FY2013 PROGRESS REPORT
OAK RIDGE NATIONAL LABORATORY'S
TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA
(TES SFA)

Environmental Sciences Division
Oak Ridge National Laboratory

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ABSTRACT

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

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1.0 PROGRAM OVERVIEW

The Oak Ridge National Laboratory (ORNL) TES-SFA seeks to advance understanding of the impact of energy production and consumption on the global earth system by improving and expediting the incorporation of terrestrial-ecosystem process understanding into Earth System Models.

Vision: Improved Land Surface Modeling for the Earth System through integrated experiment-model-observation understanding of terrestrial processes

The TES-SFA is guided by the vision that sensitivities, uncertainties, and recognized weaknesses of Earth System Models inform observations, laboratory and field experiments, and the development of ecosystem process modeling. In turn, robust understanding and findings from the field and laboratory and improved process modeling should be incorporated, with the associated uncertainties, into Earth System Models as explicitly and expeditiously as possible. The more organized, structured, or formalized this dialogue, the more efficient and effective it can be.

The TES-SFA is an integrated experiment-model-observation research program investigating the response of terrestrial ecosystems to changes in climate and atmospheric composition and how those responses feedback to force further climate and atmospheric change. The TES SFA combines experimental and observational research and process-level modeling in an iterative exchange between hypothesis developments from model simulations, the execution of observations and experiments on ecosystems and the organisms they contain, and the use of empirical results to parameterize and evaluate ecological models (Figure 1). This continuous research loop allows us to understand and predict the global terrestrial ecosystem forcing of the earth's climate, and to assess vulnerability of terrestrial ecological systems to projected changes in climate and atmospheric composition. The research is focused on how terrestrial ecosystems affect atmospheric CO_2 and other greenhouse gases and how the ecosystem processes responsible for these effects interact with climate and with anthropogenic forcing factors.

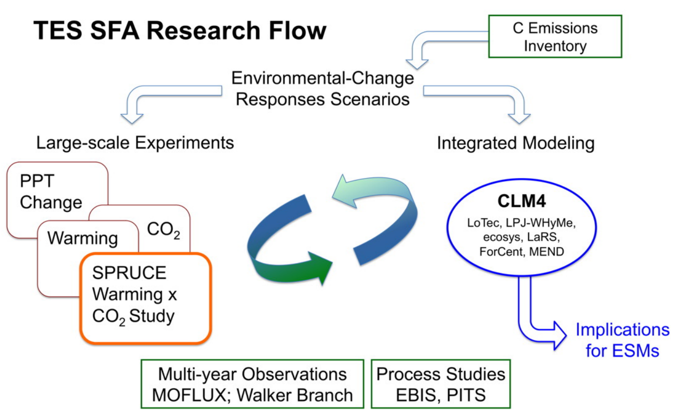

Figure 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development, and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

Our paradigm is to identify and target critical uncertainties in coupled-climate and terrestrial ecosystem processes and feedbacks, prioritized by their influence over global change predictions on decadal and century timescales. Unique experiments such as the ongoing Spruce and Peatland Responses Under Climatic and Environmental Change (SPRUCE) experiment are conducted to quantify biogeochemical responses to environmental and atmospheric change variables to improve model-based predictions of the effects of atmospheric and climatic change on ecosystems' function, composition, and feedbacks to the atmosphere and climate. Additional process research and landscape-scale, C-cycle observations in understudied ecosystems improve mechanistic representations of ecosystem processes within terrestrial C cycle and Earth-system models. TES SFA research informs and improves terrestrial land surface and biogeochemistry models, with a particular emphasis on migration of knowledge into the Community Land Model (CLM4) component of the Community Earth System Model (CESM). Integration among experiments, models, and observations improves the predictive skill of climate system models through improved fidelity of process representation in their land surface biophysics and biogeochemistry components, and generates and tests new hypotheses which address critical uncertainties in the terrestrial ecosystem components of climate system prediction.

Products of the TES SFA include primary research publications, synthesis activities (e.g., critical review papers, model-data intercomparisons, and international workshops), newly archived data, and a multi-scale model-data assimilation system delivering analyses of climate change forcings and terrestrial organism responses appropriate for local-to-global analyses.

Research conducted under ORNL's TES SFA addresses all goals of the Office of Science, Climate and Environmental Science Division (DOE/SC-0151), and focuses its efforts on Goal 2: "Develop, test, and simulate process-level understanding of atmospheric systems and terrestrial ecosystems, extending from bedrock to the top of the vegetative canopy". Results from the TES SFA also inform Goal 1: "Synthesize new process knowledge and innovative computational methods advancing next-generation, integrated models of the human-Earth system".

2.0 SCIENCE QUESTIONS, GOALS AND MILESTONES

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

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

Goals and Milestones

The TES SFA Science Plan addresses the following five research goals and associated long-term (5 to 10 year) milestones. FY2013 annual progress towards these long-term goals is summarized in this report.

Goal 1. Resolve uncertainty in the sign and magnitude of global climate-terrestrial C cycle feedbacks under future climatic warming and rising CO_2.

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

Goal 2. Understand and quantify organismal and ecosystem vulnerability to warming through the use of new experimental manipulations employing multi-level warming with appropriate CO_2 exposures and measures of water and nutrient limitations.

Long-term milestone: Conduct and complete experimental manipulations and synthesize results including the development of algorithms for characterizing changes in plant growth, mortality and regeneration, and associated changes in water balance, microbial communities and biogeochemistry under climatic change in key understudied ecosystems.

Goal 3. Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in Earth system models, and to inform mitigation strategies through ecosystem management.

Long-term milestone: Provide a flexible model of soil C storage for ecosystems based on land use metrics for incorporation in fully-coupled Earth system models.

Goal 4. Incorporate new findings on interannual and seasonal dynamics, episodic events, and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and Earth system models emphasizing the importance of the decadal time scale.

Long-term milestone: Achieve predictive capacity to simulate interannual to decadal dynamics important to water balance, biogeochemical cycling, and vegetation and microbial response to climatic and atmospheric change across ecosystems.

Goal 5. Search out key uncertainties within global land-atmosphere-climate models and future Earth system diagnosis models as the basis for proposing new measurements and experiments as new knowledge is gained.

Long-term milestone: Resolve major components of terrestrial feedback uncertainty for the entire Earth system. New model capabilities will include improved process-based representation of soil organic matter dynamics, microbial communities, and new representations of ecosystem climate change response mechanisms derived from experiments.

