2011 ANNUAL PERFORMANCE AND MANAGEMENT REPORT

TERRESTRIAL ECOSYSTEM SCIENCE
CLIMATE CHANGE SCIENCE FOCUS AREA
(TES SFA)

Environmental Sciences Division
Oak Ridge National Laboratory

Terrestrial Ecosystem Science Program
Biological and Environmental Research
DOE Office of Science

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1. PROGRAM OVERVIEW

Understanding and predicting ecosystem carbon cycles and responses in the context of climatic and atmospheric change is the focus of the Terrestrial Ecosystem Science Climate Change Science Focus Area (TES SFA). The proposed science includes large-scale manipulations, carbon cycle observations, process-level studies, and an integrating suite of modeling and prediction efforts. ORNL's environmental change manipulations are organized around a single experiment focusing on the combined response of multiple levels of warming at ambient or elevated CO_2 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. Carbon cycle modeling and research involves 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 mechanistic results of manipulative experiments to enable projections of future responses and feedbacks to climate forcing. ORNL's SFA plan and research philosophy eliminates the artificial distinction between experimental and observational studies and modeling (including model construction, parameter estimation, evaluation, and prediction). The TES SFA plan also includes limited support for core, long-term tracking of the hydrologic, biogeochemical and biological response of the Walker Branch Watershed to inter-annual climatic variations.

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 DOE National Laboratories. The proposed experiments, simulations, and measurements will 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.

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 Science 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 Science Focus Area (i.e., the TES SFA). This document includes progress-to-date reporting on all tasks of the Response and Forcing SFAs initiated October 2009 through June 2011. We also include a brief description of future planned research that will be further described in documents to be prepared for our first triennial review early in 2012.

Highlights for this reporting period October 2009 through June 2011

- Published 64 papers with 14 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 carbon dioxide 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).
- Developed new soil carbon cycle (Parton et al. 2010; Tipping et al. 2011) and root growth (Riley et al. 2009) model improvements to enhance the capacity of carbon cycle models to capture the fate and turnover of carbon.

- Proposed and demonstrated the importance of an improvement to the conventional eddy covariance theory with measurements from the MOFLUX site (Gu et al. 2011). Essentially all flux sites in the world, including MOFLUX, should reprocess their previous measurements in order to avoid bias errors in carbon and water fluxes and budgets. MOFLUX reprocessing is ongoing as of 10 July 2011.
- Demonstrated for the first time with a fully coupled Earth System Model (CESM) that carbon-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 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).

2. TES SFA PHILOSOPHY, RESEARCH, GOALS, AND MILESTONES

Due to anthropogenic carbon emissions and shifts in land use, the Earth's environment is changing on all scales, from local to global. Global change predictions made by the present generation of coupled climate-carbon cycle models are hampered by uncertainty surrounding fundamental climate-ecosystem feedbacks and by climate change impacts on ecosystem structure and function. TES SFA research is exercising an iterative modeling process 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 carbon 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-carbon model development and simulation.

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. The TES SFA's current environmental change manipulation is organized around a single climate change 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 organism decline or mortality, limitations to regeneration, biogeochemical limitations to productivity, carbon evolution).

Carbon cycle modeling and research involves the integration of biophysical, biochemical, physiological, and ecological processes into terrestrial ecosystem models. Terrestrial carbon-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 carbon 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 carbon storage and susceptibility to warming-induced decomposition, the accuracy of current models in predicting soil carbon 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 carbon, and to develop process-level models describing soil carbon response to environmental change.

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?

Goals and Milestones

Research goals and all milestones for near-, mid-, and long-term deliverables for the TES SFA are listed in the original SFA plans. In the context of annual reporting and a three-year review cycle initiated in October 2009, the following goals and their near-term (3-year) deliverables are summarized. Progress towards their completion is documented in Section 4 of this report.

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 carbon cycle feedbacks under future climatic warming and rising CO_2.*
    - Deliver a functional carbon 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 carbon sources and sinks.
    - Develop plans for new measurement and experimental needs, highlighted by forcing uncertainties [*ongoing through 2012*].
3. *Improve model representation of belowground carbon partitioning to better predict the fate of carbon under future climate warming, rising CO_2 and other climate perturbations*.
    - Short-term manipulative field measurements to quantify internal plant carbon partitioning (especially into belowground sinks) and subsequent impacts on soil nitrogen 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 carbon 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 carbon 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 carbon and water dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial carbon and Earth system models emphasizing the importance of the decadal time scale.*

- Synthesize existing land-atmosphere carbon, water and energy measurements and experimental results to constrain interannual and seasonal dynamics in terrestrial land surface and carbon models [*completed each year*].
  - MOFlux observations [*completed, archived and summarized for 2005 through 2010*].
  - Develop extreme events backbone database for drought and fire events [*on schedule for completion by December 2011*].

3. ORNL TES SFA PROGRAM STRUCTURE

3.1 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 1.

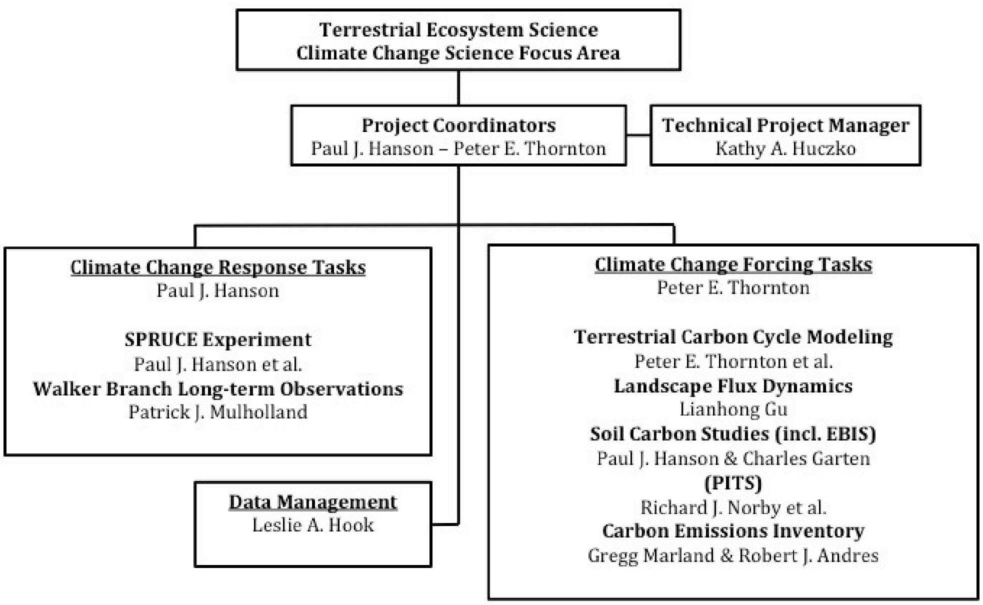

Figure 1. Organizational Chart for the TES SFA.

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 1) 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 directions, deliverables, and external views.

3.2 Project Planning and Execution

Monthly dashboard reports and teleconferences are held between the TES SFA Coordinators and DOE BER. Technical Coordinators and Task Leads are meeting 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.

3.3 Relationship of TES SFA Research To ORNL Climate Change Modeling

Global modeling activities at ORNL contribute to the development, testing and application of fully coupled climate and Earth system models needed to project the likely response of the climate system to natural and human-induced climate forcing. They deliver global and regional scale evaluations of critical uncertainties affecting the climate prediction problem at decadal and century time scales focusing on interactions between terrestrial ecosystems and climate. Global modeling helps guide the design and implementation of new measurements and experimentation, and synthesizes and integrates data and insights from experimental research and C cycle measurements.

3.4 Data Systems And Informatics

Data systems and informatics are not a separate focus area, 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 will facilitate model-data integration and provide accessibility to model output and benchmark data for analysis, visualization, and synthesis activities. Data systems and informatics will 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 will also facilitate delivery of SFA products to sponsors, the scientific community, and the public.

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. PERFORMANCE MILESTONES AND METRICS

This section provide progress-to-date summaries for each of the tasks of the combined TES SFA originally characterized as being components of individual Climate Change Response (R tasks) or Forcing (F tasks) science focus area. The summaries cover progress from October 2009 through June 2011. Full descriptions of the initial plans for these tasks can be found in the June 2009 ORNL Climate Change Program plan (http://tes-sfa.ornl.gov).

4A.1 Climate Change Response Tasks

4A.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 flexible and complete data sets needed to generate “response curves or multidimensional surfaces” for those environmental drivers needed for models to be used for projection 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 will provide a platform for testing mechanisms that control vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for organism decline or mortality, limitations to regeneration, biogeochemical limitations to productivity). The SPRUCE experiment will be conducted in a *Picea mariana* [black spruce] – *Sphagnum* spp. forest 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.

4a.1.1 SPRUCE Project Structure

The SPRUCE experiment comprises the research tasks identified in Figure 2. The key task leads and supporting personnel are indicated in the figure. A coordinating panel made up of the Response SFA research manager (Paul J. Hanson), the Minnesota USDA Forest Service contact (Randall K. Kolka), the Technical Task leaders, and a panel of external science advisors will make up the experimental advisory panel. This coordinating panel serves 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 added to the experiment when it becomes operational.

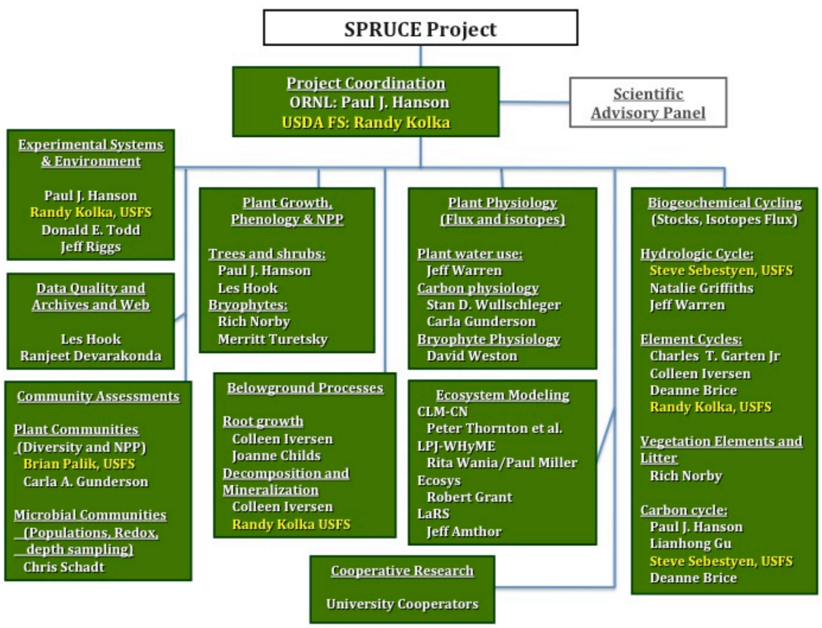

Figure 2. Organization of the SPRUCE experiment showing tasks and personnel.

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.

4a.1.2 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.

4a.1.3 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-carbon 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 indicates that the new method may produce disproportionately high carbon dioxide emissions from deep soil storage pools or enhanced root activity that have not been previously observed in warming studies. We are now actively engaged in testing these concepts at the 12-m diameter scale. ORNL scientists and engineers produced full construction plans for the concept by February 2010, established subcontracts for its construction in March, and on 18 June 2010 took ownership of a full-scale prototype of the enclosure for testing evaluation and continued improvement (Figure 3).

While planning and constructing the enclosure, we also engaged ORNL expertise in complex fluid dynamics modeling in various exercises to estimate the turbulence dynamics and energy use needs of the enclosure. Figure 4 illustrates the results of some of this work. Simulations covered various assumptions about external wind velocities, chamber design modifications, and the presence of internal vegetation. The simulations provided energy use estimates for an enclosure under conditions likely to be experienced at the Minnesota SPRUCE experimental location.

The enclosure has been populated with a variety of temperature sensors (air and soil), relative humidity sensors, an array of radiation sensors to evaluate its actual energy use, and CO_2 sampling ports to evaluate the homogeneity of temperature and atmospheric conditions within the enclosure and the energy demands needed to attain target warming temperatures.

A fully evaluated model for flow and energy balance is being used to better prepare us for the transition to propane-based air heating and provide a tool for estimating energy use. Complex fluid dynamics simulations for turbulence and energy (Figure 4) are close to the measured data from the warming prototype (data to be published). Charlotte Barbier (ORNL computational scientist) is actively adjusting boundary assumptions for her pre-measurement runs to match the characteristics and non-steady-state environments of the actual chamber.

Early results suggest that the as-built chamber which nominally exchanges air with the external environment once every 2.5 minutes (wind speed dependent) would require energy inputs on the order of 56,000 kW h per month to achieve a +5 °C warming temperature. This level of energy use is in the range of expected energy demands, but still high. ORNL engineers simulated and designed additional physical modifications to the aboveground enclosure for a frustum to further deflect external winds and limit energy losses. Following installation of the frustum the turnover time was increased and energy use went down. At a target temperature of +4 °C the enclosure is demonstrating a temperature differential per energy input value of 0.11 °C per kW of energy input.

