrative and comprehensive experimental program will be necessary to assess root functional dynamics. Field-based studies in model terrestrial ecosystems will involve paired installation of physiological and environmental monitoring equipment vertically within the soil profile to assess root function (production, mortality, respiration, nutrient and water uptake) in context of experimentally controlled environmental conditions. Targeted laboratory study of root function will be included as necessary to further explore environmental thresholds for root nutrient or water uptake rate.

Table 3.7 Future Task F2b Deliverables

Date	**Deliverable**	**Status**
2014	Initiate literature review, sensitivity analysis, data compilation and assessment of root functional representation in models in context of water and nutrient uptake dynamics. Submission of high-impact review manuscript.	Planned
2015	Initiate root nutrient module development and paired experimental facility to validate the module.	Planned
2016	Continue field and laboratory experiments, test and refine root module and initiate specific follow-on experiments as warranted. Submission of manuscript illustrating performance of root module for a point version of CLM-CN that models the field experimental facility.	Planned

3.5 NEW TASK F3C – MODELING OF MICROBIAL PROCESSING OF SOIL C

Justification – This research identifies and targets critical uncertainties in coupled climate and terrestrial ecosystem processes and feedbacks, namely, microbial-mediated decomposition of soil organic matter (SOM), sorption and desorption of depolymerized dissolved organic C (DOC), cycling in measurable soil pools, and updating controls on biochemical recalcitrance. In accordance with the CCP Science Plan and CCP Forcing SFA, we will advance the understanding and representation of terrestrial ecosystem feedbacks by providing a fully functional, validated, enzyme-based C and N mechanistic cycling model as an alternative formulation of SOM dynamics currently in the Community Land Model (CLM-CN). Current models of SOC/SON decomposition dynamics, including CLM-CN, are based on the use of conceptual pools described by first-order kinetics in which stabilization of soil C and N is solely represented by transformation to increasingly recalcitrant pools (Figure 13a). However, recent studies demonstrate that molecular structure alone does not control SOM stability, and that environmental and biological factors moderate decomposition reactions and cause sensitivity of biochemical recalcitrance to environmental conditions (Craine et al. 2010; Conant et al., 2011; Conen et al. 2006; Fang et al. 2006; von Lützow et al. 2006; Sollins et al. 2009; Schmidt et al. 2011). CLM-CN currently underestimates the amount of soil C and has a mean residence time that is short compared to measurements based on ^{14}C, lending considerable uncertainty to predicted soil C fluxes in a warmer world. Therefore to reduce the existing uncertainty in climate predictions (Lawrence et al., 2009), we first need a better understanding of how coupling of environmental and microbial processes leads to stabilization of different forms of C and N as a function of temperature.

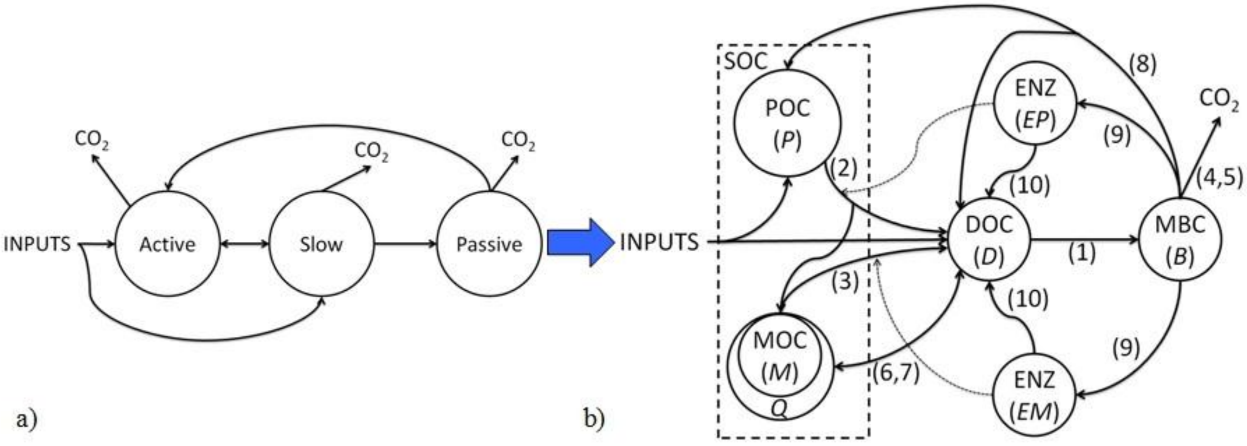

Figure 13. Carbon pools and fluxes in traditional soil pool models (a), and the new soil model (b). Circles represent C pools and arrows represent C fluxes. The soil organic carbon (SOC) has 2 components - particulate organic carbon (POC), and mineral associated organic carbon (MAOC). (1) dissolved organic C pool (DOC) uptake by microbes, (2) slow pool decomposition, (3) passive pool decomposition, (4) microbial growth respiration, (5) microbial maintenance respiration, (6) desorption, (7) sorption, (8) microbial turnover, (9) enzyme production rates (ENZ) and (10) enzyme activity rates. Also shown is C allocated to exoenzymes that are responsible for the decomposition fluxes (2), (3).

The entire mechanism of microbial degradation – enzymatically-mediated depolymerization of organic compounds – isn't directly represented in global C and N cycle models (Schimel and Weintraub, 2003; Allison, 2006; Lawrence et al., 2009; Allison et al., 2010). Enzyme production and stabilization, substrate uptake, and microbial growth efficiency, are each temperature-dependent processes that are unrelated to biochemical structure (Allison et al., 2010; Conant et al., 2011), so integrating the mechanisms of the microbial community into soil C and N cycling models is integral to predicting the response of soil C to temperature perturbations (von Lützow and Kögel-Knabner, 2009; Allison et al., 2010). Further, changes in the microbial community over time and with variant substrate availability may result in changes in decomposition rates as a function of time (Conant et al., 2011). In addition, stabilization reactions with mineral surfaces can exert a greater influence on decomposability than inherent biochemical stability, resulting in differences for different soil orders or environments (Kleber et al., 2007; Hayes et al., 2010; Haddix et al., 2011). Because adsorption and desorption are also thermodynamic processes, they are also subject to changes with temperature, and it is proposed that strongly-sorbing molecules will be more likely to desorb and become bioavailable with increased temperature, and that weakly-adsorbing molecules may be more likely to adsorb and have decreased bioavailability (Conant et al., 2011).

Previous incubation and field experiments measure multiple processes simultaneously, resulting in uncertainty in the response of soil to environmental changes because of the confounding behavior of the individual processes (Conant et al., 2011). It is therefore critical that future experiments separate and identify the <u>rates associated with each contributing process</u> rather than the sum of bulk processes, and <u>no studies to date</u> have accomplished this (Conant et al., 2011). The goal of our FY11-12 ORNL Laboratory Directors Research and Development (LDRD) project "Incorporating Molecular-Scale Mechanisms Stabilizing Soil Organic C into Terrestrial C Cycle Models" is to produce a mechanistic exoenzyme-based model of SOM cycling in soils (Figure 13b). We consider the relationship between attachment and stabilization for common OC compounds (lignin, lipid, sugars, starch) in isothermal batch sorption and long-term incubation experiments, using soils from major soil orders in arctic, tropical, and temperate climates. The turnover of the OC compounds as they cycle through *measurable soil pools* (DOC, mineral-associated OC (MOC), aggregate-protected particulate OC (POC), and microbial biomass (MBC)) is modeled through the mechanism of enzyme-facilitated microbial degradation (ENZ) based on time-zero enzyme assays (Figure 13b). The model framework is developed and parameterized from an extensive review of published data, and applied to measurements from our laboratory experiments. The ultimate outcome is a validated enzymatic soil C model that is designed to link into widely used global and-surface models used in climate change simulations.

Our LDRD experimental and modeling effort is an improvement over existing efforts in particular because we measured SOC transformations in measurable rather than conceptual soil pools. Our experiments separate the role of MOC versus POC (Figure 13b), we determine the role of mineral protection (ad/desorption) represented by pathways 6 & 7 on the residence time, and in addition, in experiments we apply different DOC substrates found in soils, e.g., lignin, starch, sugars, and lipids. We measure enzyme activities (ENZ) of the soils as a function of temperature at time-zero to govern the transformation rate of POC, MOC, and DOC into MBC (pathways 9 & 10 & 1). Finally, we measure the transfer of added DOC into MBC (pathway 1) by combining growth and maintenance respiration (pathways 4 & 5).

The LDRD represents an excellent first step towards separation and quantification of soil C cycling processes, but LDRD is a *pilot* program. Consequently, improvements in both experiments and modeling are still needed in order to provide the next generation, process-based soil C cycling model for widespread public use. The model needs to be linked into CLM-CN, and tested at regional to global scales. Further, temperature was investigated only through the measurement of activation energies at time zero and was not directly manipulated in either the sorption or incubation experiments. Oxygen and moisture content were not evaluated, and only surface soils were tested. Changes in the microbial community and enzyme activities, as a function of time or substrate, were not evaluated. Finally, because our substrates were added to soils as DOC, the microbial-mediated transformation of POC (pathway 2) and MOC (pathway 3) were only measured at the endpoint, i.e., CO_2 mineralization through coupled growth and maintenance respiration (pathways 4 & 5). As enzymatically-mediated depolymerization and production of DOC is the *major* pathway of SOC mineralization, new experiments are needed to specifically target and isolate these pathways.

Hypotheses

1. Under increasing temperature, strongly sorbing MOC-associated compounds such as lignin derivatives and lipids will be more likely to desorb from the mineral surface due to shifting of the sorption-desorption equilibrium towards reactants, and thereby become more bioavailable.
2. Under increasing temperature, recalcitrant compounds will be more likely to undergo microbial degradation due to their higher activation energies. Depolymerization of SOC and production of DOC is predicted to be the rate-limiting step in the decomposition reaction, but the mineralization

rate will be influenced by edaphic variables in addition to the activation energies of the compounds, e.g., degree of mineral or aggregate protection, and/or microbial community composition.

3. Microbial population structure, functionally and/or phylogenetically, varies as decomposition progresses and these changes can be systematically related to depletion of available substrate, and to changes in the temperature regime.
4. An exoenzyme-based soil C model can be deployed with sufficient detail to explain the regional- to global-scales patterns in soil C distribution.

Sorption Experiments – This sub-task is designed to resolve Hypothesis 1, which predicts that with increasing temperature, strongly sorbing compounds such as lignin derivatives and lipids will be more likely to desorb from the mineral surface due to shifting of the sorption-desorption equilibrium towards reactants, and thereby become more bioavailable. We will use a range of soils from surface and subsurface locations from representative soil orders globally, including but not limited to the arctic (Histosol, Gelisol), northern latitudes (Spodosol (SPRUCE soils), Inceptisol), temperate (Mollisol, Alfisol, and Ultisol (EBIS-AmeriFlux and MOFLUX soils)), and tropical (Oxisol, Ultisol) soils. Because sorption is expected to occur only with the MOC, i.e., the silt and clay fraction (< 53 µm), the soils will be physically fractionated into POC and MOC to isolate MOC processes (Figure 13b). Common substrates found in soils (sugars, amino acids, lipids, lignin, cellulose) will be labeled using ^{14}C and/or^{13}C, and ^{15}N and adsorbed to both bulk soils and to the MOC fraction, in duplicate, and allowed to reach equilibrium at a solid:solution ratio of 1:10 at a range of temperatures: 4, 15, 25, 35, and 45 °C. Subsequently, the adsorbed solids will be subjected to three sequential desorption experiments to determine the sensitivity of desorption to temperature (Figure 13b – pathways 6 & 7). The extent of ad/desorption will be measured through liquid scintillation counting (LSC) of ^{14}C and/or through mass spectrometry (MS) measurements of ^{13}C and ^{15}N in the supernatant solutions (Jagadamma et al., in prep). Thus, temperature sensitivity of adsorption and desorption processes will be measured in MOC and bulk soils, in a globally representative suite of soil orders.

Decomposition Experiments – These experiments will resolve Hypothesis 2, in which increases in temperature result in more strongly sorbing compounds being more readily degraded due to their higher activation energies and enhanced desorption. A replicate set of adsorption experiments from subtask 1, in addition to a set of POC samples, will be incubated at field moisture capacity at temperatures ranging from 4-45 °C, over 3 hours to 400 days. We will also impose moisture limitations (up to 50% reduction from field moisture capacity) on a select set of samples. We expect to find that in the face of changing temperature, moisture and microbial community, that biochemical recalcitrance will not always be the primary control over decomposition. In the case of ^{14}C labeled compounds, a base trap will be used to collect the mineralized CO_2 for LSC analysis, while in the case of ^{13}C and ^{15}N labeled substrate, gas headspace samples will be analyzed directly through MS (Figure 13b – pathways 4 & 5 & 1). In both cases, total mineralized CO_2 from SOC will be analyzed via titration or through gas chromatography (GC) (Figure 13b – pathways 2 & 3 & 1).