Research to accomplish these broad goals and objectives is organized as a series of tasks. The tasks are listed below with parenthetical identification of the listed goals that each addresses:

Spruce and Peatland Responses Under Climatic and Environmental change (SPRUCE; Goals 1, 2),
Walker Branch Watershed long-term monitoring (Goal 4),
Mechanistic C cycle modeling (Goals 1, 2, 3, 4, 5),
Partitioning in trees and soils (PiTS; Goals 4, 5),
Representing soil C in terrestrial C cycle models (Goal 3),
Terrestrial impacts and feedbacks of climate variability, events, and disturbances (Goal 4), and
Fossil C emissions (Goals 1, 5).

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

Data systems and informatics are not a separate focus area, but an integral part of the TES SFA. ORNL is developing and deploying data and information management, and integration capabilities needed for the collection, storage, processing, discovery, access, and delivery of data. Such capabilities facilitate model-data integration and provide accessibility to model output and benchmark data for analysis, visualization, and synthesis activities.

3.0 TES SFA PROGRAM STRUCTURE AND PERSONNEL

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) at ORNL. The TES SFA is supported by more than 50 dedicated scientific and technical staff at ORNL, the USDA Forest Service, and at various collaborating universities and laboratories. We have brought together exceptional multidisciplinary expertise, and are retaining and building staff flexibility to support new research priorities as they are identified.

Dr. Paul J. Hanson is the lead Coordinating Investigator for the TES SFA with Principal Investigator responsibilities for the SPRUCE experiment, and EBIS-AmeriFlux soil C process work. Dr. Peter E. Thornton is the Coordinating Investigator for all C cycle modeling tasks. During FY2014, Dr. Daniel M. Ricciuto will have responsibility for the C cycle modeling tasks of the TES SFA. Kathy A. Huczko serves as a Technical Project Manager and maintains a key focus on the development of SPRUCE experiment infrastructure. Dr. Les A. Hook serves as the Data Management Coordinator. He works with all task leads to ensure the timely archiving and sharing of SFA data products. Individual Task leads (Figure 2) 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.

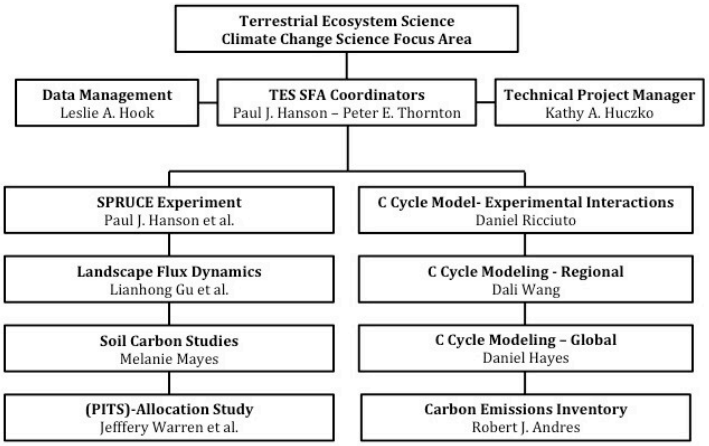

Figure 2. Organizational chart for the TES SFA effective July 2013.

Individual Task leads and participants take responsibility for their respective activities as follows:

Carbon cycle modeling activity tasks are led by Daniel Ricciuto, Dali Wang, and Daniel Hayes with participation of Jiafu Mao, Xiaoying Shi, Anthony King, and Xiaojuan Yang. These tasks integrate experimental results, observations, and modeling to improve understanding and simulation of coupled C-climate feedbacks.

Carbon allocation and root function process research is led by Jeffrey Warren with the participation of Colleen Iversen, Richard Norby and Anthony Walker. The focus is on the development of dynamic allocation representations for global models and applications.

Soil carbon process activities are led by Melanie Mayes with the participation of Christopher Schadt. They are developing next generation mechanistic soil C models for CLM-CN that include critical factors such as microbial community composition, exoenzyme-facilitated depolymerization, and mineral stabilization. Paul Hanson continues to summarize EBIS-AmeriFlux efforts.

Landscape-level Carbon and Water Flux Dynamics tasks are led by Lianhong Gu to evaluate flux of greenhouse gases associated with climate extremes utilizing eddy covariance data and associated experiments.

Carbon Emissions Evaluations are conducted by Robert Andres to characterize uncertainty analyses for understanding fossil fuel emissions for model and synthesis activities from an integrative perspective.

SPRUCE Experiment

SPRUCE is coordinated by Paul J. Hanson as the lead of a panel made up of the ORNL Lead (Hanson) the local USFS contact (Randall K. Kolka), SPRUCE technical task leaders listed below, and a SPRUCE advisory group. This panel serves as the decision-making body for major operational considerations throughout the duration of the experimental activity and it represents the governing body for vetting requests for new research initiatives to be conducted within the experimental system. SPRUCE subtasks include:

Experimental design, maintenance, and environmental documentation – Paul Hanson leads this effort in conjunction with Randall Kolka of the USDA Forest Service. W. Robert Nettles is the ORNL staff person located in Minnesota. He provides day-to-day operation and oversight for the experiment.

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

Community composition – Efforts to characterize vascular plant community compositional changes in response to the experimental treatments are led by Brian Palik of the USFS. Christopher Schadt leads a large group including collaborators focused on microbial community dynamics.

Plant Physiology – Characterization of pre- and treatment plant physiological responses to both seasonal dynamics and induced treatment regimes are led by Jeffrey Warren with the support of Stan Wullschleger and Anna Jensen.
Biogeochemical cycling responses –Work on hydrologic cycling is being led by Steve Sebestyen and Natalie Griffiths with input from Jeffrey Warren. Colleen Iversen leads the element cycling subtask. Carbon cycle observations focused on peat changes and C emissions will be coordinated by Paul Hanson, Randall Kolka and Colleen Iversen.
Modeling of terrestrial ecosystem responses to temperature and CO_2 –Daniel Ricciuto coordinates efforts to utilize and incorporate SPRUCE experimental results into improved modeling frameworks for understanding the terrestrial C cycle and its feedbacks to climate. He is assisted by Xiaoying Shi and Jiafu Mao, with continued oversight by Peter Thornton.

The TES SFA project coordinators and research task leaders together with representative members from CCSI and a cross-SFA Data Systems Manager (e.g., Thomas Boden; CDIAC) form the TES SFA Leadership Team. The TES SFA Leadership Team provides advice 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.

4. PERFORMANCE MILESTONES AND METRICS

During FY2013, many initial activities established under our iterative model-experiment-observation interaction are continuing, some have concluded in the current fiscal cycle and funding is being transitioned to the next most pressing model or process concern (See Sections 4B and 4C). Section 4A provides progress reports for the large-scale field manipulation SPRUCE, process work on C allocation, soil C cycling mechanisms, sustained landscape C and water cycle observations in Missouri, and integrated model-experiment-observation tasks. For full justifications for all research tasks, the reader is referred to the TES SFA January 23, 2012 Science Plan and Progress Report, and the July 6, 2012 Response to Review Comments produced for the TES SFA triennial review conducted in April 2012.