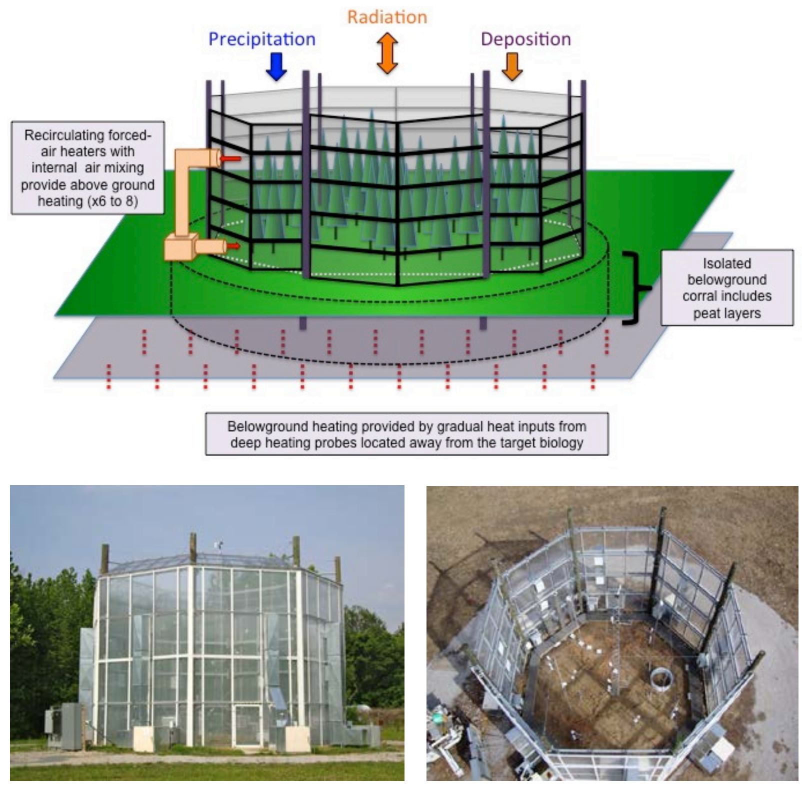

Figure 3. SPRUCE ecosystem warming enclosure concept (upper figure) and the final fully instrumented prototype (photographs). The warming enclosure has instrumentation for measuring turbulence, air temperature and relative humidity at multiple heights, and soil temperatures to depths as much as – 2m. Sampling tubes for [CO_2] measurements are also installed. Open path CO_2 and CH_4 sensors with sonic anemometers are currently being added (June/July 2011) to the central tower for "eddy-covariance-style" observations of the enclosure footprint.

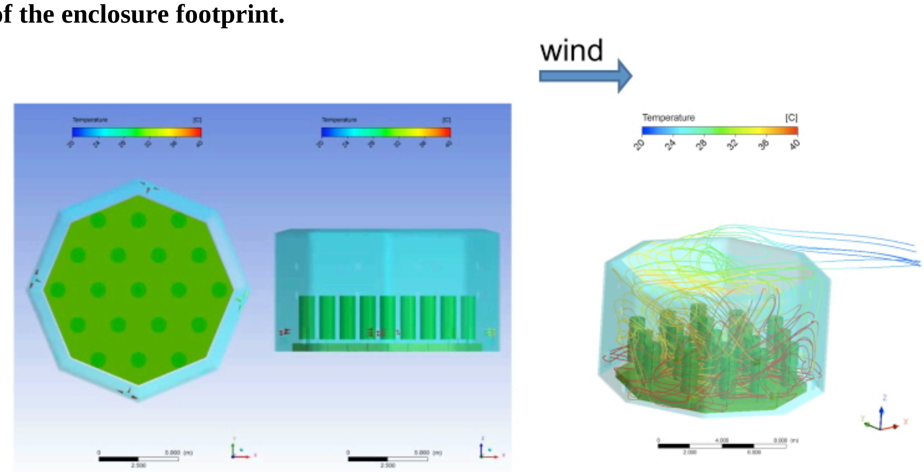

Figure 4. Conceptual diagram of the SPRUCE warming enclosure showing idealized spruce trees and an ericaceous shrub layer (left figure). Results from complex fluid dynamics simulations of the prototype warming enclosure show streamlines for "packets" of heated air as they tumble around within the enclosure and periodically become ejected. Simulations suggest substantial residence time of the air volume within the enclosure and reasonably uniform temperatures throughout the well-stirred air volume.

Site Engineering

ORNL engineers and safety personnel traveled to the Minnesota experimental site in June 2010 to gain first-hand experience with the environmental conditions of the S1 bog, evaluate a boardwalk design for access and use as a utility corridor, and to engage in scoping discussions with the local electric company and propane suppliers. 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 (Figure 5). These plans are now being pursued.

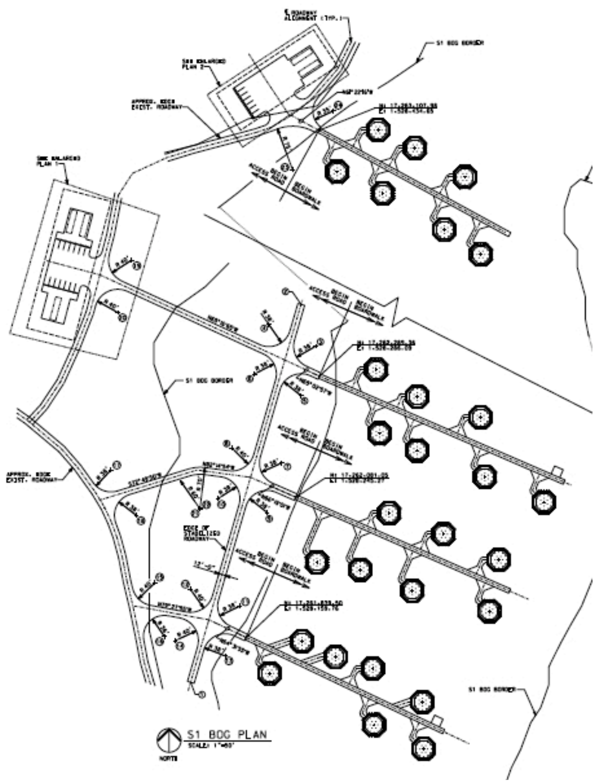

Figure 5. SPRUCE engineering site plan for the S1-bog showing the access roads, parking, parking areas, and temporary office buildings in upland areas to the west side of the bog, and the extensive network of boardwalks that must be added to the bog itself to allow repeated access to up to 28 experimental units.

Experimental Design

The SPRUCE experiment is being developed to determine ecological responses for trees, shrubs, bryophytes, microbial communities and whole-ecosystem processes across a broad range of above- and belowground temperature increases, and to test the interaction for how those responses to increased temperature will be altered by elevated atmospheric CO_2 concentration. Experimental temperature treatments will range from ambient condition 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 7 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 modify the number of treatment levels with the available 28 potential experimental units to accommodate the costs of constructing, operating, and adding instruments to the warming enclosures. A regression-based experimental design appropriate for uncovering the shape of the temperature or other environmental response curves has therefore been proposed as a better experimental design with more flexibility than traditional analysis of variance (ANOVA). Quantitative analyses with simulated data sets with a realistic variance structure revealed that a regression approach with 10 temperature levels had greater statistical power to resolve temperature responses than the originally proposed 16 plots arranged as four levels of temperature in four blocks, and at substantially lower cost and infrastructure requirements. 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 design with fewer levels of temperature and three levels of elevated CO_2 is also possible.

We plan to instrument and monitor chamberless control areas to assess the influence of the chamber infrastructure on the bog. Experimental units deployed over this broad range of temperatures would provide enough redundancy to protect against infrastructure failure while still allowing the flexibility to evaluate a range of forms for response curves. An important assumption 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 also been having an ongoing discussion of the manner in which temperature treatments would be applied. Initial assumptions would be that the treatments would be set to their target level from the start and held there for the duration of the 10-year study. Concerns about the arbitrary nature of the highest temperature treatments have led us to consider ramping temperatures over 5 years to target treatment temperature differentials and then holding them constant for the remaining operation period. This approach would allow some evaluation of the effects of rate of change on acclimation by a range of organism functional types, and the subsequent constant differential period would allow us to monitor the influence of interannual variations on the imposed treatments.

4a.1.4 Modeling: *a priori* approximations of experimental results

The SPRUCE project has engaged several modelers 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) have 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 it included an intermediate detailed model for methane flux.

Paul Miller produced a number of outputs for carbon cycle variables and species growth responses illustrated in the following figures. Figure 6(left) shows the hypothetical net ecosystem exchange of CO_2-C (NEE) from a simulated S1 forest stand under a range of warming treatments with or without exposure to elevated CO_2. According to these simulations warming treatments by themselves should reduce net carbon uptake by the bog ecosystem, however, exposure to elevated CO_2 atmospheres is projected to compensate for carbon loss induced by warming. The current version of LPJ-WHyMe does not include nutrient cycling feedbacks, which may lead to a more complex response. Net methane efflux from the bog was shown to increase with all warming and elevated CO_2 treatments, and the greatest emissions were associated with the highest temperatures combined with elevated CO_2 (Figure 6(right)). Substrate availability is likely to be driving this response within the LPJ-WHyMe model.

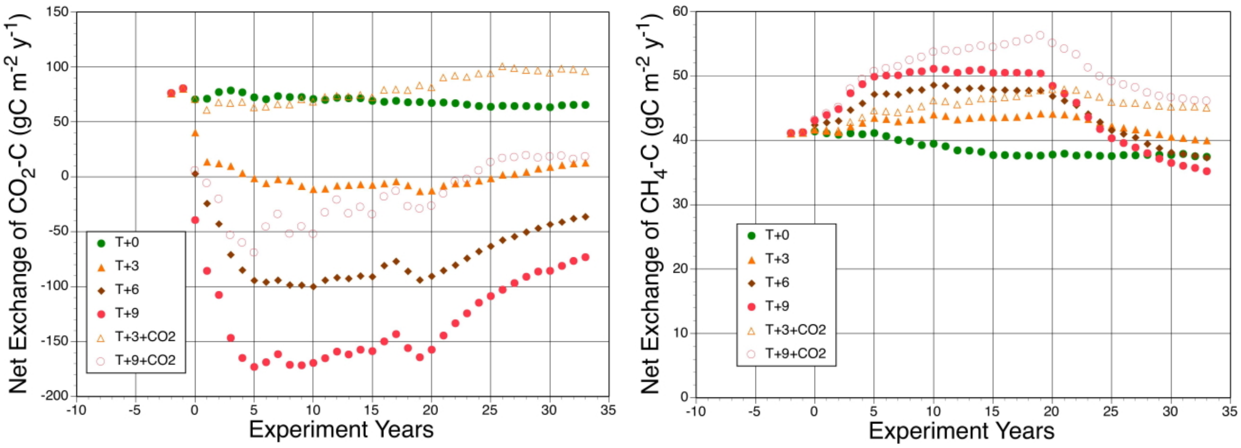

Figure 6. Simulated net ecosystem exchange of CO_2-carbon (left) and CH_4-carbon right from the S1 *Picea-Sphagnum* forest where year zero is the beginning of experimental treatments. In the CO_2 graphic negative values represent carbon release to the atmosphere.

The digital global vegetation model (DGVM) features of LPJ-WHyMe also allow for projections of species or plant functional type responses to the experimental treatments (data not shown). *Picea* trees were projected to decrease in importance with warming unless elevated CO_2 is present. With both warming and elevated CO_2 the *Picea* trees continue to prosper. Under all treatment combinations *Larix* trees are projected to become more important to the forest stand. The projected live biomass for the ericaceous shrubs and *Sphagnum* communities are considerably lower than that for *Picea* and *Larix* (note the different Y-axis magnitudes), and these functional types are not currently projected to be influenced much by the imposed treatments.

These initial simulations do not yet adequately represent the S1 bog. The modeled assumed biomass for *Sphagnum* species underestimates the measured reality in the field. Furthermore, the lack of nutrient cycling feedback phenomenon in the LPJ-WHyMe code leaves open the opportunity for a dramatic responses of all functional types if warming induced decomposition were to induce substantial mineralization of stored elements locked up in the layers of peat.

Peter Thornton (ORNL), Daniel M. Ricciuto (ORNL), and Gautam Bisht (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 carbon 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 (Figure 7). Initial runs with the original CLM-CN hydrology configuration are in general agreement with the LPJ-WHyMe results, showing strong warming-induced carbon 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).

Once the *Picea-Sphagnum* system parameterizations have been evaluated at the SPRUCE site, we will extend this implementation to the global scale by identifying the extent of similar ecosystems from existing global datasets. This extension from, experimental scale to global implementation and testing, bridges into the original Forcing SFA task on carbon cycle modeling (see section 4A.3).

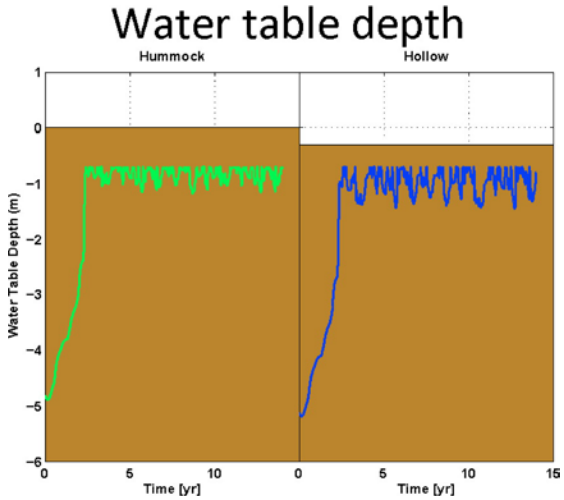

Figure 7. CLM-CN prediction of water table depth for hummock and hollow component of *Picea-Sphagnum* bog, demonstrating the ability of the new hydrology configuration to represent a perched water table characteristic of a bog environment.

A subcontract has been established to allow Robert Grant (University of Alberta) to conduct model runs with his *ecosys* model (Dimitrov et al. 2010ab). The *ecosys* model was previously configured for applications to boreal black spruce ecosystems and includes a detailed characterization of methane cycle mechanisms. Jeff Amthor (University of Sydney, and a member of our Scientific Advisory Panel) has been engaged to apply detailed tree physiological modeling algorithms within LaRS (Amthor 1996; Hanson et al. 2004) for the projection of logical *Picea* tree or seedling acclimation responses to the experimental temperature treatments. Although a subcontract is not yet established it may also be logical to fund some *a priori* model runs with the TEM model that has been applied to high latitude ecosystems (Euskirchen et al. 2009; Zhuang et al. 2004).

4a.1.5 Observations and Measurement Evaluations for SPRUCE

1. Data management and SPRUCE Web site – Hook et al.

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 Policy, Plan, and Guides are available on the SPRUCE web site: http://mnspruce.ornl.gov/content/spruce-data-policies.

The SPRUCE Web Site has been implemented (http://mnspruce.ornl.gov/) and provides project documents, images, and presentations that are available to participants and portions of the public. The site was implemented using the Drupal web site application/content management system.

2. Environmental monitoring – Hanson, Riggs, Hook et al.

Environmental monitoring stations with numerous sensors were established on the S1 Bog at the MEF over the summer and fall of 2010. 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 preliminary data are posted on the web site for project use at http://mnspruce.ornl.gov/webfm.