As depolymerization of SOM is hypothesized to be the rate-limiting step (Figure 13b – pathways 2 & 3), DOC will be periodically (0, 30, 60, 200, 400 days) extracted from the bulk and POC and MOC fractions of the soils. DOC will be analyzed via LSC or MS to determine the proportion of the original labeled compounds present in the dissolved phase. Further, extracted DOC will be analyzed via ^{13}C-Nuclear Magnetic Resonance (NMR) to determine its functional groups and the extent to which the DOC is formed from the depolymerization of various SOM substrates from the SOM itself rather than the labeled substrates.

To determine the sensitivity of different forms of SOM to temperature changes, changes in the chemistry of soil organic matter (SOM) as a function of time (0, 30, 60, 200, 400 days) will be analyzed using several complementary spectroscopic techniques including Diffuse Reflectance Fourier-transformed infrared spectroscopy (FTIR) and NMR at ORNL and through competitive proposals to the Environmental Molecular Sciences Laboratory at Pacific Northwest National Laboratory. This activity will determine the extent to which the native SOM is degraded under a variety of temperature regimes. Correlations with the production of DOC will help determine reaction pathways from POC/MOC through

DOC (pathways 2 & 3) to determine the extent of bioavailability to MBC (pathway 1) of different compounds under different conditions (Figure 13b).

Enzyme Activities and Community Composition – These measurements are designed to test Hypothesis 3, in which microbial population structure (functionally and/or phylogenetically), varies as decomposition progresses and to determine how these changes can be systematically related to depletion of available substrate and to changes in temperature. Enzyme assays (Sinsabaugh et al., 1994) will be primarily used to determine which enzymes are active and how that activity changes as a function of time, substrate, and temperature. Changes in microbial biomass will be determined as a function of time on initial soils and from small samples (< 100 mg) taken at multiple time points during the incubations (e.g., 0, 30, 60, 200, 400 days). We will also incorporate nucleic acid measures where appropriate. For example, quantitative PCR estimates of rRNA gene copy number for overall bacteria, fungi and *Archaea* will be used as a proxy for microbial biomass (Figure 13b – MBC pool) for regular sampling intervals after initial scaling to chloroform fumigation extraction based methods (Castro et al., 2010; De Graaff et al., 2010). Additionally, to better approximate activity (vs. abundance) of these groups, we will optimize methods for co-extraction of RNA and DNA and the use of the ratio of rRNA transcripts / rRNA genes as an index of the specific activity of these groups (Figure 13b –pathways 4 & 5). Similarly, where possible we will incorporate the use of functional gene markers for processes involved in SOC decomposition (e.g. laccase, cellobiohydrolase, phenol oxidase, etc.), both when particular substrates are added to the soils, and when SOM itself forms the only substrate (Figure 13b – pathway 9). Select samples (e.g. initial soils and endpoints) in the incubations will also be assessed for microbial population structure using (rRNA gene) pyrosequencing for the same broad groups of organisms (bacteria, fungi and archaea) using previously demonstrated methods (Gottel et al. 2011). Samples will be PCR amplified with barcoded DNA primers and multiplexed for sequencing using the Roche/454 instrument available in the ORNL Biosciences Division that can accommodate up to 60 samples per run.

Carbon Cycle Modeling – Hypothesis 4 states that an exoenzyme-based soil C model can be deployed with sufficient realism to explain the regional- to global-scales patterns in soil C distribution. The LDRD model currently represents coupled sorption and degradation of dissolved organic C, soil order and mineralogy, and enzymatic microbial degradation of SOM as a function of temperature (Wang et al., 2012), (e.g., Figure 13b). In this new research, the model will use experiments from the three sub-tasks above to account for temperature- and moisture-induced changes in ad/de-sorption, DOC production, SOM chemistry, microbial community distribution and function. Through the LDRD program, the model was designed as a stand-alone module within Matlab. Here, it will be re-coded into FORTRAN to replace the current decomposition portion of CLM-CN. Multiple model experiments will be performed for the purpose of determining the sensitivity of different model input parameters, including enzyme activity, sorptive capacity, microbial biomass and activity, and degradation rates as a function of temperature, enzyme concentration and soil type. The model will initially be tested using short- and long-term incubation data and literature values. Later, parameters obtained from our experiments will be input into the validated model and tested for their applicability to existing lab- and field-scale data sets (e.g., SPRUCE, EBIS-AmeriFlux, MOFLUX, and other long-term experimental sites). In particular, we will use the high temporal and spatial resolution available in the multiple TES field sites and accompanying lab experiments to test our model. For the SPRUCE site, the model can be simplified by excluding minerals (MOC) and including only the model components shown in the upper portion of Figure 13b (POC). Finally, the model will be linked into CLM-CN and tested against regional and global scale data sets.

Table 3.8 Task F3c Future Deliverables

Date	Deliverable	Status
FY2012	- Manuscript on parameter suitability and application of model to a long-term field experiment.	August 2012
FY2013	- Temperature dependence of the sorption of common soil substrates – experimental - Temperature dependence of the sorption of common soil substrates – modeling	Planned
FY2014	- Characterize the degradation of soil organic matter and fractions as a function of temperature - Determine temperature sensitivity of substrate addition and organic matter decomposition - Modeling the decomposition of soil organic matter as a function of temperature	Planned

	- Enzyme activities in multiple soil types as a function of substrate type - Development of Q-PCR proxy techniques for quantifying microbial biomass	
FY2015	- The formation of dissolved organic C from the decomposition of soil organic matter by microbial exoenzymes - Changes in soil organic matter composition as a function of temperature, time, and substrate addition - Enzyme activities in multiple soil types as a function of temperature - Development of DNA/RNA ratios of microbial enzyme activities - Incorporating microbial community composition into soil organic matter models - Validation of mechanistic modeling of microbial exoenzyme facilitated decomposition of soil organic matter - Functional mechanistic model of microbial exoenzyme facilitated decomposition of soil organic matter linked with regional and global simulations of CLM-CN model	Planned

3.6 TASK F4 – TERRESTRIAL IMPACTS AND FEEDBACKS OF CLIMATE VARIABILITY, EVENTS AND DISTURBANCES

The overall goal of Task F4 for FY2013 to FY2015 is to understand responses of ecosystem fluxes of CO_2, water vapor, sensible heat, methane, and isoprene to climate variability and to transfer such understanding to large scale earth system modeling and projections. An integrated observational and modeling approach that links fundamental processes with ecosystem fluxes has been proven effective to Task F4 in the study of terrestrial impacts and feedbacks of climate variability, extreme events and disturbances. We will continue this approach as we carry out revised plans. Sustained efforts at the MOFLUX site will focus on canopy mesophyll conductance controls on GPP, and on the belowground fraction of net primary production known to be highly uncertain (Curtis et al. 2002; Wayson et al. 2006). Fine root dynamics will be monitored for the first time at the site and these measurements to allow better understanding of net ecosystem exchanges measured by the EC technique and soil efflux measured by the automated soil chambers.

Net ecosystem exchanges measured with the eddy covariance technique play a central role in our approach. Data from MOFLUX were crucial to the recent reformulation of the eddy covariance theory and the newly recommended operational practices (Gu et al. 2012). The continuation of MOFLUX will allow our team to provide assistance to the science community as the recommended EC operational practices are adopted. Continued operation of the MOFLUX site, strategically-located within the geographically and ecologically distinct prairie-forest precipitation transition, also allows us to support other researchers conduct independent research at the site. New research on isoprene emissions will be initiated at MOFLUX for FY2013 to 2015 to take advantages of collaborative measurements conducted by Dr. Alex Guenther of NCAR.

We also plan to establish a new eddy covariance observation station at the SPRUCE site in northern Minnesota to support Task R1 science objectives. Co-located eddy covariance measurements will include net ecosystem exchanges of CO_2, methane, water vapor and sensible heat. The primary objective will be to establish baseline net ecosystem exchange data for these variables for comparison to SPRUCE manipulation data. Such data will produce temporally resolved measures for testing ecosystem models with a specific focus on the development of an efficacious CLM-Wetland model. An associated empirical objective is to quantify peatland CH_4 and CO_2 fluxes and the relationships between them respond to climate variability at hourly to interannual time scales.

3.6.1 Task F4a – MOFLUX

MOFLUX observations provide data to inform land surface models on processes that strongly affect landscape-scale fluxes but are not adequately represented in modeling structures. For FY2012 and FY2013, we propose to focus this effort on mesophyll conductance, which has yet to be represented in land surface models. Studies have showed that photosynthetic reduction caused by mesophyll diffusion limitation can be up to 25% for crop species and up to 75% for wild plants (Warren 2008, Niinemets, Flexas & Penuelas 2010). Measurements at MOFLUX site have demonstrated that the effect of mesophyll conductance on leaf photosynthesis is comparable to that of stomatal conductance. We will first develop an understanding of how mesophyll conductance affects land surface fluxes under different climate conditions with FAPIS. The mesophyll conductance parameterization is a simple function of leaf dry mass per area and can be used readily in CLM. Once it is evaluated at MOFLUX, we will develop an implementation recommendation for CLM.

Quantification of belowground biological processes is an area of opportunity that has not been fully taken advantage of in MOFLUX data streams. Since 2004, eight soil respiration chambers have been operating at MOFLUX. Due to diligent monitoring and maintenance by our technicians, there have been no major gaps in soil efflux time series. However, the variability in observed soil CO_2 efflux has been large and cannot be fully explained by soil temperature or moisture. Previous work has shown that root respiration of recent photosynthate can contribute up to 65% of total soil CO_2 efflux (Eckblad and Högberg 2001), and that the magnitude and timing of root respiration is driven more by the availability of photosynthate, and seasonal patterns of belowground carbon allocation, than soil temperature (Högberg et al. 2001). We hypothesize that new photosynthates and fine root growth are contributing to soil CO_2 efflux at the MOFLUX site. Therefore, we plan to install minirhizotrons near soil chambers to image fine root growth, which will help us to better understand the variation in ecosystem carbon fluxes. Furthermore, the strong record of leaf phonological measurements at the MOFLUX site also gives us the opportunity to examine temporal correlations between leaf and root phenology, which could help to inform models projecting seasonal patterns of carbon uptake and allocation.

A new opportunity brought about by the collaborative measurements of isoprene emission measurements at MOFLUX (Dr. Alex Guenther of NCAR) suggests adjustments in ongoing efforts of Task F4a. Measurements conducted in 2011 showed that isoprene emission at MOFLUX is strongly controlled by temperature and PAR. But compared with a more northerly site (UMBS – University of Michigan Biological Station), MOFLUX isoprene emission showed more variation with temperature, PAR and with time (Figure 14). Current earth system models need representation and parameterization of isoprene emissions. Therefore, we will coordinate measurements and modeling with the NCAR team so that variations in isoprene emission rates can be better understood. Measurements of leaf biochemistry and physiology (A/Ci curves, chlorophyll fluorescence, leaf N content, specific leaf area, predawn leaf water potential etc.) will be conducted during periods of intensive isoprene emission. Canopy temperature will be inverted from outgoing longwave radiation to see if it can provide a better fit than air temperature for observed isoprene emissions. An isoprene modeling capability will be added to the terrestrial ecosystem Fluxes And Pools Integrated Simulator (FAPIS) to better integrate available data at MOFLUX. The FAPIS – isoprene module is fully tested; it can be migrated to CLM.

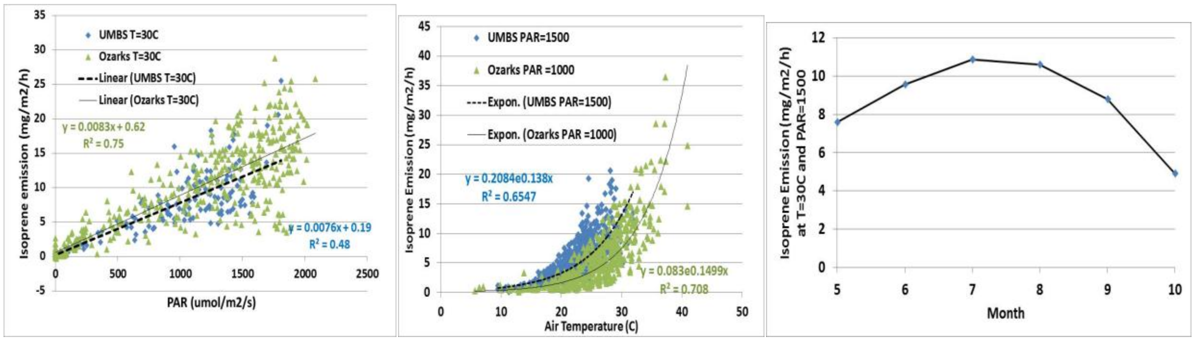

Figure 14. (Left and middle) comparison in isoprene emission between MOFLUX (Ozarks, green triangles) and UMBS (blue diamonds) for variations with PAR for a given temperature (left) and with temperature for a given PAR (middle). (Right) Temporal variation at the base rate of isoprene emission at MOFLUX.