Following the description of progress for each TES SFA science task, a table of anticipated FY2012 and FY2013 deliverables is provided showing progress and any changes made since they were proposed in January 2012. Task numbers referencing earlier and separate Response SFA and Forcing SFA tasks are out of date for the combined TES SFA and have been changed for this report.

4AI. REVIEW OF SCIENTIFIC PROGRESS BY TASK

Task 1: SPRUCE Experiment (Formerly Task R1)

As of June 2013 the project is approximately halfway through the development of infrastructure for the SPRUCE experiment. Full function of the experimental treatments is expected and being planned for in FY2014. Associated pretreatment characterization of the target Minnesota peatland has continued in parallel with infrastructure development. Such data are being used to develop a CLM-Wetlands model with the capacity to address the C-cycle, water cycle and energy dynamics of peatland systems and wetlands in general. The following text provides succinct descriptions of SPRUCE infrastructure and peatland science accomplished since January 2012.

SPRUCE Infrastructure

Aerial photographs of the SPRUCE site (Figure 3) demonstrate significant progress made over the past 12 to 18 months. Roads were added, electrical service installed, storage units and buildings delivered, boardwalks established, and instrumentation was installed for long term monitoring of environmental conditions and organism-ecosystem responses.

Figure 3. Development of the SPRUCE experimental site on the southern end of the S1 Bog on the Marcell Experimental Forest in 2012.

Full scale testing of the 12-m diameter open-top enclosures for air and belowground warming for SPRUCE were constructed and tested in Oak Ridge, Tennessee during 2011 and 2012, with limited additional testing in early 2013. These observations yielded the energy use demands for a range of target treatment temperatures (Table 1). Wind velocities had a dominant effect on the energy required to produce warmed air, while seasonal changes in temperature and rainfall had minimal impacts on the warming performance of the prototype. The enclosures developed for SPRUCE will be capable of generating warming temperature differentials as high as +9 °C resolved at 1.5 °C or better increments.

Target Temperature Differential (+°C)	Propane Requirements for Air Heating (Gal LPG week^{-1})	Electrical Requirements (kW)
0	0	0
1.5	263	0.65*
3	535	1.3
4.5	798	2
6	1061	2.6*
7.5	1333	3.8*
9	1596	5

Table 1. Measured or interpolated energy required to achieve a range of target temperature differentials within the prototype SPRUCE warming enclosure. *Extrapolated from data for measured temperature ranges. LPG = liquid propane gas.

Additions of CO_2 to the prototype chamber enabled elevated atmospheric CO_2 treatments of +500 ppm. As expected, external winds and the resulting increased internal turnover of the enclosure air volume require greater addition rates to achieve targeted levels of CO_2, but there is also enhanced demand with warmer internal temperature differentials due to the buoyancy of warm air.

Pretreatment Observations of the S1 Bog

Pretreatment observations on the S1 Bog for a range of state and response variables continue during the development of the infrastructure for experimental manipulations. The following brief summaries detail progress since January 2012 including initial calculations of a C balance for the S1 Bog.

Peat Characterization **-** To determine the initial physical, chemical, and biological properties of the peat in the SPRUCE experimental plots, a number of 2-m to 3-m deep cores were collected from each experimental plot during the week of August 13, 2012. Approximately 20 people representing ORNL, the USDA Forest Service and our university collaborators, participated in this initial sampling event. Peat cores were collected in hummock and hollow pairs at selected locations characterized by vegetation type (Figure 4). In each hummock and hollow, three adjacent cores were extracted to ensure adequate quantities of peat material for planned analyses. In the hollows of each vegetation type, the first 30 cm of peat was sampled using a modified hole saw. A Russian corer was then used to sample peat from 30 cm to 300 cm, in increments of 50-cm.

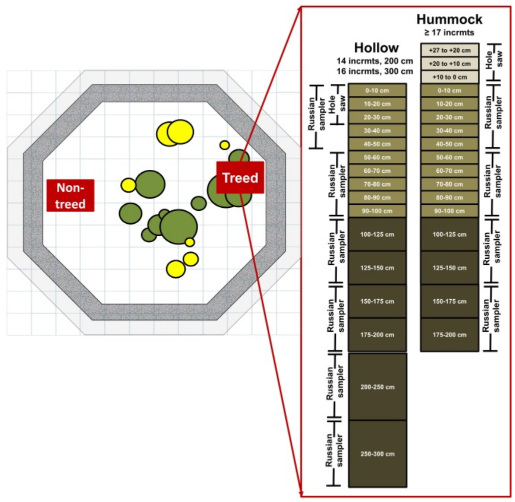

Figure 4. An example SPRUCE experimental plot indicated the 'treed' and 'non-treed' vegetation designations, and the peat sampling design. In the shallow peat layers, the peat was sectioned into 10-cm depth increments, between 100- and 200-cm depths, only two cores were taken and cores sectioned into 25-cm increments. From 200- to 300-cm depth, only one core was taken, in 50-cm increments. A hole saw was used to sample the hummocks, which ranged from +10 to +30 cm. Peat was not sampled below 200 cm depth in the hummocks.

Peat processing in the field included: (1) wet mass assessment, (2) immediate subsampling for Hg and S analyses, (3) hand homogenization, and subsampling by ORNL and collaborator labs for analysis (e.g., enzyme analysis, DNA/RNA, and FTIR/NMR) and archiving. After field subsampling, the bulk peat was frozen at -20°C and shipped to ORNL for further processing. At ORNL, peat was subsampled for fine-root standing crop before drying the remainder of the peat at 70°C to determine peat moisture content. Peat analyses underway include assessment of bulk density and characterization of bulk peat C, N, P, ^{13}C, ^{14}C, pH, lignin, and cations.

Figures 5 shows final results for mean peat bulk density for all designated treatment plots on the S1 Bog. Peat bulk density was least in the hummocks, increased through the aerobic peat layers (i.e. the acrotelm), reached a maximum at the transition zone between the acrotelm and the subtending anaerobic zone (catotelm), and stabilized around 0.15 g dry mass cm^{-3} in deeper peat layers.