3. Surveys of the S1-bog experimental site – Hanson, Kolka, et al.

An initial Bog 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. Figure 8 shows tree distribution and peat depth data collected from these efforts, respectively.

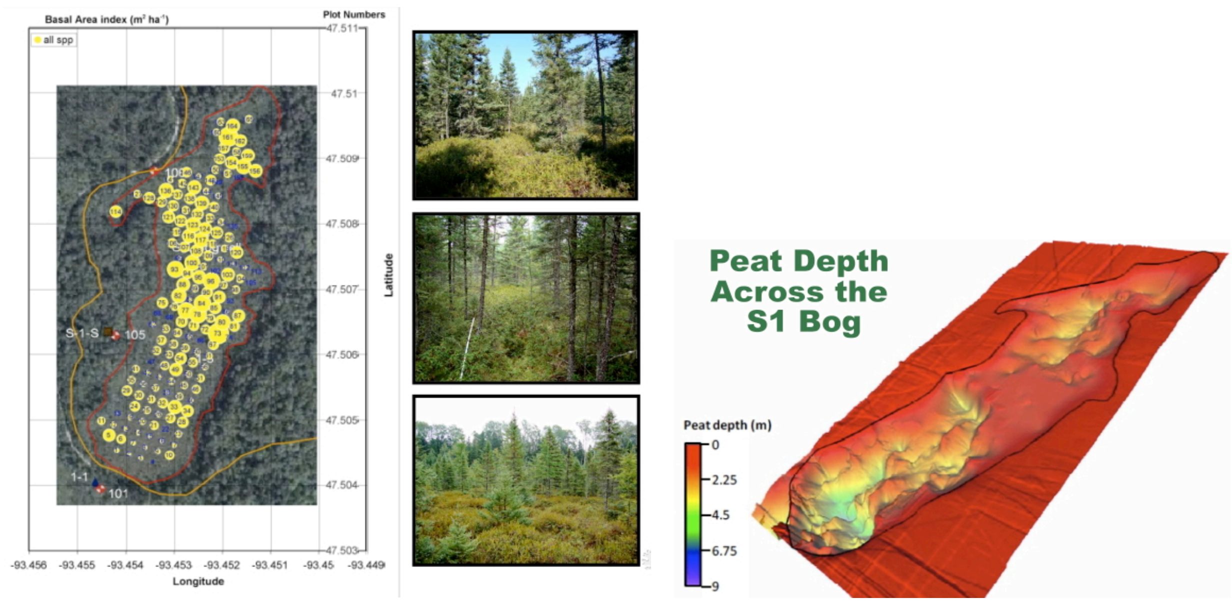

Figure 8. Left Graph: Results of the comprehensive bog vegetation survey collected in September 2009 and associated photographs of the bog vegetation from south to north (left). Right graph: A 3D reconstruction of the peat thickness for the S1 Bog of the Marcell Experimental Forest based on > 8000 ground penetrating radar observations.

4. Tree and Shrub Measurements – Hanson, Todd, Brice, Phillips, Hook, Garten and Palik

During FY2010, 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 carbon increment estimates of SPRUCE. Representative trees were harvested over a full range of sizes from saplings approximately 1 meter in height to trees now over 4 meters tall that were established following a 1974 strip cut. These measurements were supplemented in June 2011 with additional samples of especially large trees. Circumference at the base of the tree (cm), circumferences at 1-m height increments, and a circumference at dbh (1.3 m) were obtained for each harvested tree. Subsamples of wood, branch and foliar materials were collected for water content determination, and fresh weights were obtained for all components of the tree. Subsequent dry mass determinations (70 °C) were obtained on these components at ORNL and various allometric relationships evaluated. Allometric sampling has also been completed for three ericaceous shrub species: *Ledum*, *Chamaedaphne*, and *Vaccinium*. Whole above ground plants were harvested, basal diameters (mm), heights (cm), and crown widths (cm) were obtained in the field for use in the development of dry mass relationships for whole-plants, stems and foliage.

Small plots (0.25 m2) have also been sampled throughout the S1 bog to evaluate total biomass above the *Sphagnum* layer were also collected for replicate hummock and hollow locations. All vegetation materials were collected and separated by most major species.

Viable allometric relationships were developed for trees and shrubs and a 0.25 m2 plot was deemed an appropriate size for destructive sampling of annual NPP increments for forbs, grasses, and sedges.

Annual increments of terminal leaf and stem development are separated from the woody shrubs and tree seedlings within such plots for estimating total NPP contributions from those species.

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 protect the underlying shrubs and *Sphagnum* microtopography. Figure 9 shows the one example of the experimental plot data. These data will be used together with other vegetation and peat characteristic data to choose homogeneous plots for random application to experimental treatments.

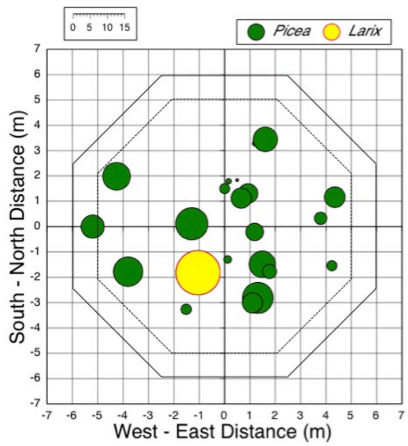

Figure 9. An example plot from the baseline tree inventory for data collected in February 2011 showing tree positions and representing individual tree diameters at 1.3 m. Similar data were collected for the characterization of plots across the S1 experimental site (Figure 8).

5. Fine root assessments – Iversen, Childs, Norby

Minirhizotrons were installed on the S-1 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 to initial measurements were done to verify the efficacy of the approach. Comparison of the two imaging dates showed new root growth occurred between July and October. On both dates most roots were near the surface, but at the very top they are mixed in with and obscured by *Sphagnum;* there were few roots deeper in the profile (Figure 10). These tubes are being monitored throughout 2011 to provide data on fine-root production and standing crop in relation to spruce density and hummock vs. hollow position, and they will provide guidance for tube placement and appropriate imaging interval in the experimental plots.

Soil sampling to characterize root mass per unit soil depth is underway. Preliminary analysis indicates that the majority of root length occurred at 5-10 cm depth for both spruce and shrubs, with the major portion being shrub roots of < 0.5 mm diameter.

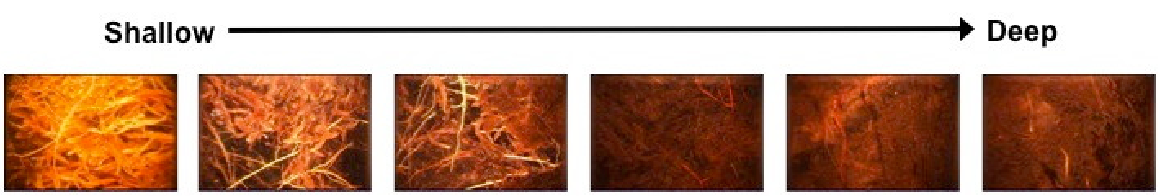

Figure 10. Example minirhizotron images from shallow to deep (~1 m) subsurface locations.

6. Sphagnum community assessments – Norby, Weston

The moss community, particularly *Sphagnum* species, plays a central role in the structure and function of the S-1 bog, and the response of that community will most likely be central to the overall response of the ecosystem to our imposed treatments. Because our research group does not have much experience with bryophytes, our initial objectives were to become familiar with the species, gain experience with measurement techniques, and establish partnerships.

6.1. Species Identification

Two dominant and two lesser species of *Sphagnum* have been tentatively identified on the S-1 bog. *S. angustifolium* is prominent throughout the bog, dominant in hollows and on the sides of hummocks. On hummock tops, it is often dried out and mixed with *S. magellanicum* or other mosses. *S. magellanicum* also is present throughout the bog, primarily on hummocks and often mixed with *S. angustifolium*. *S. fuscum* and *S. capillifolium* have been observed on S-1, but they appear to be rare. *Polytrichum* and several feather mosses are scattered throughout the bog, occasionally forming large patches in drier sites. The species have not yet been fully identified. There is some doubt whether *S. angustifolium* is correctly identified. Samples were sent to Professor Jon Shaw, a prominent bryologist at Duke University, who tentatively identified the species as *S. fallax*. Kjell Ivar Flatberg, an international expert on this subsection of the genus, thought the samples were most likely *S. angustifolium* based on microscopic analysis. Jan Janssens, Minnesota bryologist who is familiar with Marcell Experimental Forest, thought *S. angustifolium* was most likely, and pointed out that there are different forms of this species that could create some confusion. A definitive identification will be provided by genetic analysis. The distinction is important because these species have different ecological niches and amplitudes, primarily related to availability of water, and so their differential responses to warming (and associated drying) could have larger scale consequences for carbon and nutrient cycling.

6.2 Growth measurements

Sphagnum growth is determined by measuring height increment and translating that to dry mass increment. Two methods were explored for measuring height increment: the traditional “cranked” approach first described by Clymo 1970 and an unpublished “bundle” method devised by Scott Bridgham. On July 20, 2010, six cranked wires (20 cm wires with two right angle bends 1 cm apart in the middle) were inserted in a patch of *S. angustifolium* in a hollow and seven in a *S. magellanicum* patch on a hummock. The horizontal section was positioned at the top of the *Sphagnum capitula*, with 10 cm wire protruding above. On October 20, the length of wire protruding above the capitula was re-measured. As this measurement was initiated in July, the amount of length growth that had already occurred was estimated by observing bends in the *Sphagnum* stems where vertical growth had resumed after snow had bent the stems to a horizontal orientation.

For the bundle approach, 10 stems each of the two species were removed in July, cut to 5 cm length, and bundled loosely with colored string. The bundles were reinserted into the bog with the string tied to a stake for subsequent retrieval. The bundles were removed in October and stem length re-measured. These samples were oven dried and weighed after separating capitula and a 3 cm length of green stem. The number of stems per unit area was determined in a 44-cm2 circular section of a patch of each of the two species. These samples were dried and weighed to provide an estimate of standing crop, and they were analyzed for N content.

Although *S. magellanicum* had less extension growth and there are fewer stems per unit area, each plant is denser than *S. angustifolium*, and its overall production was slighter greater; however, the areal coverage of *S. angustifolium* exceeds that of *S. magellanicum* (not determined). Total annual production was estimated to be about double the production from July to October. The standing crop estimates compare well with estimates of Weishampel et al. (2009); it is similar to the estimated standing crop of spruce needles. N concentrations are consistent with literature values.

The cranked wire approach was difficult to implement on the S-1 bog because it was hard to measure length while remaining on the boardwalk. The bundle approach was easier and more accurate, although it would not be conducive to tracking seasonal growth patterns. A hybrid approach may be most valuable – bundles of stems with a crank wire inserted in the bundle.

6.3 Physiology

Moss samples were collected across three hummock-to-hollow transects consisting of different species combinations, and the samples are being analyzed for N, protein, Rubisco and light saturated photosynthesis (Asat) in response to PAR and tissue water content. The three moss species varied considerably in their Asat response to tissue water content (Figure 11).

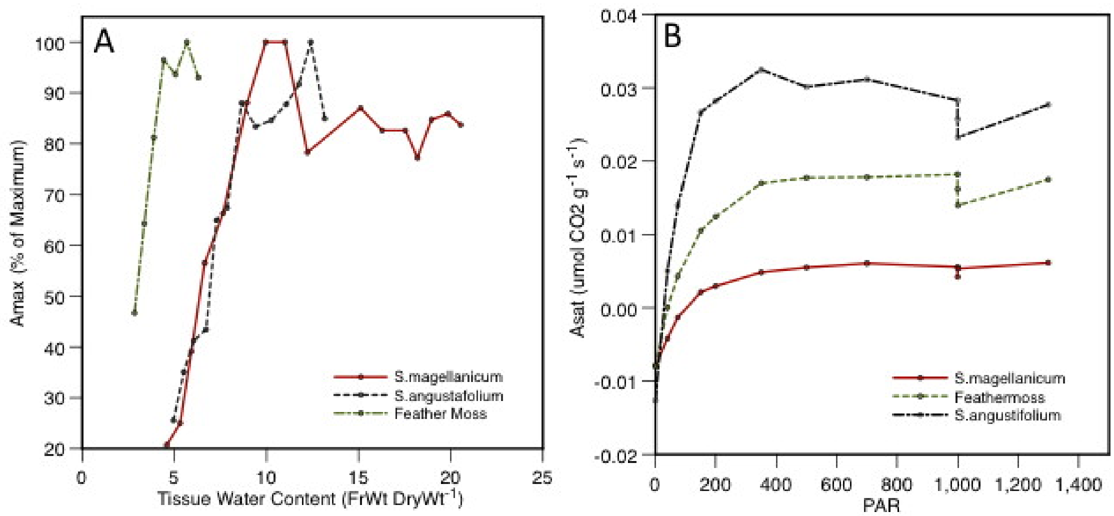

Figure 11. Photosynthetic characteristics of *Sphagnum* and feather moss as a function of tissue water content (left graph) and photosynthetically active radiation (PAR; right graph).

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 and CO_2 and altered hydrology. These data will then be used to predict whether differential physiological responses will lead to changes in bryophyte community composition and function that can influence whole-ecosystem carbon and nutrient cycling in a bog system experiencing warming, elevated CO_2, and altered hydrology. To accomplish these objectives, we have established partnerships with external experts: Dr. Jon Shaw (Duke University, evolutionary biologist, *Sphagnum* taxonomist, ecological genomics), Dr. Merritt Turetsky (University of Guelph, bryophyte ecology and decomposition), Dr. Pat Morgan (Li-Cor Inc., expert in gas exchange technology development), and Dr. Jan Janssens (University of Minnesota (retired) local bryophyte expertise). We have also initiated discussion with Dr. Merritt Turetsky (University of Guelph) to establish a collaborative research agreement to support undergraduate student participation for characterizing and quantifying pre-treatment bryophyte populations in the experimental plots.