We will continue the MOFLUX EC measurements to quantify the variability, vulnerability, and resilience of C uptake and water use. 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. 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 phenological phases will be tracked with Dr. Andrew

Richardson's PhenoCam (multiple daily images X365). 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.

With the added measurements and modeling capabilities, we will be able to answer the following questions:

1. How do ecosystem CO_2, water vapor and isoprene 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. What are the correlations between fluxes of CO_2 and isoprene?
3. Are there any signatures in ecosystem CO_2 and isoprene 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 and fine root growth to soil effluxes be quantified?
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? How do droughts and heat stress affect isoprene emission?
7. What is the long-term implication of the variability, resiliency, and thresholds in C uptake, water use and isoprene emission for the central hardwood forest – central grassland ecotone in a changing climate?

3.6.2 Task F4c – New SPRUCE Eddy Covariance Flux Observations

We plan to erect an aluminum scaffolding flux tower of 15m tall in the northern part of the S1 Bog, away from the planned manipulative experimental units. The maximal tree heights in the bog are about 7 to 8m and thus a 15m tall tower should satisfy the eddy flux measurement requirements. The exact height of the eddy covariance instrumentation will be determined with footprint analyses so that the influence from the manipulative experimental units and the upland forests surrounding the S1 Bog on flux measurements will be minimal under the prevailing wind direction from the west. The main eddy covariance instruments (CSAT3 sonic anemometers, Li7500A CO_2/H_2O open path analyzers and Li7700 CH_4 open path analyzers) have been purchased and the software needed to process data from these sensors has been developed. A profile system that measures the vertical variations in the concentrations of CO_2, CH_4 and H_2O will be developed with a Picarro CRDS G2301 analyzer. The vertical variations in the concentrations of these species will be used to determine their changes in storage in the canopy air space. A profile system that measures the vertical changes in temperature and humidity will be also deployed. Soil temperatures and moistures will be measured at different depths. The USFS has been already monitoring the water table depth in the northern part of the S1-bog. We plan to install the tower in January 2013 to take advantage of the frozen ground. Instrumentation of the flux tower will follow once the tower is erected. The flux tower is planned to be fully operational by the end of May 2013.

Measured fluxes of CO_2, water vapor, sensible heat, and methane will be used to test ecosystem models at the SPRUCE site to identify potential deficiencies in these models so that they can provide better guidance for future SPRUCE experiments and generalized for regional to global applications. Flux data analyses will initially focus on the diurnal to seasonal variations in the fluxes of CO_2, water vapor, sensible heat, and methane and how such variations are related to variations in temperature, radiation, atmospheric vapor pressure deficit, wind speed and water table depth. As the length of the available measurements grows, we will investigate the interannual variability of these fluxes and its implication for ecosystem carbon storage or release at landscape scales. By the end of FY2015, we expect we will be able to answer the following questions:

- What are the budgets of CO_2, water and methane at daily, weekly, monthly time scales at this peatland site?
- How are the methane budgets related to those of CO_2 and water at different time scales?
- What are the controlling processes for the net ecosystem exchanges of CO_2, water and methane?

Costs for the CO_2/CH_4/H_2O/temperature/humidity profile system are estimated to be $55K.

Dynamic analyses of disturbance impacts on terrestrial ecosystems

Disturbances have long been recognized as a fundamental force in shaping the structure, functioning and evolution of terrestrial ecosystems. However progress in disturbance research has been hindered by the lack of a proper model of disturbances and by the unavailability of quantitative methods to study them. We have developed a conceptual model (Sun et al. 2012) that not only unifies large-scale natural disturbances over their idiosyncrasies but also facilitates the development of quantitative methods that have broad applicability in the study of the dynamic impact on terrestrial ecosystems. We have tested the model on quantifying impacts of ice storms on forests. We plan to test the capability of the model on quantifying the impact of fires and droughts. This work will be carried out in collaboration with Dr. Robert Dickinson and his group at the University of Texas at Austin as the PhD project of a graduate student (Ying Sun). L. Gu serves as a committee member for Ying Sun's candidacy. This study represents a step forward towards a general disturbance theory.

Table 3.9 Future Task F4 Deliverables

Date	Deliverable	Status
FY2012	Submit MOFLUX data sets to the AmeriFlux data center. Install 8 minirhizotron tubes at the MOFLUX site	Ongoing & Planned
FY2013	Install the SPRUCE EC system for CO_2, CH_4, water vapor and sensible heat in northern Minnesota. Submit MOFLUX data sets to the AmeriFlux data center. Install minirhizotron camera and start taking images. Complete and test the isoprene-modeling module for FAPIS. Conduct initial observational and modeling analyses on the correlation between CO_2 fluxes and isoprene emissions. Develop implementation recommendation of mesophyll conductance modeling for CLM.	Planned
FY2014	Submit MOFLUX data sets to the AmeriFlux data center. Complete correlational analyses between fine root growth and soil respiration. Complete an analysis on the impact of temperature and PAR variation on CO_2 fluxes and isoprene emissions	Planned
FY2015	Submit MOFLUX data sets to the AmeriFlux data center. Complete a draft manuscript on the relationship between fine root growth and soil respiration. Complete a draft manuscript on the impact of temperature and PAR variability on CO_2 fluxes and isoprene emissions	Planned

3.7 TASK F5 – FOSSIL EMISSIONS

Task F5 will continue to address a number of actions consistent with the original SFA deliverables list. Specifically, Task F5 will

1. Create monthly emission inventories at the scale of states and months at a global scale – Due annually.
2. Create annual and monthly distributions of emissions – Due Annually.
3. Explore and publish uncertainty estimates associated with annual emissions – October 2012.

Data from items 1 and 2 will be made freely available to the public by CDIAC. We also expect to continue authoring peer-reviewed publications on these three items (the FY2011 SFA Annual Report lists the 14 major publications produced in the first two years of SFA funding). For example, recently submitted to the journal *Biogeosciences* is a synthesis on fossil fuel CO_2 emissions in support of the Global Carbon Project/RECCAP initiative to examine the global C balance at regional levels (Andres et al., 2012).

Uncertainty analysis of these emissions is a growing area of emphasis globally. We expect to continue our participation and leading role in uncertainty analysis of these emissions. Our current focus is on determining uncertainty at the national level. This effort continues then with determining the uncertainty associated with the sum of national totals to get a better understanding of uncertainty associated with the global total of emissions.

Table 3.10 Future Task F5 Deliverables

Date	Deliverable	Status
FY2013	Publication on uncertainty estimates associated with emissions	Oct 2012
FY2013-15	Monthly emission inventories at the scale of states and months at a global scale.	Annual
FY2013-15	Generation of annual and monthly distributions of global emissions	Annual

4. MANAGEMENT AND TEAM INTEGRATION

4.1 ORGANIZATIONAL STRUCTURE AND KEY PERSONNEL

The TES SFA includes a science and management team to guide and direct research activities. Responsibility for the TES SFA resides within the Energy and Environmental Sciences Directorate at ORNL and is aligned with associated and related activities of the Climate Change Science Institute (CCSI) of the Oak Ridge National Laboratory. The organization chart for the TES SFA is presented in Figure 15.

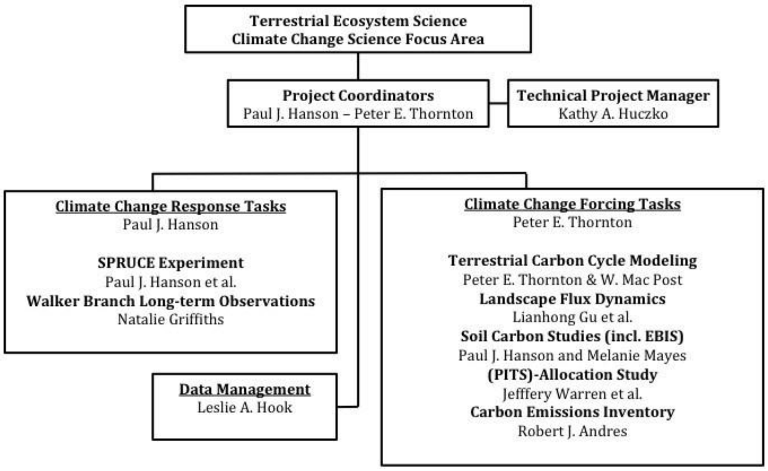

Figure 15. Organizational chart for the TES SFA effective December 2011.

Dr. Paul J. Hanson is the lead manager for the TES SFA and the Technical Coordinator for Climate Change Response Tasks. Dr. Peter E. Thornton is the other Technical Coordinator responsible for oversight of the Climate Change Forcing Tasks. Drs. Hanson and Thornton are supported by Kathy A. Huczko who brings expertise and technical skills in ORNL procedures, purchasing, contracts and engineering to the SFA. Individual Task leads (Figure 15) take responsibility for their respective initiatives in the TES SFA. Additional task-specific authority is also vested in other staff within the large SPRUCE experimental initiative.

The TES SFA project coordinators and research task leaders together with representative members from ORNL's CCSI (Jim Hack and Gary Jacobs), and a cross-SFA Data Systems Manager (e.g., Thomas Boden; CDIAC) form the TES SFA Leadership Team. The CCP Leadership Team will advise on the yearly SFA plans and budgets, monitors progress, adjusts project plans as appropriate, directs informatics development efforts, and resolves issues in a timely manner. The TES SFA benefits from advice of an established CCSI Science Advisory Panel (CCSI SAP), and has established a specific SPRUCE SAP for providing advice on our flagship experimental effort. These advisory panels are periodically solicited for their perspectives on research plans and deliverables.

4.2 PROJECT PLANNING AND EXECUTION

Monthly dashboard reports are produced for the CCSI and periodic teleconferences are held between the TES SFA Coordinators and DOE BER. Technical Coordinators and Task Leads meet at least monthly with their respective teams and staff to evaluate program integration and to ensure that research tasks are progressing and are being performed appropriately.

4.3 DATA SYSTEMS AND INFORMATICS

Data systems and informatics are not a separate task, but an integral part of the overall TES SFA concept. The open sharing of all data and results from SFA research and modeling tasks among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE's Program of Terrestrial Ecosystem Science. TES SFA researchers are identifying and deploying the data management systems and integration capabilities needed for the collection, storage, processing, archiving, access, discovery, delivery, and assimilation of available measurements, synthetic analysis results, model forcing and boundary condition data sets, and model outputs. Such capabilities facilitate model-data integration and provide accessibility to model output and benchmark data for analysis, visualization, and synthesis activities. Data systems and informatics enable the SFA vision of transforming the science of climate and atmospheric change and significantly improving global change prediction. A strong capability in this area facilitates delivery of SFA products to sponsors, the scientific community, and the public. Task specific web sites and web-based tools provide for such interactions.

The Carbon Dioxide Information Analysis Center (CDIAC) at ORNL will be the destination for these archive products (http://cdiac.ornl.gov). CDIAC provides long-term system stability, archive longevity, and reliable public data access.

4.4 COLLABORATIVE RESEARCH ACTIVITIES

A variety of collaborations are being fostered to provide necessary expertise or effort in areas critical to the completion of research tasks. In support of the SPRUCE experiment we have engaged a variety of modelers from Lund University, the University of Alberta, and the University of Sydney to produce *a priori* model results to help direct the application of treatments and the choice of measurements. We have completed an interaction with Rutgers University scientists to apply their expertise in ground-penetrating radar for the characterization of the SPRUCE experimental space, and we have established discipline-specific interactions with Dr. Merritt Turetsky (University of Guelph) in the study of the complex *Sphagnum* layer of the SPRUCE peatland biome. We will also be working closely with Dr. Joel Kostka and colleagues on a recently funded DOE BER study of microbial ecology within SPRUCE that will extend our capabilities.

We have established collaboration with Prof. Steven Running, University of Montana to maintain the strong connections that exist between the CLM and Biome-BGC models. The purpose of this effort is to coordinate a highly sophisticated though expensive model (CLM) with a highly efficient though less sophisticated model (Biome-BGC) that share construction and process representations. This allows for the evaluation of the influence of model structure and complexity on prediction uncertainty and parameter optimization.

A collaborative agreement with Richard Evans, retired director of the University of Tennessee Forest Resources Research and Education Center, and Kevin Hoyt, current director, has been important for providing access to research sites for PiTS experiments (Task F2) and assistance with infrastructure development. Also, external collaborators Douglas Lynch and Miquel Gonzalez-Meler (University of Illinois at Chicago) and Sarah O'Brien and Dionysios Antonopoulos (Argonne National Laboratory) are examining root metabolism and microbial community structure, respectively, in the PiTS girdling experiment at the historical ORNL FACE site.