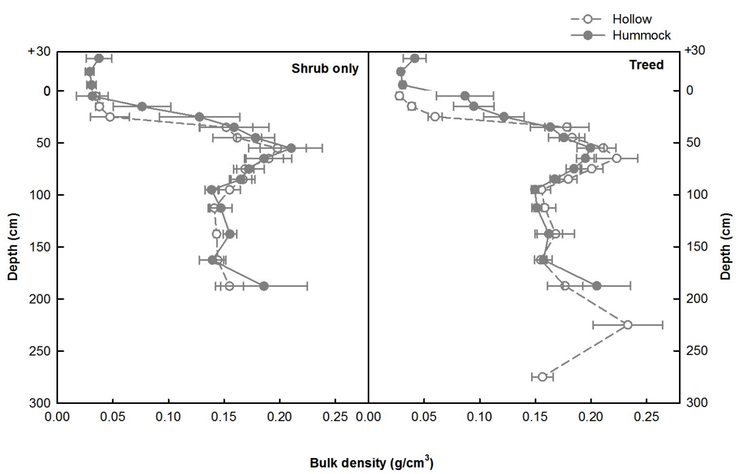

Figure 5. Bulk density of peat with depth for areas of the bog dominated by shrubs or trees.

Initial results for ^{14}C isotopic composition and age across the S1 Bog were obtained under contract with the Center for Accelerator Mass Spectrometry at LLNL (Figure 6). These data show limited spatial variation in peat isotopic signatures and age across designated treatment areas that will enable careful evaluations of warming treatment effects on the decomposition of peat stocks accumulated over thousands of years.

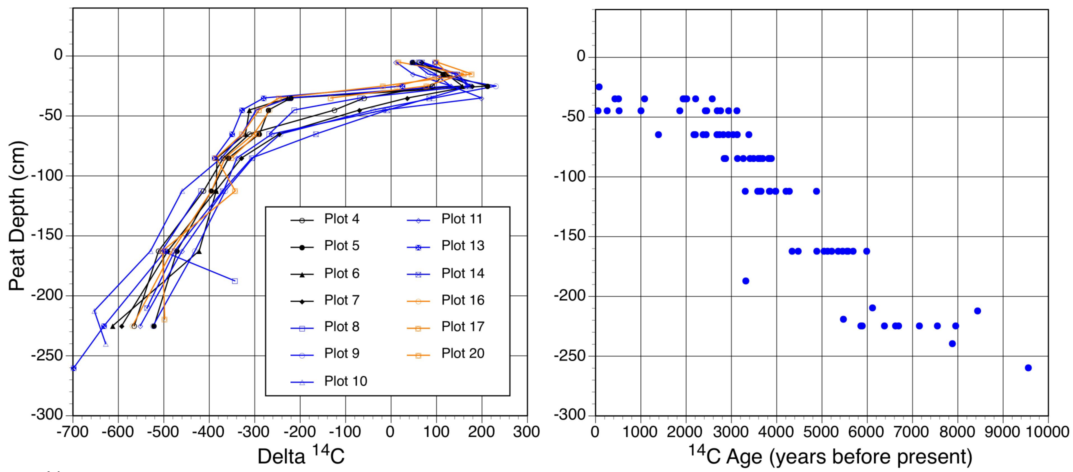

Figure 6. **^{14}C-signatures (left graph) of and initial estimates of mean peat age (right graph) by depth across the S1 Bog. Delta ^{14}C values greater than zero represent modern C accumulation since the 1950s. Peat age estimates will be revised as associated ^{13}C analyses become available.**

<u>*Bog elevation measurements*</u> – Because warming and CO_2 treatments are expected to have dramatic effects on peat C stocks, it is a distinct possibility that the overall elevation of the treatment plots dominated by organic soils may change over time. To that end we have established replicate elevation standards for periodic assessment of peat surface elevations in all treatment plots (Figure 7). These data demonstrate the mean hummock-hollow height differential to be ~25 cm. Peat elevation will be measured after snow melt in spring, at peak midsummer production and following fall senescence to track seasonal as well as long-term changes in the peat surface.

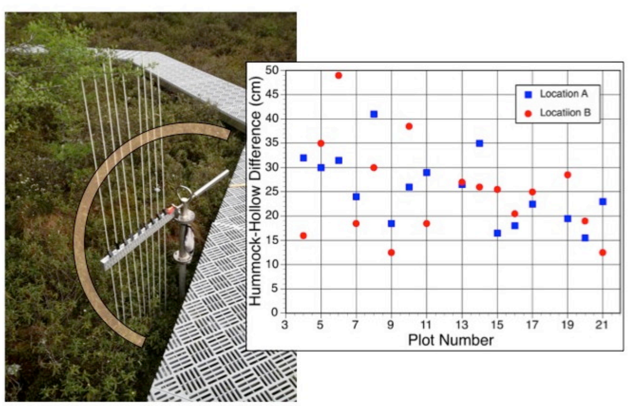

Figure 7. An example elevation standard with attached elevation survey rods for assessing a semicircular array of bog surface elevations (images) and initial data for all treatment plots demonstrating the capacity of this approach to characterize bog surface features.

<u>*Aboveground production*</u> **-** Annual assessments of C accumulation in tree tissues (*Picea* and *Larix*) are being done through annual assessments of tree diameters combined with allometric data for these species collected in 2010 and 2011. Net primary production for woody shrubs (*Ledum, Chamaedaphne, Vaccinium*, etc.) sedges (*Eriophorum*) and miscellaneous forbs (e.g., *Smilacina*) are estimated through annual clipping of paired 0.25 m^2 hummock and hollow plots in each treatment area. These have been collected for trees, shrubs, and common forbs for 2011 and 2012.

<u>*Sphagnum production*</u> - Initial estimates of *Sphagnum* production, which were based on partial year measurements in 2011, were updated in 2012. Replicated bundles of 10 *Sphagnum angustifolium* and *S. magellanicum* stems were installed on October 16, 2011 and retrieved on May 20, 2012, and measurements of the increase in stem length captured early spring growth that had been missed in 2011. New bundles were installed in May and retrieved on October 3, 2012 when the increase in stem length was again measured. Dry mass of capitula and stems was determined to convert length growth to mass production of the two species, and mass production per individual was converted to production per unit area using previously determined *Sphagnum* density. Total site production was based on 68% cover by *S.*

angustifolium and 20% cover by *S. magellanicum*. *Sphagnum* production in 2012 was thus calculated to be 671 g m^{-2}, or 275 g C m^{-2}. Standing crop, based on the top 5 cm, was 277 g C m^{-2}, so annual turnover was equal to 1.

Belowground production – Belowground contributions to NPP in the SPRUCE experiment are being evaluated through the use of minirhizotron observation systems (manual and automated) with supplemental measures of root production through ingrowth cores.

Manual minirhizotrons - We completed a 2-year investigation of fine-root dynamics in the S1 bog using minirhizotron technology. We quantified rooting distribution and production over the course of two growing seasons (2011-2012). At the same time, we used dendrobands to measure daily or weekly increases in stem basal area in order to compare the timing of root- and stem production. We collected root voucher specimens during the summer of 2011 to quantify species-specific measurements of root morphology and chemistry. Relationships between root mass per length and root C and nitrogen concentrations were used to estimate root standing crop and C and nutrient stocks using the minirhizotron data. All images from 2011, and nearly one-half of images from 2012, have been digitized to obtain root diameter and length changes over weekly sampling intervals; this process is ongoing.