7. Microbiology - Schadt

We designed and tested a custom system that will allow monitoring of redox conditions by measurement of Eh at multiple depths within the bog (Surface, 5, 10, 20, 30, 50, 100 & 200 cm). The system is based on the design described in Vorenhout et al. (2004) and used previously in floodplain (Van der Geest & Paumen 2008) and wetland systems (Unger et al. 2008). Tests were conducted in saturated soils/sediments associated with a wetland on East Fork Poplar Creek in Oak Ridge, Tennessee near the NOAA/ATDD building beginning 19 July 2010. After an equilibration of 1-4 days, the system showed highly negative redox potential over most depths with periodic rapid changes associated with large summer precipitation events. Coring revealed a surface organic horizon of 20-40 cm in depth, with an underlying sand layer; however cores could not be recovered below that depth. Depth specific temperature measurements at each redox measurement point also showed expected diurnal patterns in shallow depths that were muted deeper in the soil profile. The system successfully ran under local field conditions for nearly 4 months and was removed on 8 November 2010 for transport to the S1 bog in Minnesota.

7.1 Seasonal Examination of Depth Specific Microbial and Biogeochemical Profiles

A preliminary characterization of depth specific profiles of microbiological and physical/biogeochemical properties of the S1 peat material was begun in December 2010. These investigations are being carried out to understand how changes in peat temperature profiles affect these properties. Triplicate core samples were taken at the end of March 2011, and two additional samples will be collected throughout the growing season. These time periods were chosen to contrast the steady state under snow conditions (overall constant temperatures, surface layers near freezing and warmer temperatures in deeper soil) with the more variable summer conditions (high diurnal variation with warmer temperatures above and constant temperatures deeper) in addition to the spring transition period between these times. Cores are being sampled to depths of 1.5 to 2 m and sectioned in 10 cm increments for microbial population estimates. Biogeochemical/physical properties, temperature and Eh are measured continuously in the field using a HYPNOS data logger (Vorenhout et al 2004). The abundance of Bacteria, Archaea, Fungi are measured with 16SrRNA QPCR (Castro et al. 2010). pH, %C, %N, and %fiber content are also measured as described in other tasks.

While Eh is slightly positive in the upper depths indicating that aerobic processes will likely predominate (e.g. nitrification, methane consumption), it is driven substantially negative at depths below 50 cm, which indicates anaerobic (e.g. methanogenesis) processes will predominate. This trend is largely inverse to pH, which becomes less acidic with depth and corresponds well with patterns observed in the gross composition of the microbial community. While Bacterial and Fungal abundance decreases with depth, Archaea (group that contains all methanogens) abundance remains high resulting in dramatic shifts in the ratios of these three groups (Figure 12).

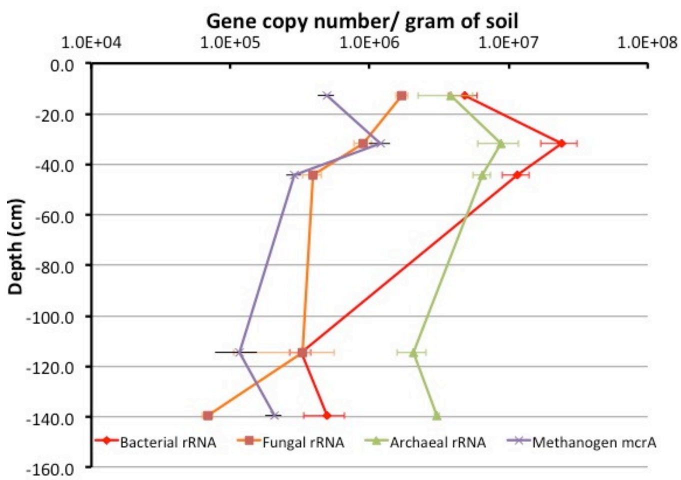

Figure 12. Changes in microbial group abundance with depth within the S1 peat profile.

8. Biogeochemical Cycling - Garten

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 nitrogen biogeochemistry, and 4) peat physicochemical characteristics. We have begun to investigate pretreatment characteristics of plant nutrient concentrations, stable carbon and nitrogen isotope ratios, and peat properties in the S1 Bog at Marcell Experimental Forest.

8.1 Plant nutrient concentrations

Plants were collected in July 2010. Different plant tissues from common S1 Bog species were analyzed for nitrogen and carbon using a LECO TruSpec® elemental analyzer (Figure 13). A comparison of the two dominant tree species indicated that *Larix* had higher foliar nitrogen concentrations and lower foliar C/N ratios than *Picea*. *Smilacina* had the highest foliar nitrogen concentration and the lowest foliar C/N ratio among six sampled herbs and shrubs. As expected, foliar nitrogen concentrations were significantly greater than those measured in woody tissues (stems, branches, and boles).

There were differences in nitrogen and C/N ratios between new growth (leaves and stems) and older plant tissues (data not shown). The observed differences could potentially complicate aboveground plant sampling for quantification of plant carbon and nitrogen stocks. The preliminary data will be used for planning pre-treatment sampling protocols for herbs, shrubs, and trees during the 2011 growing season.

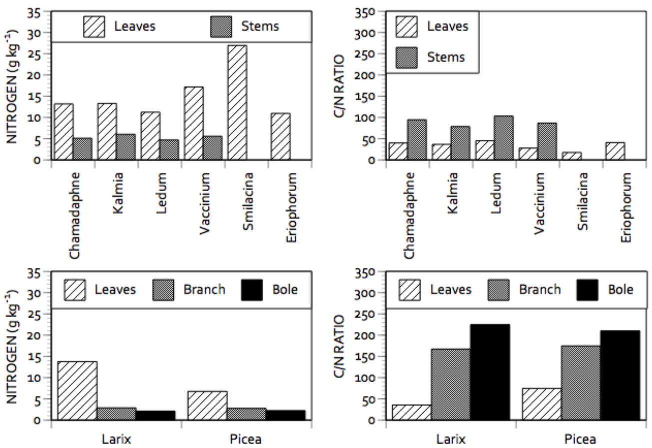

Figure 13. Nitrogen and C/N ratios in leaves and woody tissues of common S1 Bog plant species.

8.2 Whole system indicators of nitrogen 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 nitrogen 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 and changing water chemistry) to study changes in ecosystem nitrogen cycling in SPRUCE. Measurements of changing nutrient availability and changing nitrogen biogeochemistry are not trivial in a system where the substrate is either waterlogged or frozen for a significant part of the year.

8.3 Carbon pools and processes

Planned studies of carbon pools and processes include measurements of carbon 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. In the aerobic zone, warming in the SPRUCE experiment is expected to increase decomposition and increase carbon flux, but the response to warming will depend on the chemical properties of peat and carbon partitioning among pools of differing recalcitrance. Because 97% or more of the carbon in ombrotrophic bogs at Marcell is tied up in peat (Weishampel et al. 2009), our preliminary work on carbon 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.

8.4 Peat physicochemical characteristics

Peat samples were obtained in March and July 2010. In July 2010, we also tested several alternative tools for peat sampling at the S1 Bog. Peat sampling is difficult due to peat's high gravimetric water content (85 to 93% water depending on depth). 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) must be collected 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).

8.5 Elemental and isotopic analysis

Peat samples were analyzed on a LECO TruSpec® elemental analyzer for carbon and nitrogen and also analyzed for stable carbon and nitrogen isotope ratios on a SerCon Integra CN continuous isotope ratio mass spectrometer. Samples will be analyzed for carbon-14 at a later time to determine the age of peat at different depths in the S1 Bog.

Vertical profiles of stable nitrogen and carbon isotope ratios at S1 Bog were constructed on the basis of plant and peat samples collected in July 2010 (Figure 14). 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 nitrogen cycle and limited ecosystem nitrogen 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.

8.5.1 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 2010 field campaign.

Chemical extractions provide a detailed, quantitative characterization of the amount of carbon 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). Figure 15 shows the chemical composition of surface fibric peat (3 to 5% ash content) from S1 Bog and published data for peat from a similar ombrotrophic bog in Canada (see Turetsky et al. 2000).

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 carbon 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.

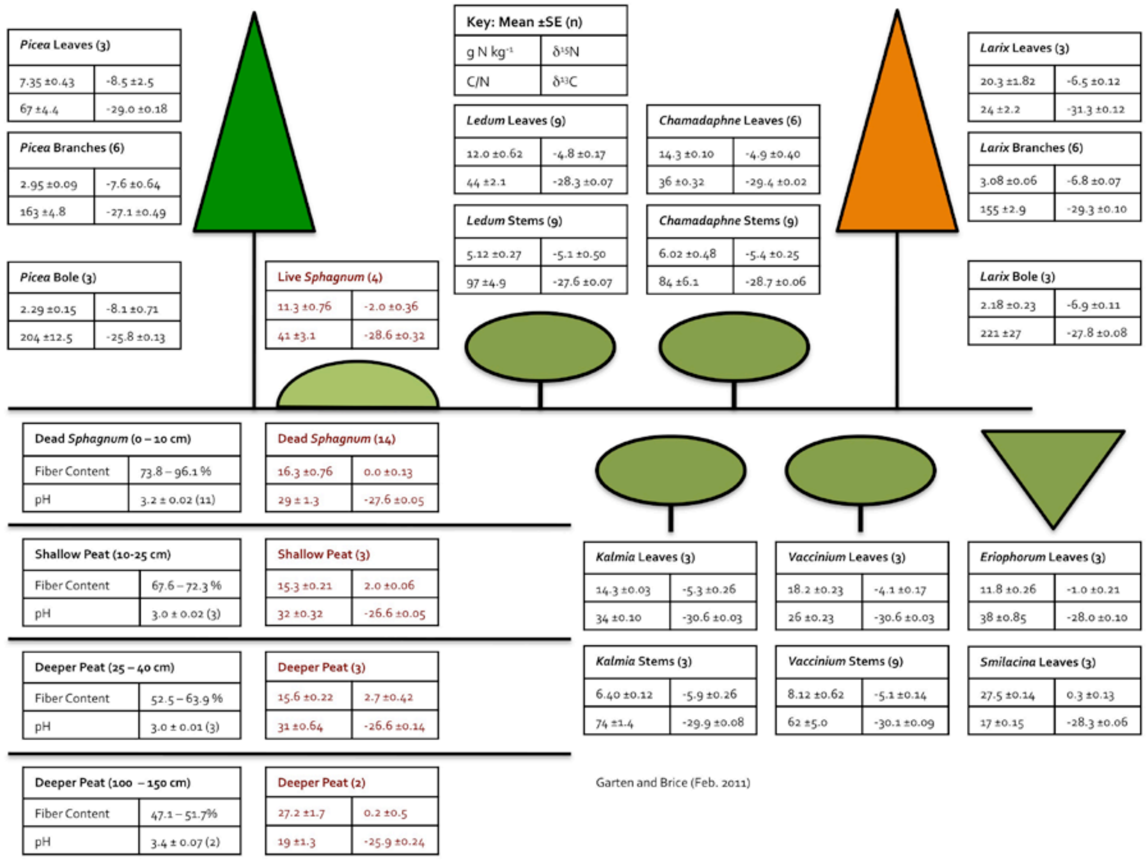

Figure 14. Nitrogen concentrations, C/N ratios, and natural abundance ^{13}C and ^{15}N at the S1 Bog.

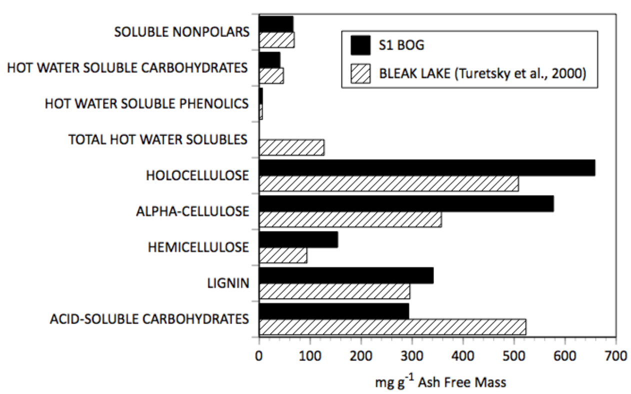

Figure 15. Amounts of nine different organic constituents in fibric peat (dead *Sphagnum*) from the S1 Bog and in peat at a second ombrotrophic bog (Bleak Lake).

8.6 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. We hypothesize that peat decomposition, as indicated by CO_2 efflux rates in the laboratory, is connected to differences in the physicochemical form of peat carbon. However, the rate and change in both the chemical form of carbon in peat and peat respiration rates in response to warming and elevated CO_2 is difficult to predict because they depend on changes in peat hydrology.

8.7 Decomposition of different peat types

Decomposition of fibric and hemic peat from the July 2010 field campaign is being 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.

We plan to compare the chemistry of organic matter in these two types of peat, by chemical extractions, to see if differences in CO_2 efflux are related to the amount of refractory organic constituents.

9. Land surface and landscape CO_2 and CH_4 flux – Hanson, Gu, Riggs, Kolka

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. Testing this approach is an ongoing objective for the summer of 2011.

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 (< 1m) 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 have assembled and completed in-lab testing of an eddy covariance system that consists of a Campbell Scientific CSAT3 sonic anemometer, a Li-Cor Li7700 CH_4 open path analyzer, and a Li-Cor Li7500A CO_2/H_2O open path analyzer. Data processing software needed for this EC system has also been developed. We are preparing to test this instrument package within the prototype enclosure in July/August 2011. We will place the system at the center of the enclosure, either near the ground or above the height of the inlets of the blowers to avoid the mean flow in the middle section created by the blowers. We expect the CH_4 flux will be close to zero for the soil condition within the enclosure while the fluxes of CO_2 and water vapor should be non-zero due to the presence of green vegetation.

10. Plant physiology – Warren, Childs, Gunderson, Wullschleger

10.1 Plant Water Relations

The overarching goal for this subtask is to understand the rates of water use by various species, physiological and environmental controls on water use, linkages between water use and carbon uptake, and potential thresholds within the soil-plant-atmosphere continuum as environmental conditions change.

Plant water relations were initially examined for S1 bog species in 2010 through laboratory and field-based research. Predawn or diel patterns of plant water potential (ψ) were measured on various species, including *Smilacina trifolia*, *Ledum groenlandicum*, *Chamaedaphne calyculata*, *Kalmia polifolia, Vaccinium sp.*, *Larix laricina*, *Pinus strobus* and *Picea mariana.* Plant water use as sap flow was investigated in *Ledum, Chamaedaphne, Vaccinium* shrubs and young (<1 m) or mature *P. mariana* trees using energy balance and thermal dissipation techniques. Pressure-volume (P-V) curves were generated for mature black spruce branches to determine the threshold for potential loss of specific leaf conductivity under drying conditions.