Subcontracted collaborations for which DOE BER funds were or will be provided through ORNL are detailed further in a description of budget details. We also continue to encourage key external groups to develop complementary research tasks for the benefit of TES SFA research tasks. A number of such proposals are currently being evaluated for funding by DOE BER.

5. PERSONNEL

ORNL is uniquely positioned to deliver the science required to support the vision of the TES SFA. The original team established in 2009 has undergone several staff changes resulting from retirements, but has been supplemented by new developing staff in both the modeling and experimental areas. The TES SFA is supported by more than 31 dedicated scientific and technical staff with an established record of research, publication and leadership in climate change research. We have established a relationship with research partners at other National Laboratories and faculty and students at universities across the country and around the world. We have brought together exceptional multidisciplinary expertise, and are retaining and building staff flexibility to support new research priorities as they are identified.

- Dr. Paul J. Hanson will be the lead for the Climate Change Response tasks. With 25 years of experience as a plant physiologist and environmental ecologist, he operated and managed the long-term (14-year) Throughfall Displacement Experiment on the Oak Ridge Reservation. He currently manages the 35-member Ecosystem Studies Group of the Environmental Sciences Division at ORNL, is a Subject Editor for *Global Change Biology,* coordinates the multi-lab Enriched Background Isotope Study, and is currently coordinating the SPRUCE study. Dr. Hanson will have overall responsibility for the SPRUCE experiment and for communicating directly with each technical task leader for a variety of functional and measurement tasks associated with that study.
- Dr. Peter E. Thornton will be the lead for the Climate Change Forcing tasks. He is a key developer of the land-surface component of the Community Climate System Model (CCSM). His recent publications emphasize the importance of N limitations on the terrestrial C cycle and climate C cycle feedbacks. 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.
- Kathy A. Huczko serves as a Technical Project Manager for the TES SFA. She brings expertise and technical skills in ORNL procedures, purchasing, contracts, project management and engineering to the SFA.
- Dr. Les A. Hook serves as the Data Management Coordinator for the TES SFA. He brings expertise and technical skills for data policy, management, and archive planning and implementation. He will work with Task leads to ensure the timely archiving and sharing of SFA data products. Along with web site developer, Ranjeet Devarakonda, will develop and maintain Task specific web sites with project information, resources, and public data access.

Individual Task leads take responsibility for their respective continuing or future initiatives in the TES SFA as follows:

Task F1abcd – C cycle modeling activities will involve Mac Post, Daniel Hayes, Daniel Ricciuto, Dali Wang, Anthony King, Robert Andres, 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.

Task F2ab – Jeff Warren, Colleen Iversen, Rich Norby with 30 years of research experience in tree physiology and global change biology are leading Task F2 and a team of scientists to develop dynamic allocation representations for global models and applications. Anthony Walker will start as a postdoctoral associate in June 2012 to lead PiTS modeling activities.

Task F3c – Melanie Mayes will provide key expertise in soil C stabilization through mineral interactions, and along with Chris Schadt (microbial ecology) and Mac Post (modeling) will lead efforts to develop the next generation of mechanistic soil C model for CLM-CN that includes critical factors such as microbial community composition, exoenzyme-facilitated depolymerization, and mineral stabilization.

Task F4abc – Lianhong Gu leads activities in landscape flux of greenhouse gases associated with climate extremes utilizing eddy covariance data and associated experiments.

Task F5 – Robert Andres is responsible for the Emissions task focusing on uncertainty analyses to enhance our understanding of fossil fuel emissions for model and synthesis activities from an integrative perspective.

Task R1 SPRUCE Personnel

Experimental design, maintenance and environmental documentation – Paul Hanson will lead this effort in conjunction with the Randall Kolka of the USDA Forest Service. Richard Norby was also a key contributor to the experimental design and optimization phases being completed. ORNL is in the process of searching for and hiring a full-time staff person to live in northern Minnesota and provide day-to-day operation and oversight for the experiment.

Plant growth phenology and net primary production (NPP) – Paul Hanson, Richard Norby and Colleen Iversen are splitting efforts in this area. Paul Hanson is leading the focus on tree and shrub growth and vegetation phenology. Richard Norby is leading efforts to characterize growth and community dynamics of the diverse *Sphagnum* communities occupying the bog surface beneath the higher plants. Belowground response measurements will be led by Colleen Iversen with notable technical assistance from Joanne Childs.

Community composition – Efforts to characterize community compositional changes in response to the experimental treatments will be led by Brian Palik of the USFS (tree demography). Chris Schadt will develop and lead a related effort on microbial community changes.

Plant Physiology – Characterization of pre- and treatment plant physiological responses to both seasonal dynamics and induced treatment regimes will be led by Jeff Warren with the support of Stan Wullschleger and a pending postdoctoral hire.

Biogeochemical cycling responses – A number of staff will share responsibility for biogeochemical cycling responses. Work on hydrologic cycling will be led by Steve Sebestyen and Natalie Griffiths with input from Jeff Warren. Colleen Iversen will lead the element cycling subtask. C cycle observations focused on peat changes and C emissions will be coordinated by Paul J. Hanson, Randall Kolka and Colleen Iversen.

Modeling of terrestrial ecosystem responses to temperature and CO_2 – Peter Thornton and Daniel Ricciuto will coordinate efforts to utilize and incorporate experimental results into improved modeling frameworks for understanding the terrestrial C cycle and its feedbacks to climate.

A coordinating panel made up of the Response SFA research manager (Hanson), the local USFS contact (Kolka), the Technical Task leaders listed above, and a SPRUCE advisory panel make up the experimental advisory panel. This panel will serve as the decision-making body for major operational considerations throughout the duration of the experimental activity and it will be the panel for vetting requests for new research initiatives to be conducted within the experimental system.

Recent Personnel Actions **–** Two ORNL scientific staff persons were hired to participate on SPRUCE (Task R1) in FY2010 to contribute to SPRUCE. Colleen Iversen was hired to lead belowground productivity and root phenology observations, and Jeff Warren was hired to co-lead plant physiological evaluations and to evaluate and isolate plant water-use and water-relations responses of trees and woody shrubs. The SPRUCE research group has also hired a postdoctoral research associate: Dr. J. Megan Steinweg.

Dr. Patrick J. Mulholland was forced to transition to full time disability in spring 2011 because of a serious illness. In preparation for this transition, the TES SFA hired Dr. Natalie Griffiths as a postdoctoral associate to fill Pat's role in Tasks R1 and R2.

Charles T. Garten Jr. retired from ORNL at the end of FY2011. TES SFA staff and our colleagues at the USDA Forest Service are adjusting the scope of their respective individual task responsibilities to cover the pre-treatment measurement objectives for Task R1.

Since the beginning of the TES SFA activities in October 2009, Daniel Ricciuto and Daniel Hayes were hired as ORNL staff, and more recently Xiaoying Shi and Jiafu Mao were hired as ORNL staff.

Dr. Gregg Marland also announced his retirement from ORNL, but continues to be engaged in the estimation and summarization of global C emissions data as an unfunded collaborator.

5.1 PROPOSED EFFORT BY TES SFA STAFF IN FUTURE FISCAL YEARS

Table 5.1 Approximate annual person hours by ORNL staff and their major research tasks in future fiscal years (160 hours = 1 person month). This table does not account for support service staff contributions for instrumentation maintenance and calibrations that are significant for the field experiments and processes work.

Personnel Contributing to Tasks	R1: SPRUCE	F1abcd: C-Cycle Modeling	F2ab: Process Studies	F3c: Soil C Processes	F4ab: Landscape Flux	F5: Fossil C Emissions
Scientific Staff						
Andres	---	---	---	---	---	416
Devarakonda	60	20	20	20	20	20
Gu	---	---	---	---	1,374	---
Hanson	1,472	---	---	160	---	---
Hayes	---	1,095	---	---	---	---
Hook	120	---	40	---	80	---
Iversen	1,215	---	200	---	---	---
King	---	320	---	---	---	---
Mao	---	624	---	---	---	---
Mayes	---	---	---	650	---	---
Norby	800	---	100	---	---	---
Ricciuto	---	1,404	---	---	---	---
Schadt	320	---	---	200	---	---
Shi	---	624	---	---	---	---
Thornton	---	552	---	---	---	---
Wang	---	1,404	---	---	---	---
Warren	1,095	---	320	---	---	---
Weston	390	---	---	---	---	---
Wullschleger	600	---	---	---	---	---
Postdoctoral Staff						
Griffiths (ORISE)	960	---	---	---	---	---
Steinweg (ORISE)	936	---	---	936	---	---
Yang (ORISE)	---	936	---	---	---	---
Walker (ORISE)	---	---	1,310	---	---	---
TBD (ORISE)	1,872	---	---	---	---	---
Technical and Support staff						
Childs (ORNL)	1,368	---	384	---	---	---
Brice (ORNL)	1,155	---	160	---	---	---
Huczko (ORNL)	220	40	80	40	20	---
McCracken	160	---	---	---	---	---
Phillips (ORNL)	580	---	---	320	---	---
TBD (ORNL-MN)	1,872	---	---	---	---	---
Person Hours By Task	15,195	7,019	2,614	2,326	1,494	436

6. FACILITIES AND RESOURCES

ORNL has been demonstrating its commitment to climate and environmental change research through substantial investments over many years in climate change modeling, the development of innovative large-scale experimental infrastructures through the Laboratory Directed Research and Development program (LDRD), and in the construction of other critical infrastructures, including a new field support building (Building 1521), greenhouses, the Joint Institute for Biological Sciences, and renovations in support of molecular ecology. The Climate Change Science Institute brought together all ORNL Climate Change staff including members of the TES SFA into a single building and has been fostering better day-to-day interactions among modelers, experimentalists and data management specialists.

The TES SFA is supported by world-class capabilities at ORNL. The National Leadership Computing Facility provides an open, unclassified resource that we will use to enable breakthrough discoveries in climate prediction. It houses the largest unclassified computing capability available to climate change researchers in the world. The Earth System Grid (ESG), which involves six DOE Laboratories and the National Center for Atmospheric Research (NCAR), integrates supercomputers with large-scale data and analysis servers located at numerous National Laboratories and research centers to create a powerful environment for next generation climate research. The Carbon Dioxide Information Analysis Center (CDIAC) is pioneering utilization of infrastructure support for data and model integration that we will use and build upon in the CCP. The Atmospheric Radiation Measurement Program data system (ARM Archive), the NASA Distributed Active Archive Center for Biogeochemical Dynamics (NASA-DAAC), and the USGS-funded National Biological Information Infrastructure (NBII) Metadata Clearinghouse provide additional expertise in this emerging research discipline.

ORNL is also home to the High Flux Isotope Reactor and the Spallation Neutron Source, which we can use to understand physical, chemical, and biological complexity in plant and soil processes. Further, ORNL has access to the Oak Ridge Reservation and National Environmental Research Park, a unique resource comprising multiple ecosystem types that are protected, available for observation and manipulation, and supported with infrastructure. Walker Branch Watershed on the Oak Ridge Reservation is a candidate core site for the National Ecological Observatory Network (NEON), a National Science Foundation continental-scale observation system whose aim is to determine long-term changes in ecosystem structure and function in response to climate and other environmental factors.

Other facilities that we plan to use are located at collaborating DOE National Laboratories. The Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (LLNL-CAMS) provides large volume, high precision ^{14}C measurements for ecosystem tracer studies. Pacific Northwest National Laboratory's Environmental Molecular Science Laboratory combines advanced instrumentation such as high-throughput mass spectrometry, advanced microscopy instruments, and NMR instruments with high performance computing. The Advanced Photon Source (APS) at ANL provides the brightest x-ray beams in the Western Hemisphere to enable analysis of chemical and physical structure of components of ecosystem biogeochemical cycles.

This page left blank for double-sided printing.

BIBLIOGRAPHY

(TES SFA publications completed since October 2009
are listed in Appendix A and not repeated here.)

Allison SD (2006) Soil minerals and humic acids alter enzyme stability: implications for ecosystem processes. *Biogeochemistry* 81:361-373.

Allison SD, Wallenstein MD, Bradford MA (2010) Soil carbon response to warming dependent upon microbial physiology. *Nature Geosciences.* 3:336-340.

Andres RJ, Boden TA, Bréon F-M, Ciais P, Davis S, Erickson D, Gregg JS, Jacobson A, Marland G, Miller J, Oda T, Olivier JGJ, Raupach MR, Rayner P, Treanton K (2012) A synthesis of carbon dioxide emissions from fossil fuel combustion. *Biogeosciences* (submitted).

Aroca R, Porcel, Ruiz-Lozano JM (2012) Regulation of root water uptake under abiotic stress conditions. *Journal of Experimental Botany* 63:43-57.

Bais HP, Weir TL, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology* 57:233-266.

Clymo RS (1970) The growth of *Sphagnum*: methods of measurement. *Journal of Ecology* 102:589–614.