Data collected throughout the growing season of 2011 indicate that: (1) minirhizotron technology, which is rarely used in bogs, facilitates the quantification of ephemeral root dynamics and should be used in other wetland systems, (2) root standing crop and production varied across a gradient of spruce and larch density (Figure 8), (3) root standing crop and production associated with raised hummock topography was much greater than that in hollow depressions, and (4) root standing crop increased quickly in the spring, well before wood growth was initiated. These measurements, which were taken prior to the SPRUCE experimental manipulation, will be used to parameterize ecosystem and land surface models in order to develop and test hypotheses regarding the expected effects of warming and elevated CO_2 on root dynamics in the bog. A manuscript is being prepared.

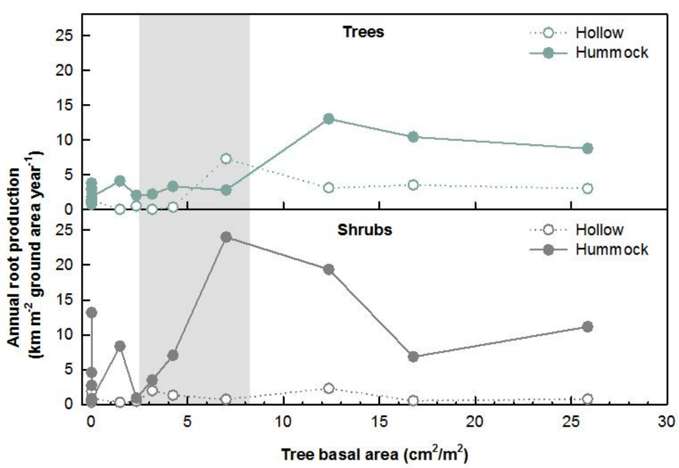

Figure 8. Root production was greatest in hummocks, and peaked at intermediate levels of tree density. The grey shaded area indicates the range of tree basal area in the SPRUCE experimental plots. Tree and shrub root production were differentiated based on the very small average diameter of shrub roots (~ 40 µm).

Building upon the methodology and scientific knowledge gained from the preliminary minirhizotron experiment in the S1 bog, four minirhizotron tubes were installed in each of 16 SPRUCE treatment plots in early October 2012. The tubes were installed at a 45-degree angle in paired hummock-hollow topography in two locations in each plot representing ‘treed’ vegetation (spruce or larch trees within 1.5 m of the minirhizotrons) and ‘non-treed’ vegetation (shrubs only within 1.5 m of the minirhizotrons). Image collection began in June 2013 and will be collected approximately weekly throughout the growing season (2013 will serve as a ‘pre-treatment’ year). Images will be digitized to obtain root length and diameter.

Automated minirhizotrons **-** Automated minirhizotrons (AMR) were also installed in the SPRUCE experimental plots in October 2012. While weekly measurements made with the manual minirhizotrons will focus on measurements of annual root production, the AMR systems will facilitate high-resolution measurements of root and fungal dynamics. The AMR are an improvement over several aspects of manual minirhizotron technology as they capture root and hyphal dynamics at greater temporal resolution, and at much higher magnification. An acrylic casing (10-cm diameter by 120-cm long) for each AMR was installed at a 45-degree angle in each of 12 SPRUCE experimental plots. Each casing will eventually house a video microscope and will be run remotely through an associated laptop. The microscope and laptop computer will be installed in the SPRUCE plots in August 2013.

Root in-growth cores - Root in-growth cores will be used to obtain newly produced fine-root tissue for nutrient analyses. We deployed preliminary root in-growth cores at the S1 bog in June 2013, in order to test a design before installation in the SPRUCE experimental plots. We constructed the in-growth cores using extruded plastic cylinders (Industrial Netting, Minneapolis, MN, USA) filled with a commercially available root-free peat moss harvested from a local Minnesota bog. The in-growth cores were placed in hummock and hollow pairs at six selected locations at the southern end of the S1 bog. The in-growth cores will be collected at the end of the growing season, and root biomass and chemistry will be determined from 10-cm depth increments.

Plant-available nutrients - Ion-exchange resin capsules (WECSA, LLC, Saint Ignatius, MT, USA) will be used to monitor *in situ* changes in plant-available nutrients (i.e., NH_4-N, NO_3-N, and PO_4^-) in the living *Sphagnum* layer, and the aerobic and anaerobic peat layers, at monthly intervals during the growing season. To test the ion-exchange resin methodology in the bog, a series of resin-access tubes (allowing repeated sampling of the same location over time) were installed in hollow microtopography in three locations at the south end of the S1 bog near the initial minirhizotron experiment in late 2010. In each location, the access tubes were installed at a 30-degree angle (from vertical) to depths of 10-cm, 30-cm, and 60-cm, in order to assess plant-available nutrient dynamics throughout the peat profile. Resin capsules were installed and exchanged every 2 weeks during the 2011 and 2012 growing seasons. Preliminary data indicated that plant-available N was least in the shallow peat profile where most of the fine roots are located (Figure 9 left).

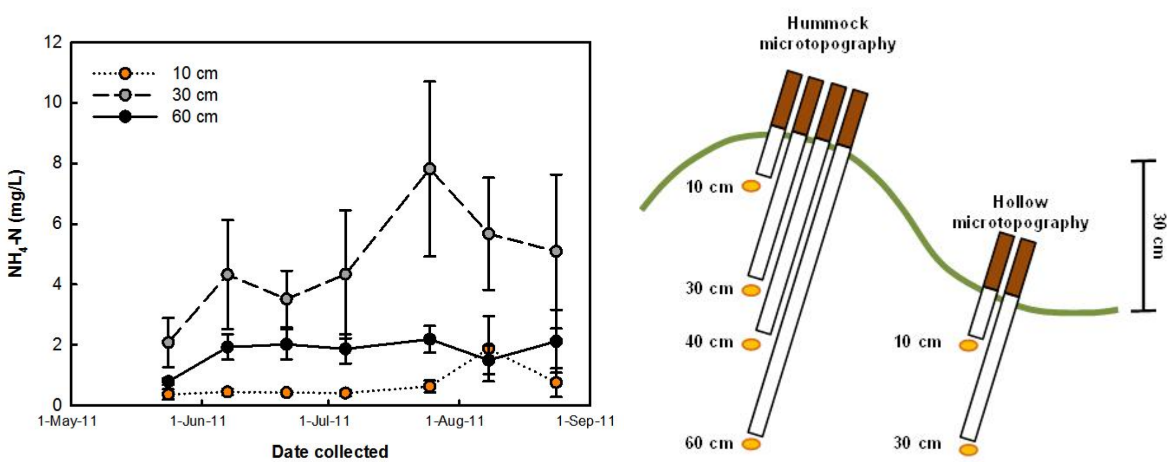

Figure 9. (Left) Plant-available NH_4-N adsorbed to ion exchange resin capsules in 2-week increments during the growing season of 2011. (Right) An array of six resin-access tubes installed across paired hummock-hollow microtopography.