10.2 Plant Carbon Physiology

A baseline physiological study of foliar gas exchange was conducted at the S1 bog on the dominant, primarily woody, vascular species. Two types of gas exchange measurements were made: (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. Sampling campaigns were conducted at the S1 Bog in late-June 2010 and in mid-September 2010 to facilitate seasonal comparisons. Light response curves at ambient [CO_2], and CO_2 response curves at saturating light were generated using several LI-6400 portable gas exchange systems positioned at the landing adjacent to the S1 Bog. Plant tissues were detached shortly before measurement and immediately re-cut under water prior to analysis. Since spruce has multiple foliar cohorts, only the current 2010 cohort was measured for this campaign. Block temperature was adjusted to near ambient; leaf temperatures thus averaged 26.5 °C in June, and 12.2 °C in September. Measurements were also taken *in situ* on attached foliage within the S1 Bog, and paired with concurrent assessment of leaf water potential (ψ) of similar foliage of the same plant. Cuvette conditions for these spot measurements were set to match the prevailing bog environment; e.g., light was controlled based on incident radiation, determined just before each set of measurements, CO_2 set to achieve approximately 390 ppm, and block temperature to that of air.

Species differences in light response were apparent. Net photosynthetic CO_2 assimilation (*A*) in shrub and herbaceous species was 90% light saturated at $\leq$ 500 μmol m^{-2} s^{-1} PAR, whereas in the tree species (*Picea* and *Larix*), *A* did not saturate even at 1500 μmol m^{-2} s^{-1} PAR. Variation within species was low, except in *Chamaedaphne*, where light saturated rates (*Asat*) varied three-fold; leaves with low rates had lower light saturation points, and lower stomatal conductance, suggesting growth in shade conditions. In other shrubs, *Asat* ranged from 9-11 μmol m^{-2} s^{-1}, compared with 8-10 μmol m^{-2} s^{-1} in *Larix*, 10-14 μmol m^{-2} s^{-1} in *Picea*, and 6-9 μmol m^{-2} s^{-1} in the herbaceous *Smilacina*.

Responses of *A* to varying intercellular [CO_2] (*Ci*) were relatively consistent within species. The major difference across species was in CO_2-saturated *A*, which varied from 13-20 μmol m^{-2} s^{-1}. Initial slopes of the *A*-*Ci* curves were similar across species, suggesting limited species differences in V_{cmax}. Preliminary analysis suggests that shrub species approached CO_2 saturation at lower concentrations than did *Picea* or *Smilacina*, which could suggest a competitive advantage for the latter in a high [CO_2] atmosphere. September measurements, in much colder weather, revealed significantly lower rates of gas exchange. In *Picea*, for example, light- and CO_2-saturated *A* were 30 to 40% lower, but V_{cmax} values were similar to those in June.

11. Hydrology and water chemistry – Mulholland and Sebestyen

We designed a subsurface corral (flow barrier) with the drainage collection system and the multilevel groundwater monitoring system, and the chemistry sampling scheme needed to characterize plot level hydrology and solution chemistry of the warmed ecosystem enclosures. The flow barrier will serve two purposes: (1) prevention of flow into the plots if snowmelt desynchronizes between the chamber and the surrounding peatland, and/or 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. A design document has been prepared, prototyping of the system has been planned, and tests of the design are planned to evaluate effectiveness. Drawings of the flow barrier and drainage system have been prepared, and a contract is being put in place to install this prototype.

The purpose of the multilevel groundwater monitoring system is to document temporal variation and changes resulting from treatment effects on groundwater chemistry at different depths in the peat. This information will be used to help identify major changes in biogeochemical processes in the subsurface environment in each experimental plot.

4a.1.6 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 small workshop at ORNL on October 7-8, 2010 entitled "Advancing minirhizotron use to examine ephemeral root dynamics in peatland and high carbon ecosystems". The workshop was funded by the New Phytologist Trust and the US DOE Office of Science. A manuscript has been prepared. 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 4.1 Progress on Task R1 Deliverables (expressed in abbreviated form):

Deliverable 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 2010
May 2010	Complete access roads, truck turnarounds and cleared areas for staging the experiment (key USFS involvement)	Completed
Summer 2010/2011	Collection of baseline understory plant data for the experimental locations on the S1 Bog	Completed
July 201 to date	Initiate continuous environmental monitoring on ambient plots	Completed
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
Spring Summer 2011	Infrastructure Development and Contracting for SPRUCE was delayed by the NEPA process, and is currently being held up while we transfer funds under an IAG to the USDA Forest Service.	Delayed: Schedule being revised

4A.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 review 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 SO4-2) in stream water. Inter-annual variation in stream water NO3- 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.

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.

Table 4.2 Progress on Task R2 Deliverables (expressed in abbreviated form):

Deliverable 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

4A.3 CLIMATE CHANGE FORCING-RELATED TASKS

The TES SFA includes five tasks (F1-F5) related to climate change forcing, employing models, experiments, and landscape C measurements to advance our understanding of terrestrial C cycle processes (Figure 16). Task F1 provides an integrative analysis framework through modeling and model-data

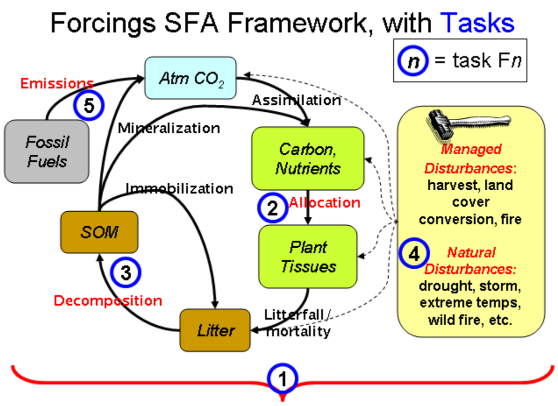

Figure 16. Overview of TES SFA Tasks F1-F5. Terrestrial ecosystem processes are considered in the context of their impact on atmospheric CO_2 (and other greenhouse gas fluxes). Red text identifies major process-level uncertainty which is addressed as part of the near-term TES SFA effort.

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.

4A.3 TASK F1 -- MECHANISTIC CARBON 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 help 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 provide an answer to the research question: *What are the sign and magnitude of the global climate-carbon cycle forcing from land, and what are the process contributions to that overall forcing across a range of spatial and temporal scales, and across multiple land ecosystems?* We are pursuing answers to these questions through several simultaneous and complementary 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).

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

Model-Data fusion with LoTEC and CLM

The Local Terrestrial Ecosystem Carbon (LoTEC) model has served as a useful testbed for model-data fusion exercises. In conjunction with the North American Carbon Program (NACP) model-data synthesis activity (see below), gap-filled meteorological forcing and flux datasets were prepared for 45 North American sites. Model-data fusion was performed using LoTEC for 10 sites with hourly net ecosystem exchange (NEE) and latent heat (LE) as data constraints to optimize 20 model parameters. We employ a genetic algorithm (GA) to find the global optimum parameter set, and Markov Chain Monte Carlo (MCMC) to explore parameter uncertainty when desired. This method performed well and was able to correctly retrieve parameters in a synthetic model-data fusion study (Fox et al. 2009).

LoTEC consistently was among the top performers among 22 participating models in this exercise (Schwalm et al. 2010; Dietze et al., in review). This good performance can be attributed to the fact that LoTEC was the only model employing a model-data fusion technique. This key difference limits the value of direct model-to-model comparisons; however, it 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 have also found that in cases when the model-data fusion fails to provide a good result, this is an indication that the model structure is flawed. For example, the inability of LoTEC to distinguish between maize and soybeans causes incorrect patterns of CO_2 uptake at a Nebraska site with crop rotation (Lokupitiya et al., in review).

We have used LoTEC to demonstrate the utility of different observation types and lengths to reduce uncertainty about key carbon cycle variables (Ricciuto et al. 2011). In this study, we performed a number of model-data fusion exercises using MCMC at a single site with flux data records that vary in length. We also performed additional simulations in which we included additional data constraints, such as initial carbon stocks and annual woody increments. Both synthetic observations (model-generated with superimposed noise) and actual observations were used. In each case, we found that parameter and prediction uncertainties decrease significantly (-40% per year) when additional years of flux data are included. Including the initial stocks and woody increment data reduce the uncertainties up to an additional 50%. This framework could be used to test proposed new observations in a similar way.

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 105 simulations, is prohibitively expensive; however the GA method has been applied successfully for optimizations with small number of parameters on a computer cluster. We have demonstrated a test case optimizing 5 key parameters at the Howland and University of Michigan Biological Station (UMBS) flux tower sites, and model predictions have improved substantially after optimization. Additional efforts are underway to estimate the sensitivity of steady state carbon pools to key parameters, and to minimize the amount of time required to spin up the model to equilibrium after modifying the parameters.

Model-data fusion studies involving larger number of parameters and/or multiple sites require the use of high performance computing on a scale of hundreds to thousands of processors. 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.

CLM point model framework

The CLM is currently integrated in the CESM, which has been designed and optimized to run global simulations. Although point-level simulations could be run in the existing framework, the process was not straightforward and not officially supported. In collaboration with NCAR, we developed PTCLM, 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 is currently on the main code trunk of CLM and was released to the wider community in June 2011. We also prepared the site-level meteorological, soil and land-use history datasets necessary to run the model at 20 North American flux tower and experimental sites. PTCLM is a key technical component of the TES SFA, connecting experimental and site-level observations to the global Earth system.

Site-level simulations at NACP sites

We applied PTCLM at 15 flux tower sites, in coordination with the NACP site-level synthesis activity (http://nacp.ornl.gov/mast-dc/int_synth_site.shtml). It is one of only a few models in that model-data intercomparison with a dynamic nitrogen cycle, and the observations from these sites proved to be an important test of this aspect of the model. 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 nitrogen uptake and allocation to new growth. By adding the capacity for nitrogen storage within the plant prior to allocation as new growth, a physiologically realistic process representation, the diurnal cycle bias in photosynthesis was greatly reduced. Elimination of this bias allowed the identification of second-order biases at several sites, leading to further hypothesis development and testing. For example, we were able to determine that over-simplified treatment of fire dynamics in CLM4 was causing a low-productivity bias at fire prone sites such as the Ponderosa pine stands at Metolius, OR. Similarly, we have determined that the model permits too much photosynthesis to occur at cold sites in the fall and spring, when temperatures are at or below freezing, but where some liquid water may still be present at depth in the soil column. Peter Thornton, Gautam Bisht, and Dan Ricciuto are currently preparing these findings as a journal article to be submitted in August 2011.

Progress on coupled carbon-nitrogen-phosphorus modeling

In spite of 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. The Hedley fractionation method provides a comprehensive assessment of soil P and has been widely used in recent decades. We have expanded an earlier study (Cross and Schlesinger, 1995) that summarized Hedley P data from the literature to create a larger Hedley P database and further investigated the relationship between distributions of different forms of P and the stages of soil development (Yang and Post, 2011). Our expanded Hedley P database generally support what the Walker and Syers[1976] conceptual model predicts: the gradual decrease and eventual depletion of primary mineral P (mainly apatite P); the continual increase and eventual dominance of occluded P; and the overall decrease of total P during soil development. The database analysis however disagrees with the Walker and Syers[1976] in that we found labile Pi and secondary Pi(non-occluded P in Walker and Syers's model) to be a significant fraction of total P throughout all soil orders with different weathering stages. Our analysis of the database also 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. The compiled Hedley P database will improve our understanding of the soil P dynamics in terrestrial ecosystems and can help us constrain P cycle dynamics in terrestrial biogeochemical models.

We have also developed a method building on existing knowledge of soil P processes and existing soil P measurements to provide a spatially explicit estimate of different forms of P in soils on the global scale (Yang et al., in preparation). We assembled data on the forms of phosphorus in soils globally, chronosequence information, and several global spatial databases (e.g. lithology, rock P content, soil orders) to develop a map of total soil P and the distribution among mineral bound, labile, organic, occluded, and secondary P forms in soils globally. The amount of P in soil labile, organic, occluded, and secondary pools is 5.6, 10.3, 14.4, and 4.7 Pg P respectively. The amount in soil mineral particles is estimated at 31.9 Pg P for a global soil total of 70 Pg P. This global soil P map will be useful for global biogeochemistry models that include P as a limiting element in biological production.

Global synthesis on canopy photosynthetic phenology based on flux network data

We have used the methodology developed by Gu et al. (2003) and Gu et al. (2009) and the global Fluxnet dataset (http://www.fluxdata.org) to investigate biotic and abiotic controls on canopy photosynthetic phenology across biome and climate zones. We have found:

1. Air temperature is the dominant factor that controls the spring recovery (both the timing and the recovery rate) of canopy photosynthesis in northern ecosystems across different vegetation types.
2. However, it is the rate of increase, rather than the absolute value, of daily mean air temperature (other than minimum, maximum air temperature or soil temperature) that determines the peak recovery rate of canopy photosynthetic capacity across vegetation types (Figure 17).
3. The gross ecosystem productivity in the second half of the year affects the peak recovery rate of canopy photosynthesis in the following spring by providing the substrate for metabolism to support new shoot and leaf growth.
4. Deciduous broad-leaf forests and grasslands are more sensitive to temperature change in spring than evergreen needle-leaf forests, probably due to their differences in life history strategies.

Improved photosynthetic parameter estimation

The largest carbon flux (the gross primary production) of the global carbon cycle is computed with the Farquhar-von Caemmerer-Berry (FvCB) model. Unfortunately, the estimation of parameters used within the FvCB model is rather difficult and uncertain. Uncertainty surrounding the parameterization of FvCB from leaf gas exchange measurements (e.g. *A/Ci* curves) for application to regional to global models is an issue that has been plaguing the carbon cycle research community for decades. This research revealed previously unrecognized complexities of the model and developed a new approach to overcoming these complexities (Gu et al. 2011). The new approach was tested with simulations, leaf gas exchange data, and chlorophyll fluorescence measurements of multiple species at the Missouri Ozark AmeriFlux site.