Conant RT, Ryan MG, Ågren GI, Birge HE, Davidson EA, Eliasson PE, Evans SE, Frey SD, Giardina CP, Hopkins FM, Hyvönen R, Kirschbaum MUF, Lavallee JM, Leifeld J, Parton WJ, Steinweg JM, Wallenstein MD, Martin Wedderstedt JÅ, Bradford MA (2011) Temperature and soil organic matter decomposition rates – synthesis of current knowledge and a way forward. *Global Change Biology* Doi:10.1111/j.1365-2486.2011.02496.x

Conant RT, Steinweg JM, Haddix ML, Paul EA, Plante AF, Six J (2008) Experimental warming shows that decomposition temperature sensitivity increases with soil organic matter recalcitrance. *Ecology* 89:2384-2391.

Conen F, Leifield J, Seth B, Alewell C (2006) Warming mineralizes young and old soil carbon equally. *Biogeosciences* 3:515-519.

Cottingham KL, Lennon JT, Brown BL (2005) Knowing when to draw the line: designing more informative ecological experiments. *Frontiers in Ecology and the Environment* 3:145-152.

Craine JM, Fierer N, McLauchlan KK (2010) Widespread coupling between the rate temperature sensitivity of organic matter decay. *Nature Geosciences* 3:854-857

Curtis PS, Hanson PJ, Bolstad P, Barford C, Randolph JC, Schmid HP, Wilson KB (2002) Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agriculture and Forest Meteorology* 113:3-19.

Davies WJ (2007) Root growth response and functioning as an adaptation in water limiting soils, *In:* Advances in molecular breeding toward drought and salt tolerant crops, MA Jenks et al. (eds), Springer, pp 55-72.

Dimitrov DD, Grant RF, LaFleur PM, Humphreys E (2010a) Modeling the subsurface hydrology of Mer Bleue bog. *Soil Science Society of America Journal* 74:680-694 doi: 10.2136/sssaj2009.0148.

Dimitrov DD, Grant RF, LaFleur PM, Humphreys E (2010b) Modeling the effects of hydrology on ecosystem respiration at Mer Bleue bog. *Journal of Geophysical Research, Biogeosciences* 115:G04043 doi: 10.1029/2010JG001312.

DOE (2009) *DOE Climate Change Research Program: Strategic Plan*: http://www.sc.doe.gov/ober/CCRD/climate%20strategic%20plan.pdf

Ekblad A, Högberg P (2001) Natural abundance of ^{13}C in CO_2 respired from forest soils reveals speed of link between tree photosynthesis and root respiration. *Oecologia* 127:305-308.

Euskirchen ES, McGuire AD, Chapin FS, et al. (2009) Changes in vegetation in northern Alaska under scenarios of climate change, 2003-2100: implications for climate feedbacks. *Ecological Applications* 19:1022-1043.

Fang C, Smith P, Smith JU (2006) Is resistant organic matter more sensitive to temperature than the labile organic matter? *Biogeosciences* 3:65-68.

Feddes RA, Hoff H, Bruen M, Dawson T, de Rosnay P, Dirmeyer O, Jackson RB, Kabat P, Kleidon A, Lilly A, Pitman AJ, (2001), Modeling root water uptake in hydrological and climate models. *Bulletin of the American Meteorological Society* 82(12): 2797-2809.

Feddes RA, Roats PAC (2004) Parameterizing the soil-water-plant root system. In proceedings of the Symposium on Unsaturated Zone Modeling, Wageningen, Netherlands, Oct. 3-5, 2004, *Unsaturated-Zone Modeling: Progress, Challenges and Applications,* Book Series: Wageningen UR Frontis Series eds. Feddes FA, DeRooij GH, VanDam JC. Volume 6, 95-141pp.

Frankenberg C, Fisher JB, Worden J, Badgley G, Saatchi SS, Lee J-E, Toon GC, Butz A, Jung M, Kuze A, Yokota T (2011) New global observations of the terrestrial carbon cycle from GOSAT: Patterns of plant fluorescence with gross primary productivity. *Geophysical Research Letters* 38:L17706, doi: 10.1029/2011GL048738.

Gottel NR, Castro HF, Kerley M, Yang ZM, Pelletier DA, Podar M, Karpinets T, Uberbacher E, Tuskan GA, Vilgalys R, Doktycz MJ, Schadt CW (2011) Distinct microbial communities within the endosphere and rhizosphere across contrasting soil types. *Applied and Environmental Microbiology* 77:5934-5944.

Gu L, Post WM, Baldocchi D, Black TA, Verma SB, Vesala T, Wofsy SC (2003) Phenology of Vegetation Photosynthesis. Chapter 7.2 in *Phenology: An Integrated Environmental Science*, Mark D. Schwartz, Editor, Kluwer Academic Publishers, Dordrecht, the Netherlands, 592pp.

Haddix ML, Plante AF, Conant RT, Six J, Steinweg JM, Magrini-Bair K, Drijber RA, Morris SJ, Paul EA (2011) The role of soil characteristics on temperature sensitivity of soil organic matter. *Soil Science Society of America Journal* 75: 56-68.

Hanson PJ, Swanston CW, Garten CT Jr., Todd DE, Trumbore SE (2005) Reconciling change in Oi-Horizon Carbon-14 with mass loss for an oak forest. *Soil Science Society of America Journal* 69:1492-1502.

Hayes MHB, Swift RA, Byrne CM, Simpson AJ (in prep) The isolation and characterization of humic substances and humin from grey brown podzolic and gley grassland soils. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1 – 6 August (2010), Brisbane, Australia, 198-201.

Hayes DJ, McGuire AD, Kicklighter DW, Gurney KR, T.J. Burnside, Melillo JM (2011) Is the northern high latitude land-based CO_2 sink weakening? *Global Biogeochemical Cycles*, 25(3):GB3018; doi: 10.1029/2010gb003813.

Hayes MHB, Swift RA, Byrne CM, Simpson AJ (2010) The isolation and characterization of humic substances and humin from grey brown podzolic and gley grassland soils. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1 – 6 August (2010), Brisbane, Australia, 198-201.Jagadamma S, Mayes MA, Steinweg JM, Phillips JR Sorption of 14C labeled organic carbon compounds on mineral surface of global soils. In preparation.

Herron PM, Gage DJ, Cardon ZG (2010) Micro-scale water potential gradients visualized in soil around plant root tips using microbiosensors. *Plant, Cell & Environment* 33: 199-210, doi: 10.1111/j.1365-3040.2009.02070.x

Hodge A (2004), The plastic plant: root responses to heterogeneous supplies of nutrients. *New Phytologist* 162(1): 9-24.

Hodge A, Berta G, Doussan C, Merchan F, Crespi M (2009) Plant root growth, architecture and function. *Plant and Soil* 321(1-2): 153-187.

Högberg P, Nordgren A, Buchmann N, Taylor AFS, Ekblad A, Högberg MN, Nyberg G, Ottosson-Löfvenius M, Read DJ (2001) Large-scale forest girdling shows that current photosynthesis drives soil respiration. *Nature* 411:789-792.

Hopmans JW, Bristow KL (2002) Current capabilities and future needs of root water and nutrient uptake modeling. *Advances in Agronomy* 77:103-183.

Kim HJ, Hummel JW, Sudduth KA, Motavalli PP (2007) Simultaneous analysis of soil macronutrients using ion-selective electrodes. *Soil Science Society of America Journal* 71(6): 1867-1877.

Kleber M, Sollins P, Sutton R (2007) A conceptual model of organo-mineral interactions in soils: self-assembly of organic molecular fragments into zonal structures on mineral surfaces. *Biogeochemistry* 85:9-24.

Lawrence CR, Neff JC, Schimel JP (2009) Does adding microbial mechanisms of decomposition improve soil organic matter models? A comparison of four models using data from a pulsed rewetting experiment. *Soil Biology & Biochemistry* 41:1923-1934.

Maurel C, Simonneau T, Sutka M (2010) The significance of roots as hydraulic rheostats. *Journal of Experimental Botany* 61(12): 3191-3198.

Miller PA, Wania R & Univs. Kuopio, Copenhagen, Helsinki, Stockholm & Lund, Komi SC (2010) Present-day and Future Carbon Fluxes from Northwestern Russian Tundra – An Integrative Approach. (in preparation).

Mu Q, Zhao M, Running SW (2011) Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment* 115:1781–1800.

Nemani RR, Keeling CD, Hashimoto H, Jolly WM, Piper SC, Tucker CJ, Myneni RB, Running SW (2003) Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* 300:1560–1563.

Niinemets U, Flexas J, Penuelas J (2011) Evergreens favored by higher responsiveness to increased CO_2. *Trends in Ecology and Evolution* 26:136-142.

Norby RJ, Zak DR (2011) Ecological lessons from free-air CO_2 enrichment (FACE) experiments. *Annual Review of Ecology, Evolution, and Systematics* 42:181-203.

Oleson KW, Lawrence DM, Bonan GB, Flanner MG, Kluzek E, et al. (2010), Technical description of version 4.0 of the Community Land Model (CLM). NCAR/TN-478+STR.

Oswald SE, Menon M, Carminati A, Vontobel P, Lehmann E, Schulin R (2008) Quantitative imaging of infiltration, root growth, and root water uptake via neutron radiography. *Vadose Zone Journal* 7(3): 1035-1047.

Pierret A, Moran CJ, Doussan C (2005), Conventional detection methodology is limiting our ability to understand the roles and functions of fine roots. *New Phytologist* 166(3): 967-980.

Randerson JT, Hoffman FM, Thornton PE, Mahowald NM, Lindsay K, Lee Y-H, Nevison CD, Doney SC, Bonan G, Stockli R, Covey C, Running SW (2009) Systematic assessment of terrestrial biogeochemistry in coupled climate-carbon models. *Global Change Biology* 15:2462–2484.

Rebel KT, de Jeu RAM, Ciais P, Viovy N, Piao SL, Kiely G, Dolman AJ (2011) A global analysis of satellite derived and DGVM surface soil moisture products. *Hydrology & Earth System Sciences Discussions* 8:4281–4312.

Rewald B, Ephrath JE, Rachmilevitch S (2011), A root is a root is a root? Water uptake rates of Citrus root orders. *Plant Cell and Environment* 34(1): 33-42.

Riley WJ, Subin ZM, Lawrence DM, Swenson SC, Torn MS, Meng L, Mahowald NM, Hess P (2011) Barriers to predicting changes in global terrestrial methane fluxes: Analyses using CLM4Me, a methane boigeochemistry model integrated in CESM. *Biogeosciences Discussions* 8:1733-1807.

Running SW, Nemani RR, Heinsch FA, Zhao MS, Reeves M, Hashimoto H (2004) A continuous satellite-derived measure of global terrestrial primary production. *Bioscience* 54:547–560.

Sassan SS, Harris NL, Brown S, Lefsky M, Mitchard ETA, Salas W, Zutta BR, Buermann W, Lewis SL, Hagen S, Petrova S, White L, Silman M, Morel A (2011) Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences of the United States of America* 108:9899–9904.

Schimel JP, Weintraub MN (2003) The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model. *Soil Biology and Biochemistry* 35:549-563.

Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kogel-Knabner I, Lehmann, J, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Trumbore SE (2011) Persistence of soil organic matter as an ecosystem property. *Nature* 478:49-56.

Shevliakova E, Pacala SW, Malyshev S, Hurtt GC, Milly PCD, Caspersen JP, Sentman LT, Fisk JP, Wirth C, Crevoisier C (2009) Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink. *Global Biogeochemical Cycles* 23(GB2022):1-16, doi:10.1029/2007GB003176.

Simunek J, Huang K, and van Genuchten MTh (1998), The HYDRUS code for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 6.0, Research Report No. 144, U.S. Salinity Laboratory, USDA-ARS, Riverside, California, 164 pp.

Simunek J, Hopmans JW (2009) Modeling compensated root water and nutrient uptake. *Ecological Modelling* 220(4): 505-521.

Sinsabaugh RL (1994) Enzymic analysis of microbial pattern and process. *Biology and Fertility of Soils* 17:69-74.

Sollins P, Kramer MG, Swanston C, Lajtha K, Filley T, Aufdenkampe AK, Wagai R, Bowden RD (2009) Sequential density fractionation across soils of contrasting mineralogy: Evidence for both microbial- and mineral-controlled soil organic matter stabilization. *Biogeochemistry* 96:209-231.

Sperry JS, Adler FR, Campbell GS, Comstock JP (1998), Limitation of plant water use by rhizosphere and xylem conductance: results from a model. *Plant, Cell and Environment* 21: 347–359.

Sun Y, Gu L, Dickinson RE, Zhou B (2012) Spatial and temporal patterns of forest greenness after the massive 2008 Chinese ice storm and their implications for studies of large natural disturbances. *Geophysical Research Letters* (In review).

Sutton R, Sposito G (2005) Molecular structure in soil humic substances: the new view. *Environmental Science and Technology* 39:9009.