Resin capsules were installed in the SPRUCE experimental plots in June 2013. An array of six tubes was installed near the water sampling wells in each SPRUCE experimental plot. The access tubes were distributed across a paired hummock-hollow surface in order to capture microtopographic differences in nutrient availability (Figure 9 right). A second array of six tubes was installed near plant community composition subplot in each SPRUCE experimental plot (for a total of twelve access tubes per plot). Resin capsules will be exchanged every 3 weeks during the 2013 growing season.

SPRUCE Plant Physiology – Our focus on physiological processes is to understand the rates and seasonal dynamics of water use and C exchange by the different plant functional types within the bog, including the canopy trees, shrubs, herbs/grasses, and various mosses, especially *Sphagnum* species.

Measurements have characterized key processes that must be monitored and modeled to interpret cumulative responses of ecosystem processes to the planned warming and elevated CO_2 treatments.

In FY2013 we continue to characterize the photosynthesis, respiration, and water relations of the bog vegetation. Building upon previous soil-plant water relation work in 2010 and 2011, we have identified a *Granier*-style heat dissipation probe for long-term monitoring of sap flow through the dominant trees. These probes have been deployed in eight *Picea* and four *Larix* trees of various sizes since June 2012. Overwinter performance has shown little to no detectable sap flow in winter. In June 2013 species-specific probe calibrations were initiated *in situ*. Because we anticipate the experimental treatments will increase atmospheric vapor pressure deficit and lead to drier soils and increase water table depth, we plan to assess the mechanisms of drought stress by measurement of root, branch and leaf hydraulic conductivity of *Picea* trees. Results will provide estimates of water potential (drought) thresholds for catastrophic xylem cavitation and failure.

Seasonal C dynamics (photosynthesis, respiration and storage) of the woody vegetation and their responses to changing temperature and CO_2 continues are a key focus. During 2012-13, photosynthetic capacity and respiration was assessed using gas exchange, including light, CO_2, and temperature response curves on detached plant material. Late season A-Ci curves were produced for *P. mariana*, *L. laricina*, *Ledum groenlandicum*, *Chamaedaphne calyculata,* and *Kalmia polifolia.* These measurements provide a full seasonal understanding of photosynthetic capacity of the common woody species. For example, late season *P. mariana* net assimilation rates (A_{net}) at 25 °C were low (2-8 μmol CO_2 m^{-2} s^{-1}) compared to its seasonal maximum in July at 25 °C (12 μmol CO_2 m^{-2} s^{-1}).

In April 2013, photosynthetic capacity of *P. mariana* was assessed across a broad range of temperatures (2-45 °C) and CO_2 concentrations (45 to 1600 ppm) on detached material in the laboratory. From these response surfaces (Figure 10), critical thresholds of the photosynthetic capacity (maximum rate of Rubisco activity (V_{cmax}), maximum rate of electron transport (J_{max}) and triose phosphate utilization (TPU)) can be identified. Early-season overwintering needles did not respond to temperature or CO_2, showing insensitivity to environmental conditions. In contrast, there was a significant temperature response in late season needles, with a 32 °C temperature optimum for V_{cmax} and TPU, and J_{max} optimum a few degrees lower. Midseason (July/August) measurements will continue this summer to fill out the seasonal photosynthetic response surfaces in support of mechanistic modeling efforts.

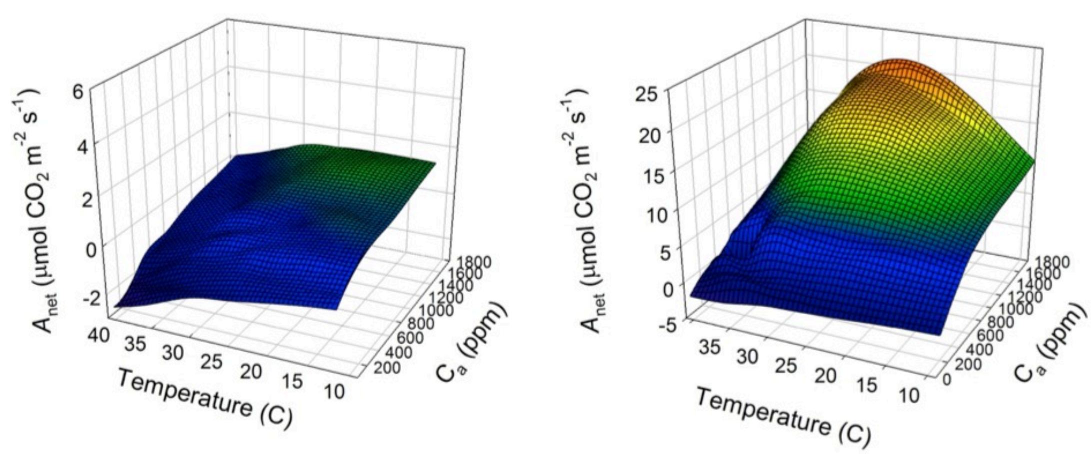

Figure 10. Examples of temperature response surfaces in current year needles measured in April and October, respectively.

Respiration has been identified by an S1 Bog STELLA interpolative model to be one of the largest uncertainties affecting net C balance. In April 2013, stem respiration (R_{day}) rates at ambient temperature (4 °C) were 0.16, 0.10, 0.31 and 0.36 μmol CO_2 mg^{-1} s^{-1}, for *P. mariana*, L. *laricina*, *C. calyculata* and *L. groenlandicum,* respectively. Temperature response curves will be repeated in mid- and late-season 2013 to estimate seasonal patterns in woody respiration; results will be used to assess and refine model parameters.

To further explore *P. mariana* photosynthetic capacity and internal C dynamics, we are assessing seasonal patterns of nutrient and nonstructural carbohydrate (NSC) storage for different plant tissues (foliage, branch, stem, and root). Needle age and canopy position both affected C/N ratio, with 1-2 year-old needles at the top of the tree having the greatest photosynthetic capacity and lowest C/N ratio was positively correlated with needle age. In January, 2013, total NSC content varied between species and organ from 0.5 to 12.5% DW. In *P. mariana* and *L. laricina* trunk and basal branch tissue had lower (0.8 and 3.7%) total NSC compared with branch tips (3.8 and 4.6%). The woody stems of *C. calyculata* and *Vaccinium oxycoccos* had ~8% total NSC, much higher than the other shrubs (~4%). During 2013 and 2014, NSC samples will be collected at critical phenological stages for each of the woody species.