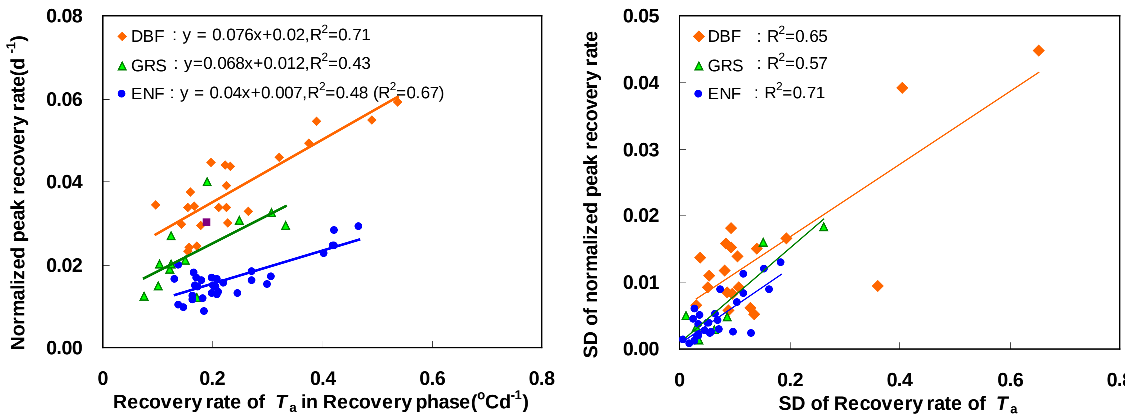

Figure 17. Relationship of the normalized peak recovery rate (PRR) of canopy photosynthesis (left panel) and its standard deviation (SD, right panel) with the rate of increase in daily mean air temperature (Ta) in spring and its standard deviation. DBF: deciduous broad-leaf forest; ENF: evergreen needle-leaf forest; GRS: Grassland.

Launch of LeafWeb to serve the carbon-cycle research community

Early 2011, we launched LeafWeb to provide data analysis and gathering service to the carbon cycle research community (leafweb.ornl.gov). LeafWeb's main function is SErvice-in-Exchange-for-Data-Sharing (SEEDS). It targets individual investigators with point data sources. The objective is to develop a global database of biochemical, physiological, and biophysical properties of single leaves to support studies of plant functions and terrestrial carbon cycle modeling. LeafWeb provides automated numerical analyses of leaf gas exchange measurements using the method of Gu et al. (2011). With the approval of the user, the data LeafWeb receives are preserved and captured for global carbon cycle synthesis and modeling. As investigators use LeafWeb and contribute their data, the resulting "global leaf database" will grow, enabling point data sources to contribute synergistically to global carbon cycle studies. LeafWeb is a collaborative effort between CDIAC and TES SFA Tasks F1 and F4.

Table 4.3 Progress on Task F1a Deliverables (expressed in abbreviated form):

Deliverable Date	**Deliverable**	**Status**
Oct 2009	Gap-filled input forcing datasets for conducting simulations at AmeriFlux and FLUXNET sites.	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 updating and analysis.	Completed
Mar 2011	Submit manuscript quantifying parameter uncertainty when considering various data streams and constraints with EC data (CO_2, H_2O, sensible heat) and biometric data.	Underway
Sep 2011	Submit manuscript evaluating CLM performance across NACP site-level synthesis flux tower sites.	Underway

Task F1b: Regional and Global Land Ecosystem Modeling

NACP Regional Synthesis

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., submitted). The primary objective of the work was to synthesize and compare 19 TBMs, including CLM, to assess current understanding of the terrestrial carbon cycle in North America. The analyses focused on model simulations and data currently available from analyses that have been completed by ongoing NACP projects and other recently published studies. Bringing a wide range of model estimates and available data together provides a valuable assessment of the current state of understanding of regional carbon flux across North America. The TBM flux estimates are compared and evaluated over different land regions of North America. There is significant disagreement among the models in their estimates of gross primary production (GPP) and heterotrophic respiration (Rh). The range in estimates from the models appears to be driven by a combination of factors, including the representation of photosynthesis, the source of environmental driver data, time step, and whether nutrient limitation is considered in soil carbon decomposition. The results of this study highlight the amount of disagreement in current estimates of carbon flux across North America; they also highlight 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.

Evaluation of CLM GPP and NDVI against remote sensing observations

We compared monthly GPP simulated by the latest half-degree CLM4 with satellite estimates of GPP from the MODIS GPP (MOD17) dataset on a 10-yr period, January 2000–December 2009 (Mao et al., submitted). The assessment is presented in terms of long-term mean carbon assimilation, seasonal mean distributions, amplitude and phase of the annual cycle, and intraannual and interannual GPP variability and their responses to climate variables. For the long-term annual and seasonal means, major GPP patterns are clearly demonstrated by both products, but there are systematically overestimating or underestimating of GPP for CLM4, in particular, the overestimating magnitude of GPP over the tropical evergreen forests. Comparisons of the phase of the averaged seasonal cycle show that CLM4 has longer carbon absorption period than MODIS at most Plant Functional Types (PFTs), indicating an earlier onset in spring and later offset in autumn for the growing season. 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 prep).

North American carbon budget by inventory

The inventory-based approach to estimating land surface NEE can retain significant information at the sub-continental scale, and can account for lateral transfers of forest and agricultural products. We carried out an inventory-based analysis of the North American carbon budget (Hayes et al., in prep). The strongest sinks for atmospheric CO_2 were associated with the agricultural regions 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. In the case of the forward models, the discrepancy points to the need for improved accounting of the impacts of disturbance, as well as management actions including the removal and transfer of harvested products. In the case of the inversion approach, this discrepancy lends support to the inversion variants that have relatively low sources in the tropical zone. 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 in turn provide the initial surface flux estimates for inversions analyses. Confidence in our ability to understand and predict the role of the North American carbon cycle in the global climate system will improve as the estimates from these different approaches begin to convergence.

Table 4.4 Progress on Task F1b Deliverables (expressed in abbreviated form):

Deliverable Date	Deliverable	Status
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

Task F1c: Coupled Earth System Modeling

We investigated how climate, rising atmospheric CO_2 concentration, increasing anthropogenic nitrogen deposition and land use change influenced continental river flow over the period 1948–2004 using the Community Land Model version 4 (CLM4) with coupled river transfer model (RTM), a global river routing scheme (Shi et al. 2011). The model results indicate that the global mean river flow shows significant decreasing trend and climate forcing likely functions as the dominant controller of the downward trend during the study period. Nitrogen deposition and land use change account for about 5% and 2.5% of the decrease in simulated global scale river flow, respectively, while atmospheric CO2 accounts for an upward trend. However, the relative role of each driving factor is heterogeneous across regions in our simulations. The trend in river flow for the Amazon river basin is primarily explained by CO_2, while land use change accounts for 27.4% of the downward trend in river flow for the Yangtze river basin. 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 composition, carbon-nitrogen interaction and land use change, particularly for regional scales.

We have now completed testing of a configuration of the Community Earth System Model (CESM1), which includes CLM, for the purpose of quantifying the contributions of single and multiple forcing factors on global-scale ecosystem-climate feedbacks. This system will be applied to a series of fully-coupled simulations in calendar year 2011, with analysis of results and submission of a manuscript by April 2012.

Table 4.5 Progress on Task F1c Deliverables (expressed in abbreviated form):

Deliverable Date	Deliverable	Status
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-carbon cycle feedbacks, using the existing structure, process representations, and parameterizations of CLM-CN.	Completed
Mar 2011	Submit manuscript investigating the influence on climate-carbon cycle feedbacks of new parameterizations emerging from site-level data assimilation of eddy covariance observations.	Underway
Sep 2011	Submit manuscript investigating the influence on climate-carbon cycle feedbacks of new parameterizations emerging from regional-scale data assimilation and fingerprint analyses.	Underway

4A.4 TASK F2 -- PARTITIONING IN TREES AND SOIL (PITS)

Norby, Iversen, Warren, Garten, Childs, Weston, Thornton, Gu

The Partitioning in Trees and Soil (PiTS) task was established with the objective of improving the carbon (C) partitioning routines in existing ecosystem models based on the concepts gathered from plant partitioning models and tested against field observations and manipulations. The approach we are pursuing, which was inspired in part by our research experience in the free-air CO_2 enrichment (FACE) experiment, 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 belowground varies with short-term changes in GPP. Activities during the first 18 months of the project included locating an appropriate research site, and assembling equipment, supplies, and support facilities. The research site was chosen after an extensive survey of the Oak Ridge Reservation and surrounding area. The important criteria were proximity to electrical power, relatively small trees (< 7 m) that are well spaced, capability to dig the pits and site security. The site we chose is located on the University of Tennessee Forest Resources Research and Education Center (FRREC) in Oak Ridge, TN, (http://forestry.tennessee.edu/ORForest.html) and has a small grove of 6-m tall, 5-year-old planted loblolly pine (*Pinus taeda* L.). Richard Evans, director of the FRREC, agreed to allow site access and assist with site development and maintenance. A NEPA compliance screening of the project through a NEPA Action Review was completed and a categorical exclusion was obtained. Electrical service to the site was established through the City of Oak Ridge. A temporary office and instrument shelter was rented and delivered to the site.

In mid-April, 2010, a 2-m wide × 1-m deep soil pit was dug adjacent to eight loblolly pine trees using a compact track loader (Bobcat). The purpose of the pit was to allow us to associate root and soil dynamics with specific trees, and to provide greater access to soil at depth. In mid-May, the pit was instrumented with a series of tools for tracking C partitioning within the tree and soil. Measurements were specifically planned to facilitate our paired modeling efforts. Root observation windows consisting of thin acetate were installed in the pit at the base of each tree to allow access to roots of a known age. Minirhizotron tubes were inserted horizontally into the pit face approximately 50 cm from each tree to track the timing and vertical distribution of root growth. Stainless steel tubes were inserted in the pit wall to assess CO_2 in soil air at various depths. Soil water probes were inserted adjacent to each tree into the soil to track vertical patterns of soil water dynamics. Variable-length heat dissipation sap flow probes were inserted into each tree to facilitate modeling of gross primary production. Each tree was fitted with a digital dendrometer to track small-scale temporal changes in tree growth and water use. Automated soil respiration chambers were installed adjacent to each tree to track soil carbon efflux.

The trees were labeled with a pulse of ^{13}C-enriched CO_2 on September 1, 2010. The trees were first enclosed in a temporary plastic chamber, and the soil surface was sealed off with a tarp. Fans within the chamber dispersed 50 L of 99 atom percent $^{13}CO_2$. The $^{13}CO_2$ content of the air was monitored during the 2-hour exposure with a Picarro Cavity Ring-Down Spectroscopy analyzer, and leaf temperature was monitored with an infrared thermometer; the exposure was halted and the plastic removed when leaf temperatures exceeded 35 °C. Immediately after the labeling event, needle samples were collected for ^{13}C analysis. Next, four trees were subjected to high shade (HS) treatments (90% shade cloth) and the other four to low shade (LS) treatments (30% shade cloth) to alter gross primary productivity (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 C exchange rate (CER) were assessed for each tree over a three-week period. The progression of the ^{13}C label was concurrently tracked from the atmosphere through foliage, phloem, roots, and soil CO_2 efflux. The HS treatment significantly reduced C uptake, sap flow, stem growth and root standing crop, and resulted in greater residual soil water content to 1 m depth. Sap flow was strongly correlated with CER on the previous day, but not the current day, with no apparent treatment effect on the relationship. The ^{13}C label was immediately detected in foliage on label day (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.

We were successful in manipulating C availability and incorporating a ^{13}C label into the trees. There was adequate label to track the rapid flux of C from the canopy to the phloem in the lower bole, and the subsequent appearance of ^{13}C in roots and soil CO_2 efflux. Although some roots clearly accumulated the ^{13}C label, others did not, which illustrates the sampling challenges posed by differential C flux through old roots, dilution with existing soluble carbohydrate pools, and partitioning into new root biomass. Likewise, soil gas contained the ^{13}C label at some locations but not at others. The extreme heterogeneity in belowground $^{13}CO_2$ distribution precluded analysis of C partitioning by depth or between soil and root respiration, without knowledge of density and proximity of roots to each sampling location. Nevertheless, the experiment was valuable for providing information about the timing of C transport through the plant-soil system. The data collected from our project are being used to test a point version of a land surface biogeochemical model that incorporates autotrophic/heterotrophic C-nitrogen interactions—the Community Land Model (CLM-CN). 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 reduction of solar radiation to simulate shade treatments manipulations. Modeled 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. An initial manuscript has been submitted and is in review as an invited contribution for a special issue of *Tree Physiology* on carbon allocation.

The general work plan for the PiTS project has been to conduct a series of short-term manipulations with a range of tree species. Our initial experiment with loblolly pine has provided guidance for additional experiments. We have identified a grove of dogwood trees that are more widely spaced and not as tall as the pines, which will make possible better control of the ^{13}C label application, better access to the canopy for intensive measurements, more clearly differentiated shade treatments, and better isolation of root systems. We learned that the pit did not create the enhanced measurement opportunities we had anticipated, and it caused some potential artifacts; hence, we will not use a pit in the next experiments. It also was considered important to have the minirhizotrons installed well in advance of the labeling. In light of these lessons, our work plan for the remainder of the initial 3-year funding period will be to set up in a dogwood plantation for a manipulation in 2012, and in the interim, exploit the opportunity of the residual ^{13}C label in the soil of the completed FACE experiment. Plant and soil samples collected from a previously CO_2-enriched FACE plot confirmed that the soil is relatively ^{13}C depleted, but new leaves have little remaining ^{13}C signal from the FACE exposure. Carbon partitioning in the FACE sweetgum plantation will be manipulated by girdling the stems.

Table 4.6 Progress on Task F2 Deliverables (expressed in abbreviated form):

Deliverable Date	**Deliverable**	**Status**
Mar 2010	We will identify sites for pits and construct and instrument the first phase of the PiTS Facility by March 2010.	Completed
Sep 2010	Observations will be made during the 2010 growing season, and by September have preliminary data sets and an evaluation of the second phase for the facility. DICP code will be developed in 2010.	Completed
2011	As 2010 observations are completed and synthesized, new trenches will be constructed. Based on progress in using the 2010 data to inform both physiological and ecosystem models, new measurements and manipulations will be proposed. DICP code will be tested against measurements in 2011.	Modified as described above, work underway

4A.5 TASK F3 -- REPRESENTING SOIL C IN TERRESTRIAL C CYCLE MODELS

Achieving a generalized mechanistic formulation

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 are 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 carbon forms. Coarse texture soils at the University of Michigan Biological Station (UMBS) site in MI may allow deeper transport and net retention of carbon than at the other sites. Cold conditions enhance the accumulation of carbon 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.