Swanston CW, Torn MS, Hanson PJ, Southon JR, Garten CT, Hanlon EM, Ganio L (2005) Initial characterization of processes of soil carbon stabilization using forest stand-level radiocarbon enrichment. *Geoderma* 128:52-62.

Thornton PE, Lamarque JF, Rosenbloom NA, Mahowald NM (2007) Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochemical Cycles* 21(4):GB4018 doi:10.1029/2006GB002868

Thornton PE, Doney SC, Lindsay K, Moore JK, Mahowald N, Randerson JT, Fung I, Lamarque JF, Feddema JJ, Lee YH (2009), Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model. *Biogeosciences* 6(10): 2099-2120.

Trumbore S, Gaudinski JB, Hanson PJ, Southon JR (2002) A whole-ecosystem carbon-14 label in a temperate forest. *EOS* 83:265,267-268.

Vargas R, Allen MF (2008), Dynamics of fine root, fungal rhizomorphs, and soil respiration in a mixed temperate forest: Integrating sensors and observations. *Vadose Zone Journal* 7(3): 1055-1064.

Von Lützow M, Kögel-Knabner I (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. *European Journal of Soil Science* 57:426-445.

Von Lützow M, Kögel-Knabner I (2009) Temperature sensitivity of soil organic matter decomposition – what do we know? *Biology and Fertility of Soils* 46:1-15.

Vorenhout M, van der Geest HG, van Marum D, Wattel K, Eijsackers HJP (2004) Automated and continuous redox potential measurements in soil. *Journal of Environmental Quality* 33:1562-1567.

Wang G, Post WM, Mayes MA, Frerichs J, Jagadamma S Typical lignocellulose-degrading enzymes: a synthesis of kinetic properties. *Soil Biology and Biochemistry* (In review).

Wania R, Ross I, Prentice IC (2009a) Integrating peatlands and permafrost into a dynamic global vegetation model: I. Evaluation and sensitivity of physical land surface processes. *Global Biogeochemical Cycles* 23:GB3014.

Wania R, Ross I, Prentice IC (2009b) Integrating peatlands and permafrost into a dynamic global vegetation model: II. Evaluation and sensitivity of vegetation and carbon cycle processes. *Global Biogeochemical Cycles* 23:GB015.

Wania R, Ross I, Prentice IC (2010) Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1.3.1. *Geoscientific Model Development* 3:565-584 doi: 10.5194/gmd-3-565-2010.

Warren CR (2008) Stand aside stomata, another actor deserves centre stage: the forgotten role of the internal conductance to CO_2 transfer. *Journal of Experimental Botany* 59:1475-1487.

Wayson CA, Randolph JC, Hanson PJ, Schmid HP, Grimmond CSB (2006) Comparison of soil respiration methods in a mid-latitude deciduous forest. *Biogeochemistry* 80:173-189.

Webb EK, Pearman GI, Leuning, R (1980) Correction of flux measurements for density effects due to heat and water vapor transfer. *Quarterly Journal of the Royal Meteorological Society* 106:85-100.

Weishampel P, Kolka R, King JY (2009) Carbon pools and productivity in a 1-km2 heterogeneous forest and peatland mosaic in Minnesota, USA. *Forest Ecology and Management* 257:747-754.

Wieder RK, Starr ST (1998) Quantitative determination of organic fractions in highly organic, *Sphagnum* peat soils. *Communications in Soil Science and Plant Analysis* 29:847-857.

Zhao MS, Running SW (2010) Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* 329:940–943.

Zhuang Q, Melillo JM, Kicklighter DW, Prinn RG, McGuire AD, Steudler PA, Felzer BS, Hu S. (2004) Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model. *Global Biogeochemical Cycles* 18:GB3010.

This page left blank for double-sided printing.

APPENDIX A: TES SFA PUBLICATIONS SINCE OCTOBER 2009

Published Papers

1. Amthor JS, Hanson PJ, Norby RJ, Wullschleger SD (2009) A comment on "'Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality' by Aronson and McNulty". *Agricultural and Forest Meteorology* 150:497-498.
2. Andres RJ, Gregg JS, Losey L, Marland G, Boden TA (2011) Monthly, global emissions of carbon dioxide from fossil fuel consumption. *Tellus B*, 63:309-327. Published online: 12 April 2011. doi: 10.1111/j.1600-0889.2011.00530.x.
3. Beaulieu JJ, Tank JL, Hamilton SK, Wollheim, WM, Hall RO, Mulholland PJ, Peterson BJ, Ashkenas LR, Cooper LW, Dahm CN, Dodds WK, Grimm NB, Johnson SL, McDowell WH, Poole GC, Valett HM, Arango CP, Bernot MJ, Burgin AJ, Crenshaw C, Helton AM, Johnson L, O'Brien JM, Potter JD, Sheibley RW, Sobota DJ, Thomas SM (2010) Nitrous oxide emission from denitrification in stream and river networks. *Proceedings of the National Academy of Sciences of the United States of America* (published online 20 December 2010).
4. Brosi GB, McCulley RL, Bush LP, Nelson JA, Classen AT, Norby RJ (2011) Effects of multiple climate change factors on the tall fescue-fungal endophyte symbiosis: infection frequency and tissue chemistry. *New Phytologist* 189:797-805.
5. Castro HF, Classen AT, Austin EE, Norby RJ, and Schadt CW (2010) Soil microbial community responses to multiple experimental climate change drivers. *Applied Environmental Microbiology* 76:999-1007.
6. Chen X, Post WM, Norby RJ, Classen AT. Modeling soil respiration and variations in source components using a multi-factor global climate change experiment. *Climatic Change* (published online 14 Dec 2010) doi: 10.1007/s10584-010-9942-2
7. Classen AT, Norby RJ, Campany CE, Sides KE, Weltzin JF (2010) Climate change alters seedling emergence and establishment in an old-field ecosystem. *PLoS ONE* 5:e13476.
8. De Graff M-A, Classen AT, Castro HF, Schadt CW (2010) Labile soil carbon inputs mediate the soil microbial community composition and plant residue decomposition rates. *New Phytologist* 188:1055–1064
9. De Graaff, M-A, Schadt CW, Rula K, Six J, Schweitzer J, Classen AT (2011) Elevated [CO_2] and plant species diversity interact to alter root decomposition. *Soil Biology and Biochemistry* 43:2347-2354; DOI: 10.1016/j.soilbio.2011.07.006
10. Engel EC, Weltzin JF, Norby RJ, Classen AT (2009) Responses of an old-field plant community to interacting factors of elevated [CO_2], warming, and soil moisture. *Journal of Plant Ecology* 2:1-11.
11. Friedlingstein P,Houghton RA, Marland G, Hackler J, Boden TA, Conway TJ, Canadell JG, Raupach MR, Ciais P, Le Quéré C, (2010) Update on CO_2 emissions. *Nature Geoscience* 3:811-812; DOI: 10.1038/ngeo1022
12. Fröberg M, Hanson PJ, Trumbore SE, Swanston CW, Todd DE (2009) Flux of carbon from ^{14}C-enriched leaf litter throughout a forest soil mesocosm. *Geoderma* 149:181-188.
13. Garten CT Jr. (2011) Comparison of forest soil carbon dynamics at five sites along a latitudinal gradient. *Geoderma* 167-168:30-40, doi:10.1016/j.geoderma.2011.08.007
14. Garten CT Jr, Classen AT, Norby RJ (2009) Soil moisture surpasses elevated CO_2 and temperature in importance as a control on soil carbon dynamics in a multi-factor climate change experiment. *Plant and Soil* 319:85-94.
15. Gaudinski JB, Torn MS, Riley WJ, Swanston C, Trumbore SE, Joslin JD, Majdi H, Dawson TE, Hanson PJ (2009) Use of stored carbon reserves in growth of temperate tree roots and leaf buds: analyses using radiocarbon measurements and modeling. *Global Change Biology* 15:992-1014.
16. Gray SB, Classen AT, Kardol P, Yermakov Z, Miller RM (2011) Multiple climate change factors interact to alter soil microbial community structure in an old-field ecosystem. *Soil Science Society of America Journal* 75:2217-2226.

17. Gregg, JS, Losey LM, Andres R J, Blasing TJ, Marland G (2009) The temporal and spatial distribution of carbon dioxide emissions from fossil-fuel use in North America. Journal of *Applied Meteorology and Climatology* 48:2528-2542.
18. Gu L, Massman WJ, Leuning R, Pallardy SG, Meyers T, Hanson PJ, Riggs JS, Hosman KP, Yang B (2012) The fundamental equation of eddy covariance and its application in flux measurements. *Agricultural and Forest Meteorology* 152:135-148; doi:10.1016/j.agrformet.2011.09.014
19. Gu L, Pallardy SG, Tu K, Law BE, Wullschleger SD (2010) Reliable estimation of biochemical parameters from C3 leaf photosynthesis-intercellular carbon dioxide response curves. *Plant, Cell and Environment* 33:1852-1874.
20. Gu L, Post WM, Baldocchi DD, Black TA, Suyker AE, Verma SB, Vesala T, Wofsy SC (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.
21. Gunderson CA, O'Hara KH, Campion CM, Walker AV, Edwards NT (2010) Thermal plasticity of photosynthesis: the role of acclimation in forest responses to a warming climate. *Global Change Biology* 16:2272-2286 doi: 10.1111/j.1365-2486.2009.02090.x
22. Gunderson CA, Edwards NT, Walker AV, O’Hara KH, Campion CM, Hanson PJ (2011) Forest phenology and a warmer climate – growing season extension in relation to climatic provenance. *Global Change Biology* (accepted)
23. Hanson PJ, Gunderson CA (2009) Root carbon flux: measurements versus mechanisms. *New Phytologist* 184:4-6.
24. Hanson PJ, Childs KW, Wullschleger SD, Riggs JS, Thomas WK, Todd DE, Warren JM (2011) A method for experimental heating of intact soil profiles for application to climate change experiments. *Global Change Biology* 17:1083-1096.
25. Hayes DJ, Turner DP, Stinson G., McGuire AD, Wei Y., West TO, Heath LS, deJong B, McConkey BG, Birdsey RA, Kurz WA, Jacobson AR, Huntzinger DN, Pan Y, Post WM, Cook RB (2012) Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions and a new approach for estimating net ecosystem exchange from inventory-based data**.** *Global Change Biology,* in press; doi: 10.1111/j.1365-2486.2011.02627.x.
26. Helton AM, Poole GC, Meyer JL, Wollheim WM, Peterson BJ, Mulholland PJ, Stanford JA, Arango C, Ashkenas LR, Cooper LW, Dodds WK, Gregory SV, Hall RO, Hamilton SK, Johnson SL, McDowell WH, Potter JD, Tank JL, Thomas SM, Valett HM, Webster JR, Zeglin L (2011) Thinking outside the channel: nitrogen cycling in networked river ecosystems. *Frontiers in Ecology and the Environment* 9:229-238.
27. Hollinger DY, Ollinger SV, Richardson AD, Meyers TP, Dail DB, Martin ME, Scott NA, Arkebauer TJ, Baldocchi DD, Clark KL, Curtis PS, Davis KJ, Desai AR, Dragoni D, Goulden ML, Gu L, Katul GG, Pallardy SG, Paw U KT, Schmid HP, Stoy PC, Suyker AE, Verma SB (2010) Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. *Global Change Biology* 16: 696-710.
28. Huntzinger DN, Post WM, Wei Y, Michalak AM, West TO, Jacobson AR,. Baker IT, Chen JM, Davis KJ, Hayes DJ, Hoffman FM, Jain AK, Liu S, McGuire AD, Neilson RP, Poulter B, Raczka BM, Tian HQ, Thornton P, Tomelleri E, Viovy N, Xiao J, Zeng N, Zhao M, Cook R (2012) North American Carbon Program (NACP) Regional Interim Synthesis: Terrestrial Biospheric Model Intercomparison, *Ecological Modeling*, in press.
29. Iversen CM, Murphy MT, Allen MF, Childs J, Eissenstat DM, Lilleskov EA, Sarjala TM, Sloan VL, Sullivan PF. 2011. Advancing the use of minirhizotrons in wetlands. *Plant and Soil* [Available on-line: DOI 10.1007/s11104-011-0953-1.]
30. Jain A, Yang X, Kheshgi H, McGuire A D, Post W, Kicklighter D (2009) Nitrogen attenuation of terrestrial carbon cycle response to global environmental factors. *Global Biogeochemical Cycles* 23:GB4028.
31. Jonas M, White T, Marland G, Lieberman D, Nahorski A, Nilsson S (2010) Dealing with uncertainty in GHG inventories: how to go about it? pp. 229-245, In: *Coping with Uncertainty: Robust Solutions*

[K. Marti, Y. Ermoliev and M. Makowski (eds.)]. Springer, Berlin, Germany [pp. 277, ISBN: 978-3-642-03734-4].