Sphagnum Physiology – The goal for the moss physiology activities this year was the generation of modeled response surfaces for the dominant *Sphagnum* species subjected to multiple levels of CO_2, temperature, and light. We focused on *S. angustifolium* and *S. magellanicum*, which together account for 88% of the total moss cover at the S1 bog site. We found that the wet-site hollow dominating species, *S. angustifolium,* had greater assimilation rates under light-saturating conditions and at temperature optimum relative to the hummock prominent species *S. magellanicum.* The data suggest no significant difference in the response of net photosynthesis to CO_2 concentration. These results from growth-chamber-grown plant material will provide the baseline values by which field observations will be evaluated against. The focus of this upcoming year is in comparing seasonal and diel field-based measures against the modeled projections of net photosynthesis generated from these data.

In 2012 we assessed peat and *Sphagnum* water content dynamics and measurement techniques. Peat hydraulic conductivity is high, which allows substantial soil water redistribution and capillary wicking to the *Sphagnum* surface. Bog surface monoliths were collected containing a heterogeneous mix of moss species. These were used to produced water release curves in the laboratory. This allowed us to assess and link surface water content with water content at depth, and to test and calibrate soil moisture sensors. Based on the results we have identified a frequency domain capacitance soil water sensor that will be deployed in the experimental plots. The sensor will also provide an estimate of the threshold for loss of capillary wicking and surface desiccation (at approximately 18% peat water content at 10 cm depth), which can be directly linked to the steep hydraulic threshold controlling *Sphagnum* photosynthesis.

Microbial Communities and Processes **-** During the pretreatment/construction we have been focusing on two primary areas: the first is to understand the spatial and temporal variation in microbial communities across the S1 Bog, and the second is to implement a series of microcosm studies to understand collective microbial community ecophysiological responses to various perturbations (temperature, moisture, etc.) that are giving us the ability to refine our hypotheses of what to expect under the SPRUCE treatments.

Spatio-temporal variability in microbial community structure - Biogeochemical characteristics and microbial populations within the S1 bog where the SPRUCE experiment is being constructed vary largely as function of depth below the surface. Aerobic heterotrophic populations of fungi and bacteria dominate in surface layers (0-25 cm), along with an abundance of methanotrophic bacteria. Intermediate peat depths (25 – 70 cm) are dominated by anaerobic populations of acetoclastic methanogens and fermentative Crenarchaea and bacteria. Deep peat (> 75 cm) is dominated by Crenarchaea and hydrogenotrophic methanogen populations. While these depth specific conditions dominate the character and composition of the bog system as a whole, fairly sizable spatial variation exists across the bog, across hummock-hollow topography, and across seasons. These studies are being combined with metagenomic data collected by the Joel Kostka Laboratory at Georgia Tech under a separate project for a joint publication.

Microbial exoenzyme temperature responses - The rate of enzyme activity, like all biochemical reactions, is responsive to changes in temperature. Surface peat temperatures can change an average of 3 °C daily and range from 0-20 °C throughout the year, whereas peat temperatures at 2 m are relatively stable, changing less than 0.2 °C daily and remain within a 4-10 °C range throughout the year. Enzyme temperature response changes based on season, peat depth and enzyme type were investigated. Temperature response assays were performed for samples based on season and peat depth on a high density temperature gradient block. The response of enzymes to temperature, calculated as activation energy, was determined by measuring enzyme activities at 15 temperature points ranging from 2 °C to 65 °C. The enzyme temperature response, activation energy, was similar between seasons with no measurable difference between winter and summer. There was a small increase in activation energy with depth, indicating enzymes below the surface were more responsive to increases in temperature, which was unexpected since temperatures are more stable. Enzyme type was the strongest variable, with leucine-amino peptidase, a protease, exhibiting almost no response to assay temperature, whereas β-glucosidase and phosphatase were strongly influenced by temperature. Disparities in temperature response between enzymes involved in different nutrient cycles could result in a decoupling of the nutrient cycling with warming. Results are being written up for a *Soil Biology and Biogeochemistry* paper.

Microbial responses of hummock and hollow communities to moisture stress thresholds - The unique hummock-hollow microtopography of peat bogs may result in spatially distinct microbial and invertebrate communities and function. It is anticipated that warming will alter plot water balance and lead to a strong declines in hummock moisture and moderate declines in hollow moisture. In this mesocosm incubation study, we determined how microbial and invertebrate communities, enzyme activity, and respiration in hummock and hollows would change following exposure to simulated moderate and severe drought. The hummock and hollow peat mesocosms responded differentially to the drying scenarios. Hollow samples exposed to a 50% moisture reduction resulted in a decline in six of seven hydrolytic activities within two days of drying. This reduction was maintained throughout the experiment for three N-enzymes, one C enzyme, and one P enzyme. There was also a decline in fungal gene copies with drought in the first 13 days following dry-down. In hummock samples, activity in the two peptidase enzymes increased under drought, while other microbial metrics, oxidative enzymes and microbial gene copy numbers, were unaffected by moisture treatment. Total respiration was similar between moisture treatments in the first 26 days following drying; however, there was twice as much CO_2 respired from hummock mesocosms compared with hollows. Invertebrate analyses are ongoing at this time. Overall, hummock microbial communities and function were largely unaffected by moisture stress, perhaps suggesting their communities are adapted to the more variable moisture levels experienced in the native bog environment.

SPRUCE Hydrology and Water Chemistry - Two years of baseline data have been collected from the S1 bog to examine the spatial and temporal variation in peat pore water chemistry and inform the sampling regime in the experimental chambers. There was little spatial variation in surface water chemistry, and surface water chemistry tended to mirror the chemistry of bog outflow water. In contrast, there were large differences in peat pore water chemistry with depth (from 0 – 3 m into the peat), with higher nutrient concentrations and lower concentrations of total organic C (TOC) in deeper peat pore water (Figure 11). Therefore, we will strategically limit spatial variation in chemistry within each experimental chamber and focus on depth-variable pore water samples. Together with measurements of water isotopes, these baseline data suggest that there are two different pools of water within the peat: shallower waters that originate from precipitation and near-surface peat, and deeper waters that have long residence times and evidence of limited exchange with the regional groundwater aquifer. Under the high temperature treatments in the SPRUCE experiment, evapotranspiration will increase, and these deep, high-nutrient pools may become available for plant and microbial uptake.