New EBIS Publications from Oak Ridge Efforts

Using EBIS-Oak Ridge manipulation data Kramer et al. (2010) demonstrated that forms of carbon leached from fresh forest leaf litterfall were not a detectable carbon source for the underlying mineral soil microbes. Recent leaf-litter carbon 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 carbon 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 carbon is the major (>60%) source of carbon 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 carbon cycling model – DayCent (Parton et al. 2010). EBIS field studies quantified the fate and transport of uniquely enriched carbon 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 carbon 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 carbon cycle models for forests within land surface models may provide better global carbon cycle projections.

Tipping et al. (in press) used the DyDOC model to simulate the soil carbon 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 carbon 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} a^{-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} a^{-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} a^{-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).

Task F3b: Modeling soil carbon turnover in eastern forests

Key ORNL Personnel: Garten, Brice

The aim of this study was to compare the turnover time of labile soil carbon (C), in relation to temperature and soil texture, in several forest ecosystems that are representative of large areas of North America. Carbon and nitrogen (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. Carbon-13 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 4.7 Progress on Task F3 Deliverables (expressed in abbreviated form):

Deliverable 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.	In Progress, LBNL lead
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.	In progress
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
Jun 2011	Complete bulk-^{14}C analyses for all sites, plots, and soil pools.	In progress

4A.6 Task F4 -- Terrestrial impacts and feedbacks of climate variability, events and disturbances

Task F4 focuses on episodic Extreme Weather, Climate and Disturbance Events (EWCDEs) as related to carbon and water cycles and vegetation dynamics. Its goal is to enable mechanistic representation of impacts and feedbacks of EWCDEs in Earth system diagnosis and prediction. Task F4 contains three subtasks: (a) strategic flux measurements at the Missouri Ozark Flux (MOFLUX) site, (b) network synthesis and EWCDE database, and (c) rapid, collaborative response to developing EWCDEs. We apply a variety of research tools, including the eddy covariance (EC) technique, leaf and soil measurements, modeling / data assimilation, remote sensing, and network synthesis.

Task F4.1: 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, 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. In late July 2010, a lightning strike destroyed the NOAA/ATDD sonic anemometer and other equipment (mostly operated by NOAA/ATDD). The loss of the NOAA tower top EC flux system was not seriously detrimental due to the existence of a parallel ORNL 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 ORNL EC flux systems for some months 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.

Task F4.2: MOFLUX Science

Interannual variability in MOFLUX carbon and water budgets

A comprehensive analysis on the interannual variability and climate controls of MOFLUX forest ecosystem carbon and water budgets is now under way. Preliminary results indicated that the MOFLUX forest ecosystem is a carbon sink (Table F4.1). However, the interannual variability is large and mostly controlled by water availability. The mean predawn leaf water potential is found to be an excellent predictor of annual carbon budget and in particular, the summer carbon budget (Figure 18). The carbon and water budgets are closely coupled (Figure 18).

A word of caution - A new advance in the EC theory made at the MOFLUX site (see the next section) means that previous flux measurements of trace gases and water vapor will have to be re-processed by all flux sites, including MOFLUX, to avoid substantial biases in estimated carbon and water budgets. At the MOFLUX site, flux measurements in 2011 are being processed according to the new theory. Codes required for reprocessing previous flux measurements have been developed and are currently being applied to the data in 2010. We expect we will be able to complete the reprocessing of data in 2004 to 2009 by the end of December 2011. The reprocessed data will be submitted to AmeriFlux Data Center afterwards and annual budgets will be re-calculated based on the reprocessed flux data.

Table F4.1 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	[illegible] 4
Annual ET (mm)	699	654	586	735	713	801	[illegible]

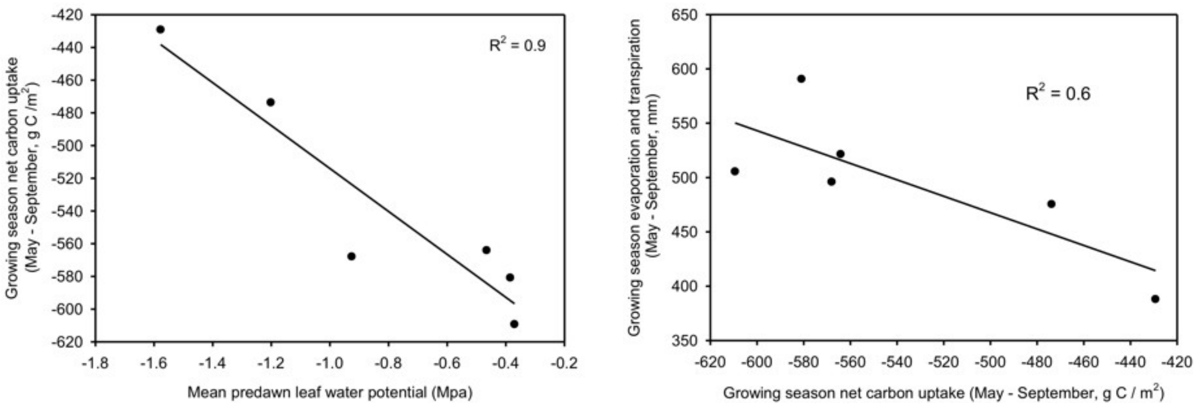

Figure 18. (Left) The relationship between growing season net carbon uptake (negative indicates uptake) and mean predawn leaf water potential. (Right) the relationship between carbon and water budgets during the growing season,

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 carbon 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 has led to several potentially very significant advances in the eddy covariance theory and its application (Gu et al. 2011). We derived a new fundamental equation of eddy covariance that allows the net ecosystem exchange (NEE) of an atmospheric greenhouse gas to be measured with the constraint of the conservation of mass of any other atmospheric constituent. We showed the conservation of mass of dry air can be used to constrain flux measurements of atmospheric greenhouse gases as has been done by the flux community. However, the conventional WPL steady-state theory must be replaced with the newly developed nonsteady-state theory. This is achieved by introducing to the flux equation an additional term called the dry air storage adjustment. Measurements from MOFLUX showed that without this new term, flux measurements are biased diurnally and seasonally. That means, essentially all eddy flux sites in the world will have to reprocess their data in order to correct for these biases. Additionally, measurements from MOFLUX demonstrated that it is reasonable to determine NEEs with mixing ratio-based turbulent flux measurements but the storage change must be replaced with the effective storage change introduced in Gu et al. (2011).

Canopy physiology and phenology studies

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 19) indicated peak efficiency in utilization of high light levels in early summer and declines thereafter.

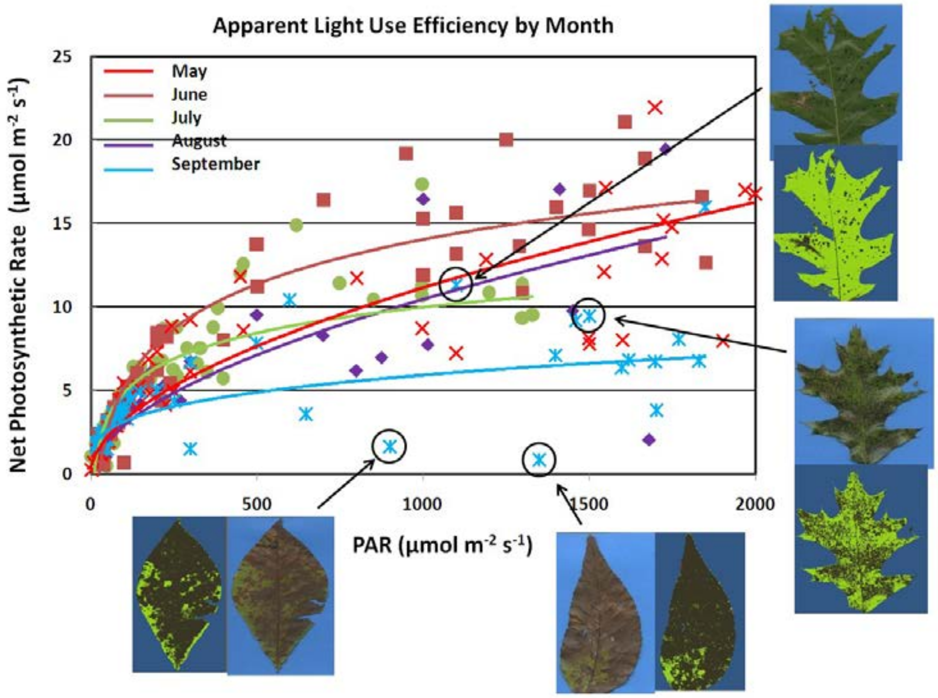

Figure 19. Response of net photosynthesis to PAR at monthly intervals during the 2010 growing season. Data fitted by exponential curve functions. Circled data points illustrate the association of particular net photosynthetic rates with level of leaf necrosis as illustrated by scanned leaves. Adjacent image emphasizes the necrotic area as determined by win Folia Pro software. Side leaves are black oak; bottom leaflets are shagbark hickory.

These data support the existence of an early-summer peak in photosynthetic capacity as indicated by V_{cmax} and J_{max} data obtained concurrently 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.

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 (Figure 20). 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<shagbark hickory<white oak<black oak (Figure 20a). DR peaked in mid season (mid-July), declining thereafter (Figure 20b). 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 (Figure 20c), as would be expected given the greater leaf mass per unit area in upper canopy leaves previous seen in MOFLUX work (not shown). Also, as expected, DR tended to increase with leaf temperature (Figure 20d).

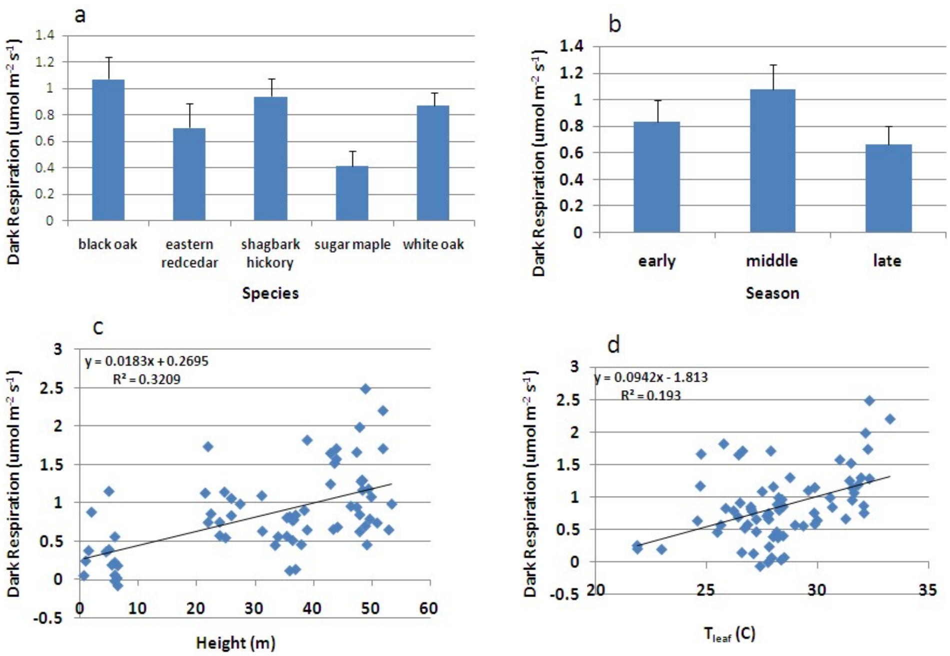

Figure 20. Dark respiration data from early-, mid- and late-season measurements at MOFLUX. Dark respiration displayed as a function of: species (a), season (b), height of leaf in the canopy (c), and leaf temperature (d). Bars in (a) and (b) = 1 SE.

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 datasets 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 seven multi-site/regional synthesis efforts that have already resulted in peer-reviewed publications (see 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 exchanges of CO_2 (Xiao et al. 2011), model-data intercomparisons (Schwalm et al. 2010), climate controls on net terrestrial carbon exchanges on global scales (Yi et al. 2010), network-wide nighttime ecosystem respirations (van Gorsel et al. 2009), land surface albedo products (Román et al. 2009) and their relationships to leaf nitrogen content (Hollinger et al. 2010). Over the years, multiple research teams have conducted complementary but separately funded studies at the MOFLUX site to take advantage of the facility and datasets we provide.

Currently, three independent research projects are operating at the MOFLUX site: high-precision CO_2 concentration measurements led by Dr. Kent Davis from Pennsylvania State University, VOC measurements led by Dr. Alex Guenther of NCAR and Dr. Mark Potosnak of DePaul University, and soil moisture measurements by the project of Cosmi-ray Soil Moisture Observing System (COSMOS, http://cosmos.hwr.arizona.edu).

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.

Task F4.3: 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 carbon shifts between pools and vegetation recovery after large-scale extreme events

We have used the massive 2008 China ice storm as a case study to investigate how large-scale extreme events in temperate regions affect terrestrial carbon cycles and how vegetation recovers after extreme events. We provided guidance to our Chinese colleagues on ground-based surveys while we ourselves conducted remote sensing-based assessment of the ice storm damage on forests as well as post-storm vegetation recovery. The storm caused 20 million hectares of forests, which was equivalent to 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 indicated that the forest greenness index in the region recovered fully in a few months (data not shown). We hypothesize that tree species in the region have exceptional capacity for resprouting which allowed forests to take advantage of the rapid post-storm temperature rise and recover. If our findings are vindicated with ground-based studies, resprouting may be a crucial mechanism for post-disturbance vegetation recovery and should be included in dynamic vegetation modeling.

Table 4.8 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.