32. Jonas M, Marland G, Winiwarter W, White T, Nahorski Z, Bun R, Nilsson S. (2010) Benefits of dealing with uncertainty in greenhouse gas inventories: introduction. *Climatic Change* 103:3-18.
33. Jones CD, Hughes JK, Bellouin N, Hardiman SC, Jones GS, Knight J, Liddicoat S, O'Connor FM, Andres RJ, Bell C, Boo K-O, Bozzo A, Butchart N, Cadule P, Corbin KD, Doutriaux-Boucher M, Friedlingstein P, Gornall J, Gray L, Halloran PR, Hurtt G, Ingram WJ, Lamarque J-F, Law RM, Meinshausen M, Osprey S, Palin EJ, Parsons Chini L, Raddatz T, Sanderson MG, Sellar AA, Schurer A, Valdes P, Wood N, Woodward S, Yoshioka M, Zerroukat M (2011) The HadGEM2-ES implementation of CMIP5 centennial simulations. Geosci. Model Dev. 4:543-570. doi:10:5194/gmd-4-543-2011.
34. Kardol P, Campany CE, Souza L, Norby RJ, Weltzin JF, Classen AT. (2010) Climate change effects on plant biomass alter dominance patterns and community evenness in an experimental old-field ecosystem. *Global Change Biology* 16:2676-2687.
35. Kardol P, Cregger MA, Campany CE, Classen AT (2010) Soil ecosystem functioning under climate change: plant species and community effects. *Ecology* 91:767-781.
36. Kardol P, Reynolds WN, Norby RJ, Classen AT (2011) Climate change effects on soil microarthropod abundance and community structure. *Applied Soil Ecology* 47:37-44.
37. Kardol P, Todd DE Jr., Hanson PJ, Mulholland PJ (2010) Long-term successional forest dynamics: species and community responses to climatic variability. *Journal of Vegetation Science* 21:627-642.
38. Kloster S, Mahowald NM, Randerson JT, Thornton PE, Hoffman FM, Levis S, Lawrence PJ, Feddema JJ, Oleson KW, Lawrence DM (2010) Fire dynamics during the 20th century simulated by the Community Land Model. *Biogeosciences* 7:1877-1902 DOI: 10.5194/bg-7-1877-2010.
39. Kramer C, Trumbore S, Fröberg 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.
40. Leakey ADB, Ainsworth EA, Bernard SM, Markelz RJC, Ort DR, Placella SA, Rogers A, Smith MD, Sudderth EA, Weston DJ, Wullschleger SD, Yuan SH (2009) Gene expression profiling: opening the black box of plant ecosystem responses to global change. *Global Change Biology* 15:1201-1213.
41. Le Quere C, Raupach MR, Canadell JG, Marland G and 27 others (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* 2:831-836.
42. Lee X, Goulden ML, Hollinger DY, Barr A, Black TA, Bohrer G, Bracho R, Drake B, Goldstein A, Gu L, Katul G, Kolb T, Law BE, Margolis H, Meyers T, Monson R, Munger W, Oren R, Paw U KT, Richardson AD, Schmid H-P, Staebler R, Wofsy S, Zhao L (2011) Observed increase in local cooling effect of deforestation at higher latitudes. *Nature* 479:384-387; doi:10.1038/nature10588
43. Luo Y, Melillo J, Niu S, Beier C, Clark JS, Classen AT, Davidson E, Dukes JS, Evans RD, Field CB, Czimczik CI, Keller M, Kimball BA, Kueppers LM, Norby RJ, Pelini SL, Pendall E, Rastetter E, Six J, Smith M, Tjoelker MG, Torn MS (2011) Coordinated approaches to quantify long-term ecosystem dynamics in response to global change. *Global Change Biology* 17:843-854.
44. Lutz BD, Bernhardt ES, Roberts BJ, Mulholland PJ (2011) Examining the coupling of carbon and nitrogen cycles in Appalachian streams: the role of dissolved organic nitrogen. *Ecology* 92:720-632, doi: 10-1890/10-0899.l.
45. Marino GP, Kaiser DP, Gu LH, Ricciuto DM (2011) Reconstruction of false spring occurrence over the southeastern United States, 1901-2007: Increasing risk of spring freeze damage? *Environmental Research Letters* 6: Article Number: 024015; DOI: 10.1088/1748-9326/6/2/024015
46. Marland, G, (2010) Accounting for carbon dioxide emissions from bioenergy systems. *Journal of Industrial Ecology* 14:866-869.
47. Marland G (2010) The U.S. NRC report on monitoring and verification of national greenhouse gas emissions inventories, pp. 177-182, *Proceedings of the 3rd International Workshop on Uncertainty in Greenhouse Gas Inventories*, Lviv, Ukraine, 22-24 September, 2010, Lviv Polytechnical National University.

48. Mulholland PJ, Roberts BJ, Hill WR, Smith JG (2009) Stream ecosystem responses to the 2007 spring freeze in the Southeastern United States: Unexpected effects of climate change. *Global Change Biology* 15:1767-1776.
49. Mulholland PJ, Webster JR (2010) Nutrient dynamics in streams. *Journal of the North American Benthological Society* 29:100-117.
50. Nassar R, Jones DBA, Suntharalingam P, Chen JM, Andres RJ, Wecht KJ, Yantosca RM, Kulawik SS, Bowman KW, Worden JR, Machida T, Matsueda H (2010) Modeling global atmospheric CO_2 with improved emission inventories and CO_2 production from the oxidation of other carbon species. *Geoscientific Model Development*. 3:689-716.
51. Nassar R, Jones DBA, Kulawik SS, Worden JR, Bowman KW, Andres RJ, Suntharalingam P, Chen JM, Brenninkmeijer CAM, Schuck TJ, Conway TJ, Worthy DE (2011) Inverse modeling of CO_2 sources and sinks using satellite observations of CO_2 from TES and surface flask measurements. *Atmospheric ChemIstry and Physics* 11:6029-6047. doi:10.5194/acp-11-6029-2011.
52. Nelson RG, Hellwinckel CM, Brandt CC, West TO, De La Torre Ugarte DG, Marland G (2009) Energy use and carbon dioxide emissions from cropland production in the United States, 1990-2004. *Journal of Environmental Quality* 38:418-425.
53. Noormets A, Chen J, Gu L, Desai A (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.
54. Oleson KW, Lawrence DM, Bonan GB, Flanner MG, Kluzek E, Lawrence PJ, Levis S, Swenson SC, Thornton PE (2010) Technical description of version 4.0 of the community land model (CLM). *NCAR Technical Note*. NCAR/TN-478+STR 257 pp.
55. 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* 115:G04001, doi: 10.1029/2009JG001193
56. Ricciuto DM, King AW, Dragoni D, Post WM (2011) Parameter and prediction uncertainty in an optimized terrestrial carbon cycle model: Effects of constraining variables and data record length. *Journal of Geophysical Research-Biogeosciences* 116: G01033; DOI: 10.1029/2010JG001400
57. Riley WJ, Gaudinski JB, Torn MS, Joslin JD, Hanson PJ (2009) Fine-root mortality rates in a temperate forest: estimates using radiocarbon data and numerical modeling. *New Phytologist* 184:387-398.
58. Román MO, Schaaf CB, Yang X, Woodcock CE, Strahler AH, Braswell RH, Curtis PS, Davis KJ, Dragoni D, Goulden ML, Gu L, Hollinger DY, Kolb TE, Meyers TP, Munger JW, Privette JL, Richardson AD, Wilson TB, Wofsy SC (2009) The MODIS (Collection V005) BRDF/Albedo Product: Assessment of spatial representativeness over forested landscapes. *Remote Sensing of Environment* 113:2476-2498.
59. Schwalm CR, Williams CA, Schaefer K, Anderson R, Arain MA, Baker I, Barr A, Black TA, Chen GS, Chen JM, Ciais P, Davis KJ, Desai A, Dietze M, Dragoni D, Fischer ML, Flanagan LB, Grant R, Gu LH, Hollinger D, Izaurralde RC, Kucharik C, Lafleur P, Law BE, Li LH, Li ZP, Liu SG, Lokupitiya E, Luo YQ, Ma SY, Margolis H, Matamala R, McCaughey H, Monson RK, Oechel WC, Peng CH, Poulter B, Price DT, Riciutto DM, Riley W, Sahoo AK, Sprintsin M, Sun JF, Tian HQ, Tonitto C, Verbeeck H, Verma SB (2010) A model-data intercomparison of CO_2 exchange across North America: Results from the North American Carbon Program site synthesis. *Journal of Geophysical Research-Biogeosciences*, 15, Article Number: G00H05.
60. Shi X, Mao J, Thornton PE, Hoffman FM, Post WM (2011) The impact of climate, CO_2, nitrogen deposition, and land use change on simulated contemporary global river flow. *Geophysical Research Letters* 38: L08704; DOI: 10.1029/2011GL046773
61. Shi X, Mao J, Wang Y, Dai Y, Tang X (2011) Coupling a terrestrial biogeochemical model to the Common Land Model. *Advances In Atmospheric Sciences* 28: 1129-1142; DOI: 10.1007/s00376-010-0131-z
62. Shirley K. Marland E, Cantrell J, Marland G, (2011) Managing the costs of sequestration in durable, carbon-containing products. *Mitigation and Adaptation Strategies for Global Change* 16:325-346.

63. Takagi H, Saeki T, Oda T, Saito M, Valsala V, Belikov D, Saito R. Yoshida Y, Morino I, Uchino O, Andres RJ, Yokota T, Maksyutov S (2011) On the benefit of GOSAT observations to the estimation of regional CO_2 fluxes. *Scientific Online Letters on the Atmosphere (SOLA)* 7:161-164, doi:10.2151/sola.2011-041.
64. Thornton PE, Doney SC, Lindsay K, Moore JK, Mahowald NM, Randerson JT, Fung I, Lamarque J-F, Feddema JJ, Lee Y-H (2009) Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model. *Biogeosciences Discussions* 6:3303–3354.
65. Tipping E, Chamberlain PM, Fröberg M, Hanson PJ, Jardine PM (2011) Simulation of carbon cycling and Dissolved Organic Carbon transport in forest soil locally enriched with ^{14}C. *Biogeochemistry* (in press).
66. van Gorsel E, Delpierre N, Leuning R, Black A, Munger JW, Wofsy S, Aubinet M, Feigenwinter C, Beringer J, Bonal D, Chen B, Chen J, Clement R, Davis KJ, Desai A, Dragoni D, Etzold S, Grünwald T, Gu L, Heinesch B, Hutyra LR, Jans WWP, Kutsch W, Law BE, Leclerc MY, Mammarella I, Montagnani L, Noormets A, Rebmann C, Sonia W (2009) Estimating nocturnal ecosystem respiration from the vertical turbulent flux and change in storage of CO_2. *Agricultural and Forest Meteorology* 149:1919-1930.
67. Vargas R, Baldocchi DD, Bahn M, Hanson PJ, Hosman KP, Kulmala L, Pumpanen J, Yang B (2011) On the multi-temporal correlation between photosynthesis and soil CO_2 efflux: reconciling lags and observations. *New Phytologist* 191:1006-1017; doi:10.1111/j.1469-8137.2011.03771.x
68. Villalpando SN, Williams RS, Norby RJ (2009) Elevated air temperature alters an old-field insect community in a multifactor climate change experiment. *Global Change Biology* 15:930-942.
69. Vorenhout, M, HG van der Geest, D van Marum, K. Wattel, and HJP Eijsackers. 2004. Automated and continuous redox potential measurements in soil. *Journal of Environ Quality* 33:1562-1567.
70. Wang T, Ciais P,Piao SL, Ottle C, Brender P, Maignan F, Arain A, Cescatti A, Gianelle D, Gough C, Gu L, Lafleur P, Laurila T, Marcolla B, Margolis H, Montagnani L, Moors E, Saigusa N, Vesala T, Wohlfahrt G, Koven C, Black A, Dellwik E, Don A, Hollinger D, Knohl A, Monson R, Munger J, Suyker A, Varlagin A, Verma, S (2011) Controls on winter ecosystem respiration in temperate and boreal ecosystems. *Biogeosciences* 8:2009-2025; doi: 10.5194/bg-8-2009-2011.
71. Wang W, Ichii K, Hashimoto H, Michaelis AR, Thornton PE, Law BE, Nemani RR (2009) A hierarchical analysis of terrestrial ecosystem model Biome-BGC: equilibrium analysis and model calibration. *Ecological Modelling* 220:2009-2023.
72. Wang D, Ricciuto D, Post W, Berry M (2011) Parallel computing for terrestrial ecosystem carbon modeling (2010) Accepted for *Springer Encyclopedia on Parallel Computing* http://refworks.springer.com/mrw/index.php?id=2303
73. Warren JM, Brooks JR, Dragila MI, Meinzer FC (2011) In situ separation of root hydraulic redistribution of soil water from liquid and vapor transport. *Oecologia* 166:899-911;DOI:10.1007/s00442-011-1953-9
74. Warren JM, Iversen CM, Garten Jr CT, Norby RJ, Childs J, Brice D, Evans RM, Gu L, Thornton P, Weston DJ (2011) Timing and magnitude of C partitioning through a young loblolly pine (*Pinus taeda* L.) stand using ^{13}C labeling and shade treatments. *Tree Physiology*, doi: 10.1093/treephys/tpr129
75. Wullschleger SD, Strahl M (2010) Climate change: a controlled experiment. *Scientific American* 302(3):78-83.
76. Wullschleger SD, Childs KW, King AW, Hanson PJ (2011) A model of heat transfer in sapwood and implications for sap flux density measurements using thermal dissipation probes. *Tree Physiology* 31:669-679.
77. Xiao J, Zhuang Q, Law BE, Chen J, Baldocchi DD, Cook D., Oren R, Richardson AD, Wharton S, Ma S, Martin T., Verma SB, Suyker,.E, Scott RL, Monson RK, Litvak M, Hollinger DY, Sun G, Davis KJ, Bolstad PV, Burns SP, Curtis PS, Drake BG, Falk M, Fischer ML, Foster DR, Gu L, Hadley JL, Katul GG, Matamala,R. McNulty,S. Meyers,TP, Munger JW, Noormets A, Oechel WC, Paw U KT, Schmid HP, Starr G, Torn MS, Wofsy SC (2010) A continuous measure of gross primary

production for the conterminous U.S. derived from MODIS and AmeriFlux data. *Remote Sensing of Environment* 114:576-591.