Deliverable Date	Deliverable	Status
2010	Fix tower leg damaged by ice (unforeseen event)	Completed
2010	Submit flux and complementary biological datasets to AmeriFlux.	Completed

2010	Complete analysis on soil respiration, paper submitted.	Rescheduled
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	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	In progress
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
2011	Historical data on forest damage from ice storms, fires and droughts are compiled and entered into EWCDE database.	Two papers published, one in progress

4A.7 Task F5 -- Fossil emissions

Fiscal year 2011 has seen continuing efforts within Task 5 toward maintaining and improving an up-to-date and publicly available data base on CO_2 emissions from fossil fuel consumption, examining and confronting the uncertainty in emissions estimates, and addressing issues of greenhouse gas accounting broadly. We have now made available, on-line, emissions data by country through 2008; have compiled preliminary annual estimates, by country, through 2010; and have developed and published for the first time national data at monthly time steps.

The earliest estimates of emissions through 2009 were published promptly in a short but high-impact paper with the Global Carbon Project (in *Nature Geoscience*), and the initial estimates for 2010 will have high impact when the magnitude of the recent increases is fully distributed. We are chairing the fossil-fuel component of a Global Carbon Project initiative to examine the global carbon balance at regional levels. We have continued to explore the uncertainty in emissions estimates and served on the scientific steering committee for the 3rd International Workshop on Uncertainty in Greenhouse Gas Emissions.

In the broader scope of greenhouse gas accounting, we have participated in one national and one international workshop on the time value of carbon emissions and how it should be treated in life cycle and footprint analyses (i.e. do emissions now have the same value as emissions some years in the future, does delaying emissions have value?). We have defended the view that delaying emissions and temporary sequestration do have value. We have contributed to improving methods on accounting for emissions from harvested wood products (including through an IPCC working group) and from biomass used for energy.

A research plan for US carbon cycle science, with Gregg Marland as one of 4 co-chairs, was completed in FY 2011.

Table 4.9 Progress on Task F5 Deliverables (expressed in abbreviated form):

Deliverable Date	Deliverable	Status
Sep 2010	Preliminary emissions 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

4B. Future Plans and Scientific Goals

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 this process, and to put the research group and our collaborators on a solid footing for evaluating organism to ecosystem responses and functional responses to the imposed treatments when they are initiated.

The existing CLM-CN terrestrial carbon cycle model will continue to be modified to allow it to fully capture the carbon 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 carbon allocation mechanisms stemming from the results of Task F2 work will also be a key focus of upcoming modeling-experiment dialogs.

Fundamental uncertainties remain regarding the contribution of belowground productivity to the fate and storage of carbon within upland and peatland soils, and the TES SFA group is developing new task descriptions of such work for evaluation during the triennial review. We have also identified the characterization of root function within soils with respect to carbon exchange, water extraction and nutrient uptake and cycling to be a key area of uncertainty for which new experimental or process level studies will be developed to accommodate time and funding made available with the completion of existing Tasks. We will also consider building on our recent success using neutron imaging as a novel and non-destructive tool to quantify high-resolution uptake of soil water by individual maize roots, redistribution of water with soil and roots, and water transport through the stem to the atmosphere. With further development, this technique may be used to interrogate soil-root water fluxes in context of myriad mechanistic plant processes (e.g., aquaporin function, nutrient uptake, root-mycorrhizae interactions), and their response to imposed environmental changes.

4C. NEW SCIENTIFIC RESULTS THAT MAY INFLUENCE TES SFA RESEARCH DIRECTIONS

At this early stage in the TES SFA (1 year and 9 months of funded activity), the iterative process among experiments, observations and the terrestrial carbon cycle modeling tasks has not dictated a new direction for the SFA. Process level studies focusing on mechanisms of soil carbon cycle transport and accumulation rates within soils are being completed in FY2011 and 2012, and will open the opportunity for a redirection of effort in other research areas.

4D. COLLABORATIVE RESEARCH ACTIVITIES

A variety of collaborations are being fostered in support of various research tasks. Such collaborations provide necessary expertise or effort in areas critical to the completion of a research task. 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 a collaboration with Prof. Steven Running at the University of Montana, to maintain the strong connections that exist between the CLM and Biome-BGC models. The purpose of this effort is to have both a highly sophisticated though expensive model (CLM) and a highly efficient though less sophisticated model (Biome-BGC) that share as much as possible in their logical construction and process representation. This will allow us to evaluate the influence of model structure and complexity on prediction uncertainty and parameter optimization.

We continue our collaborations with Dr. Bill Parton (Colorado State University) on the EBIS-AmeriFlux project (Tasks F3a) to translate our fundamental tracer work on soil carbon cycling directly to functional ecosystem carbon cycle models.

Subcontracted collaborations for which DOE BER funds are provided through ORNL are detailed further in Section 5B. We are also encouraging key external groups to develop complementary research tasks for the benefit of TES SFA research tasks.

5. STAFFING AND BUDGET SUMMARY

5A. FY2011 FUNDING ALLOCATION BY PROGRAM ELEMENT (TASK) AND INDIVIDUAL RESEARCHER

ORNL received authorization from DOE BER of $7,755K for FY2011, we also carried over $2,262K of FY2010 funds from projects 3ERKP720 (Forcing SFA) and 3ERKP721 (Response SFA) for support of scientific efforts and the continued development of experimental infrastructure for SPRUCE. An additional $50K of funding was allocated during the year. Available funding and its allocation to various research Themes and Tasks is presented in Table 5.1, and by Investigators and Key Staff in Table 5.2.

Table 5.1. Funding allocation by TES SFA research tasks with actual costs as of 6/30/2011.

Task	FY2011 Budget ($K)	Percent of Annual Effort (%)[1]	9-Month Expenses ($K)
FY2011 Budgets			
TES SFA -3ERKP788	$7,806	---	$3,600
Forcing SFA – 3ERKP720 (carryover $)	$790	---	686
Response SFA – 3ERKP720 (carryover $)	$1,473	----	1,423
Total funds available in FY2011	**$10,069**	---	$5,709
Climate Change Response Tasks			
R1. SPRUCE – Science	$3,014	61	$1,725
R1. SPRUCE – Engineering	$200		$77
R1. SPRUCE – Infrastructure	$2,989		$1,117
R2. Walker Branch	$264	3.4	$138
Climate Change Forcing Tasks			
F1. Carbon Cycle Modeling	$1,745	17	$1,542
F2. PITS	$349	3.5	$129
F3. Soil Carbon Activities	$500	5	$310
F4. Landscape Flux Dynamics (MOFLUX)	$699	7	$515
F5. Emissions	$309	3.1	$128

[1]Percent of effort is based on planned expenditures of FY2011 funds. Carryover funds from 3ERKP721 have been primarily used to support SPRUCE engineering and infrastructure development. Carryover funds from 3ERKP720 support Tasks F1 through F5.

Table 5.2. FY2011 effort and funding by TES Investigators and related ORNL staff through 30 June 2011. These totals include combined effort under the TES SFA and any effort charged to carryover funds from the previous Forcing and Response SFAs.

Person	Primary Tasks	Projected Time (Person Hours)	Actual Time (PH to date)	Actual 9-month Cost ($K)
Scientific Staff				
Andres	F5	188	224	$32K
Garten	R1, F3	1072	812	$126K
Gu	R1, F4	1874	1381	$215K
Gunderson	R1	1792	1280	$169K
Hanson	R1, F3	1765	1242	$220K
Hayes	F1	1380	952	$110K
Hook	R1	357	256	$34K
Iversen	R1, F2	672	642	$74K
King	F1	632	285	$44K
Marland	F5	348	348	$61K
Mulholland	R1	118	118	$21K
Norby	R1, F2	506	454	$90K
Post	F1	1042	614	$109K
Ricciuto	F1	1880	1388	$184K
Schadt	R1	197	96	$13K
Thornton	F1, R1	1200	588	$91K
Wang	F1	640	636	$84K
Warren	R1, F2	880	603	$70K
Weston	R1	563	406	$54K
Wullschleger	R1	552	44	$8K
Other Scientific Staff	Various tasks	40	53	$7K
Technical Staff				
Brice, D.J.	R1, R2, F2, F3	1509	1157	$109K
Childs, J.	R1, F2	1432	766	$72K
Kerley, M.K.	R1	0	269	$28K
Devarakonda, R.	R1	100	93	$10K
McCracken, M.K.	R2	408	246	$23K
Phillips, J.R.	R1	406	264	$25K
Todd, D.E.	R1, F3	1754	1229	$145K
Other Technical staff	Various tasks	0	68	$7K
Technical Project Management				
Huczko, K.A.	R1, F1, F2	720	352	$40K
Other Admin. Support	Various tasks	0	143	$15K
ORNL Crafts				
Riggs, J. – Instrumentation	R1, F2, F3	~1000	785	$78K
Sluss, D. - Instrumentation	R1, F2, F3	~1000	1180	$113K
Other Craft/Mgmt. Support	R1, F2, F3	As needed	1388	$134K

Engineering & Computational Support				
Childs, K. (energy model)	R1	As needed	8	$1K
Barbier, C. (energy model)	R1	As needed	132	$16K
Belcher, D.	R1	As needed	173	$21K
Ellis, J.	R1	As needed	25	$3K
Jekabsons, E.	R1	As needed	127	$15K
Jones, L.	R1	As needed	70	$8K
Newkirk, G. (purchasing)	R1	As needed	82	$12K
Tavino, C.	R1	As needed	13	$2K
Thomas, W.	R1	As needed	In kind	$0K
Materials	All tasks	NA	NA	$410K
Travel	All tasks	NA	NA	$119K

5B. FUNDING ALLOCATION TO EXTERNAL COLLABORATORS

A number of subcontracts were established or continued under the TES SFA to further our research goals.

To facilitate *a priori* modeling of the SPRUCE Experiment (Task R1) subcontracts were put in place with Dr. Paul Miller at Lund University ($12K), Dr. Robert Grant at the University of Alberta ($10K), and with Dr. Jeff Amthor at the University of Sydney ($24K). Dr. Merritt Turetsky at the University of Guelph was contracted () to provide expertise and student support in the study of *Sphagnum* and belowground processes as a part of the SPRUCE experiment. An interagency agreement (IAG) between ORNL/DOE and the USDA Forest Service Marcell Experimental Forest has also been put in place ($100K) to facilitate tree removal and site preparation of the upland areas of the S1 watershed for the SPRUCE experiment. Peat depth surveys of the S1 bog were executed under subcontract by a group from Rutgers University ($54K).

Development of the SPRUCE warming prototype in Oak Ridge was facilitated by several engineering and construction subcontracts ($285K). NEPA Environmental Assessment activities also required a contract with SAIC ($56K) to produce the necessary documents while avoiding internal conflict of interest issues.

In support of Task F1 a contract was placed with the University of Montana ($63K) to provide support for coordination of CLM and Biome-BGC model development, providing a test case to study the influence of model structure and complexity on prediction uncertainty and parameter optimization. Debbie Huntzinger was supported ($57K) to coordinate regional synthesis efforts within NACP. An overview paper has been submitted (Huntzinger et al.) describing the work.

Under Task F3a, the EBIS-AmeriFlux continued to provide site support ($10K per year per site) for the operation and oversight of our remote field study locations in Missouri (University of Missouri), Michigan (University of Michigan), New Hampshire (USDA Forest Service), and Massachusetts (Harvard University). Dr. Bill Parton was provide a subcontract ($45K) through Colorado State University to use EBIS-AmeriFlux data to further refine the FORCENT model developed as a part of EBIS-Oak Ridge. Surveys of macrobiotic populations at all EBIS-AmeriFlux sites were conducted by the USDA Forest Service throughout 2010 ($20K).

In support of Task F4, collaborators at the University of Missouri are under contract ($306K) to conduct day-to-day operations of the MOFlux tower instrumentation, and make periodic physiological and growth observations.

Through the Oak Ridge Institute for Science and Engineering (ORISE) we also developed a number of subcontracts for the support of postdoctoral associates working on the TES SFA including: Natalie Griffiths, Jiafu Mao, Xiaoying Shi, Meg Steinweg, and Xiaojuan Yang.

Small subcontracts for chemical analyses conducted in support of various tasks are also in place with a variety of institutions.

5C. 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 the spring of 2011because of a serious illness. The TES SFA hired Dr. Natalie Griffiths as a postdoctoral associate to fill Pat's role in Tasks R1 and R2 in preparation for this unfortunate transition.

Charles T. Garten Jr. has announced his plans to retire 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. Charles will wrap up all of research and commitments to Task F3 before the end of FY2011.

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

5D. NATIONAL LABORATORY INVESTMENT IN THE PROGRAM

Concepts for the belowground warming technologies used for the SPRUCE Experiment (Task R1) were initiated with ORNL LDRD funds totaling $480K in FY2008 and FY2009. Current LDRD funding ($200K) is being used to develop neutron imaging as a novel and non-destructive tool to quantify high-resolution uptake of soil water by individual maize roots, redistribution of water with soil and roots, and water transport through the stem to the atmosphere. Such approaches may have direct application to the identification of process-level mechanisms for use within ecosystem models.

Partial support for new terrestrial carbon-cycle modeling staff was provided by the ORNL General Hire program to facilitate building a broader modeling base to take on the breadth of the activities funded under the TES SFA.

Dr. Melanie Mayes has obtained LDRD funding to develop new methods to evaluate soil carbon characterization and turnover. This ORNL investment is expected to lead to new tasks of the TES SFA.

5E. CAPITAL EQUIPMENT

Capital equipment funds were used to purchase open-path CO_2 and CH_4 monitoring systems for use and application in the SPRUCE experiment. Significant funding for experimental infrastructure development for the SPRUCE field facilities are not classified as capital expenditures, but represent an analogous investment for the planned decadal duration of that large-scale and long-term field experiment.

Given planned large investments in experimental infrastructure in FY2012 capital equipment funds are not budgeted, but future investments in new instrumentation will enhance our research opportunities. Specific needs include: incubators for laboratory based carbon and nutrient metabolism in Sphagnum and both mineral and organic soils;; and a high-resolution, portable spectral radiometer for non-destructive determination of nitrogen, surface moisture, and species distribution.

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APPENDIX A: TES SFA PUBLICATIONS SINCE OCTOBER 2009

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APPENDIX B: TES SFA WWW RESOURCES

TES SFA Web Resources:
TES SFAweb site: http://tes-sfa.ornl.gov

SPRUCE Experiment Web Resources:
Project Web Site: http://mnspruce.ornl.gov

APPENDIX C: 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 2011).

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.