78. Xiao JF, Zhuang QL, Law BE, Baldocchi DD, Chen JQ, Richardson AD, Melillo JM, Davis KJ, Hollinger DY, Wharton S, Oren R, Noormets A, Fischer ML, Verma SB, Cook DR, Sun G, McNulty S, Wofsy SC, Bolstad PV, Burns SP, Curtis PS, Drake BG, Falk M, Foster DR, Gu LH, Hadley JL, Katulk GG, Litvak M, Ma SY, Martinz TA, Matamala R, Meyers TP, Monson RK, Munger JW, Oechel WC, Paw UKT, Schmid HP, Scott RL, Starr G, Suyker AE, Torn MS (2011) Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agricultural and Forest Meteorology* 151:60-69.
79. Yang B, Pallardy SG, Meyers TP, Gu LH, Hanson PJ, Wullschleger SD, Heuer M, Hosman KP, Riggs JS and Sluss DW (2010) Environmental controls on water use efficiency during severe drought in an Ozark Forest in Missouri, USA. *Global Change Biology* 16:2252-2271, doi: 10.1111/j.1365-2486.2009.02138.x.
80. Yang X, Post WM (2011) Phosphorus transformations as a function of pedogenesis: A synthesis of soil phosphorus data using Hedley fractionation method. *Biogeosciences* 8:2907-2916, doi:10.5194/bg-8-2907-2011
81. Yang X, Wittig V, Jain AK, Post W (2009) Integration of nitrogen cycle dynamics into the Integrated Science Assessment Model for the study of terrestrial ecosystem responses to global change. *Global Biogeochemical Cycles* 23:GB4029 doi: 10.1029/2009GB003.
82. Yi C, Ricciuto D, Li R, Wolbeck J, Xu X, Nilsson M, Aires L, Albertson JD, Amiro B, Ammann C, Arain M, de Araujo AC, Aubinet M, Aurela M, Barcza Z, Barr A, Berbigier P, Beringer J, Bernhofer C, Black AT, Bolstad PV, Bosveld FC, Broadmeadow MSJ, Buchmann N, Burns SP, Cellier P, Chen J, Chen J, Ciais P, Clement R, Cook BD, Curtis PS, Dail DB, Davis KJ, Dellwik E, Delpierre N, Desai AR, Dore S, Dragoni D, Drake BG, Dufrêne E, Dunn A, Elbers J, Eugster W, Falk M, Feigenwinter C, Flanagan LB, Foken T, Frank J, Fuhrer J, Gianelle D, Goldstein A, Goulden M, Granier A, Grünwald T, Gu L, etc. (2010) Climate control of terrestrial carbon exchange across biomes and continents. *Environmental Research Letters* 5, Article Number 034007.
83. Zhou B, Gu L, Ding Y, Shao L, Wu Z, Yang X, Li C, Li Z, Wang X, Cao Y, Zeng B, Yu M, Wang M, Wang S, Sun H, Duan A, An Y, Wang X, Kong W (2011) The Great 2008 Chinese ice storm, its socioeconomic-ecological impact, and sustainability lessons learned. *Bulletin of the American Meteorological Society* 92, 47-60.
84. Zhou B, Li Z, Wang X, Cao Y, An Y, Deng Z, Letu G, Wang G, Gu L (2011) Impact of the 2008 ice storm on moso bamboo plantations in southeast China. *Journal of Geophysical Research-Biogeosciences* 116, Article Number: G00H06.

Manuscripts Submitted for Peer Review

85. Andres RJ, Boden TA, Bréon F-M, Ciais P, Davis S, Erickson D, Gregg JS, Jacobson A, Marland G, Miller J, Oda T, Olivier JGJ, Raupach MR, Rayner P, Treanton K (2012) A synthesis of carbon dioxide emissions from fossil fuel combustion. *Biogeosciences* (submitted).
86. Hayes, DJ, Turner DP, Stinson G, McGuire A, Wei Y, Heath LS, West TO, McConkey BG, deJong B, Birdsey RA, Kurz WA, Jacobson AR, Huntzinger DN, Pan Y, Post WM, Cook RB (in review) Reconciling estimates of the contemporary North American carbon balance among inventory-based approaches, terrestrial biosphere models and atmospheric inversions. *Global Change Biology* (submitted).
87. Ganshin A, Oda T, Saito M, Maksyutov S, Valsala V, Andres RJ, Fischer R, Lowry D, Lukyanov A, Matsueda H, Nisbet EG, Rigby M, Sawa Y, Toumi R, Tsuboi K, Varlagin A, Zhuravlev R (2011) A global coupled Eulerian-Lagrangian model and 1 × 1 km CO_2 surface flux dataset for high-resolution atmospheric CO_2 transport simulations. *Geosci. Model Dev. Discuss.* 4:2047-2080 (in review).
88. Huntzinger et al. North American Carbon Program (NACP) Regional Interim Synthesis: Terrestrial Biospheric Model Intercomparison. *Biogeosciences* (submitted).
89. Jagadamma S, Mayes MA, Steinweg JM, Phillips JR Sorption of ^{14}C labeled organic carbon compounds on mineral surface of global soils. In preparation.

90. Keppel-Aleks G, Wennberg PO, Washenfelder RA, Wunch D, Schneider T, Toon GC, Andres RJ, Blavier J-F, Connor B, Davis KJ, Desai AR, Messerschmidt J, Notholt J, Roehl CM, Sherlock V, Stephens BB, Vay SA, Wofsy SC (2011) The imprint of surface fluxes and transport on variations in total column carbon dioxide. *Biogeo. Discuss.* (submitted)
91. Luyssaert S, Gwenaël A, Andres R, Bastviken D, Bellassen V, Bergamaschi P, Bousquet P, Chevallier F, Ciais P, Corazza M, Dechow R, Erb K, Etiope G, Fortems-Cheiney A, Grassi G, Hartman J, Jung M, Lathière J, Lohila A, Moosdorf N, Njakou Djomo S, Otto J, Papale D, Peters W, Peylin P, Raymond P, Rödenbeck C, Saarnio S, Schulze E-D, Szopa S, Thompson R, Verkerk P, Vuichard N, Wang R, Wattenbach M, Zaehle S (2012) The European CO_2, CO, CH_4, and N_2O balance between 2001 and 2005. *Biogeosciences* (submitted).
92. Mao J, Shi X, Thornton PE, Piao S, Wang X (2012) Causes of spring vegetation greenness trends in the northern mid-high latitudes from 1982 to 2004. *Environmental Research Letters* (accepted).
93. Mao J, Thornton PE, Shi X, Zhao M and Post WM (2012) Remote sensing evaluation of CLM4 GPP for the period 2000 to 2009. Journal of Climate (in Review)
94. McFarlane KJ, Torn MS, Hanson PJ, Porras RC, Swanston CW, Callaham MA Jr., Guilderson TP (201?) Comparison of soil organic matter dynamics at five temperate deciduous forests with physical fractionation and radiocarbon measurements. *Biogeochemistry* (accepted pending revisions).
95. Parsekian AD, Slater L, Sebestyen SD, Kolka RK, Ntarlagiannis D, Nolan J, Hanson PJ (2012) On the potential to reduce uncertainties in assessments of peat volumes and carbon stocks using ground penetrating radar. (prepared for re-submission to Soil Science Society of America Journal (submitted).
96. Sun Y, Gu L, Dickinson R Zhou . (2012) Forest photosynthetic recovery from the massive 2008 Chinese ice storm. *Geophysical Research Letters* (in Review).
97. Steinweg JM, Frerichs J, Mayes MA, Jagadamma S Activation energy of extracellular enzymes in a global suite of soils. *Soil Biology and Biochemistry* (submitted).
98. Wang D, Post WM, Wilson BE Several Computational Opportunities and Challenges Associated with Climate Change Modeling. *IEEE Transactions* (submitted).
99. Wang D, Ricciuto D, Post W, Berry M (2011?) Parallel computing for terrestrial ecosystem carbon modeling. Accepted for *Springer Encyclopedia on Parallel Computing* http://refworks.springer.com/mrw/index.php?id=2303
100. Weber CF, Zak DR, Hungate BA, Jackson RB, Vilgalys R, Evans RD, Schadt CW, Megonigal JP, Kuske CR (2011) Responses of soil cellulolytic fungal communities to elevated atmospheric CO_2 are complex and variable across five ecosystems. *Environmental Microbiology* (submitted)

This page left blank for double-sided printing.

APPENDIX B: NOTEWORTHY PUBLICATIONS FROM PREVIOUS ORNL EXPERIMENTS OR OBSERVATIONAL STUDIES

With TES SFA support, ORNL staff continue to finalize previous research in the form of final publications and archived data. The following completed or accepted publications summarize new works produced since October of 2009.

Woody Plants in Warmer Atmospheres

- Gunderson et al. (2009) describe the acclimation of photosynthesis to prevailing temperatures, in saplings of four species in an open-top chamber (OTC) warming experiment at +0°, +2°, and + 4 °C. Optimum temperatures for photosynthesis shifted in concert with daytime air temperature. Seasonal acclimation in mature trees and experimental trees was not different from treatment-induced differences.
- Gunderson et al. (2011 accepted pending revisions) describe the responses of forest phenology to atmospheric warming. In a four-year field experiment, budburst was earlier in saplings grown in OTCs at +2° and +4 °C, and senescence and abscission were delayed, extending the growing season by 6 -28 days. Responses were compared to a 16-year record of canopy phenology in a mixed deciduous forest on the nearby Walker Branch Watershed.
- Carla Gunderson is also completing a manuscript on the impacts of warming on growth in four species of deciduous trees, native to either warmer or cooler parts of eastern North America. Trees grew in the field for four years, from seedlings to saplings, in OTCs maintained at 0°, 2°, or 4 °C above local ambient temperatures. Pooling all species, biomass of the “virtual forest” increased with warming, after the first year, such that biomass was up to 45% higher in the +4° trees, and 20% higher in the +2 °C treatment, though differences were significant only in year two. (To be completed summer of 2012).

Community and Ecosystem Response to Multiple Environmental Changes

The DOE BER funded OCCAM project investigators published articles covering microbial community (Castro et al. 2010, De Graff et al. 2010, Kardol et al. 2010), seedling emergence and establishment (Classen et al. 2010), endophyte interactions (Brosi et al. 2011) and plant species diversity (De Graff et al. 2011, Kardol et al. 2010) responses to multifactor elevated CO_2, warming and irrigation treatments.

Methods and Technologies for Advancing Climate Change Experiments

- Wullschleger and Strahl (2010; *Scientific American*) describe several sizable outdoor experiments for temperature, precipitation, and CO_2 concentrations that have been under way for more than a decade. They concluded that enough data have now been generated to improve models that predict climate, providing a more accurate picture of how woodlands, prairies and agricultural crops may change in a future world. They also concluded that new experiments are also needed to clearly predict the response of boreal, tundra and tropical plants and of ecosystems.
- Wullschleger et al. (2011) reported on the development of a numerical model that takes into account the thermal properties of wood, the physical dimensions and thermal characteristics of the probes, and the conductive and convective heat transfer that occurs due to water flow in the sapwood. The team of plant scientists and engineers observed that the fundamental calibration equation upon which technique is based was highly sensitive to variation in water content, sapwood density, radial gradients, wound diameter, and other operational characteristics of this technique. It was shown that use of the original calibration equation could result in significant over- and under-estimation of water flow and confound estimates of transpiration, a common ecosystem property measured by this approach.