The prototype of the subsurface corral (flow barrier) and drainage collection system was installed and tested in 2012. The corral is necessary to provide a barrier for root in-growth and the collection/measurement of water runoff volume and chemical composition from each experimental chamber. To test water-holding capacity, the corral outlet was plugged, and 6,000 gallons of water were added. Minor leakage through corral wall joints was observed, but water levels were higher after the addition, and stabilized over time. A new sealant type and procedure has soved this issue.

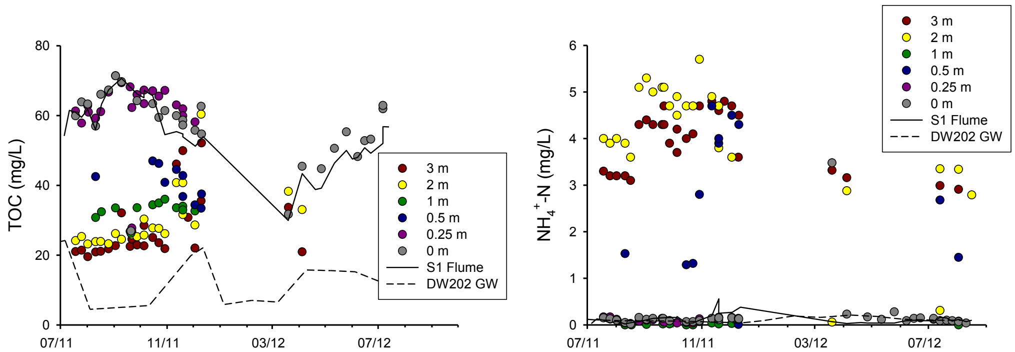

Figure 11. Total organic carbon (TOC) and ammonium (NH4+-N) concentrations of water collected by depth (0 – 3 m), and concentrations in the S1 bog outflow (solid line) and in regional groundwater (DW202 GW; dotted line)

CO_2/CH_4 flux and model – Simultaneous surface flux measurements of CO_2 and CH_4 are being made using open-path analyzers and custom-designed chambers designed to enclose the combined hummock-hollow topography of the bog (Figure 12, left). This measurement approach enables point-in-time observations of the combined shrub/forb/*Sphagnum*/microbial community for a 1.13 m^2 area of the bog. Ensemble observations collected diurnally, seasonally and under variable light conditions inform a model of C exchange that encompasses all of the CH_4 fluxes and the majority of the CO_2 fluxes from the bog. Only tree bole and foliar C exchange is missing. A comparison of these data with historical approaches (Figure 12 left) shows good agreement and provides the basis for modeling much of the C flux from this peatland. A paper describing the technique, seasonal and spatial variation in CO_2 and CH_4 flux and annual cumulative C gain is being prepared for publication from pre-treatment observations collected since the fall of 2011.

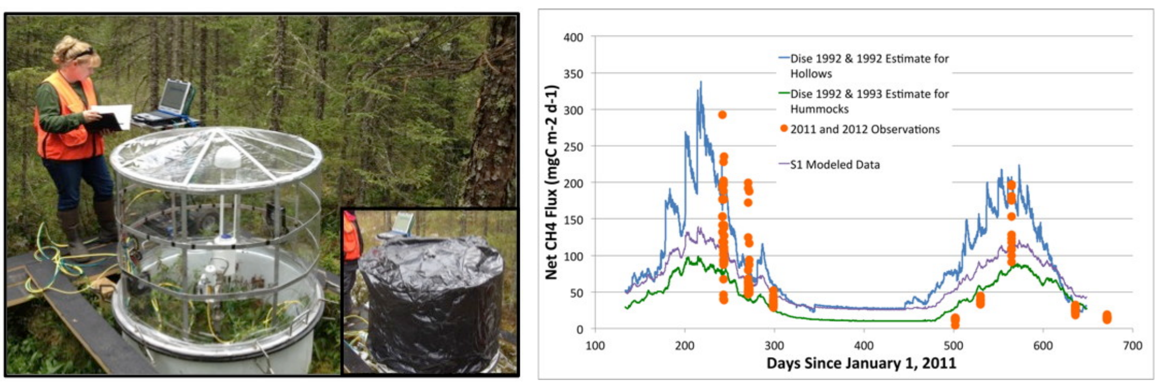

Figure 12. Custom designed CO_2 and CH_4 flux chamber and observations of flux superimposed over modeled estimates from the current and past data sets.

Carbon Budget for the S1 Bog - Data from pre-treatment measurements of ecosystem C stocks (trees, shrubs, forbs, peat), foliar and stem gas exchange, surface CO_2 and CH_4 flux, and annual assessments of above and belowground components of NPP have been combined into a simple interpolative model of C flux (Figure 13). These data indicate annual variation in bog net C flux (C gain in 2011 and loss in 2012). Both woody-tissue respiration and losses of dissolved organic C, which are yet to be resolved for the S1 bog, can tip the balance in favor of C loss or gain.

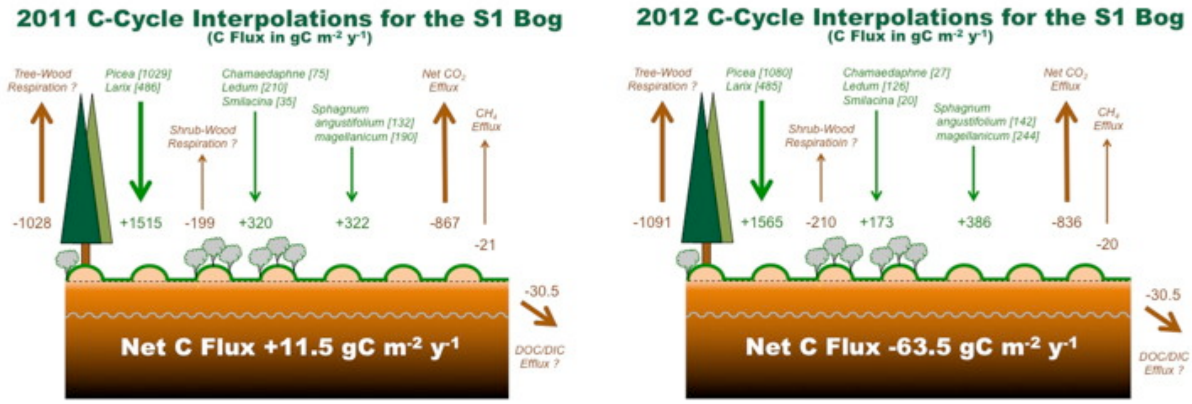

Figure 13. Interpolated C budgets for the S1 bog in 2011 and 2012 showing interannual variation in the C sink-source strength of the ecosystem driven by variations in weather. Further measures of woody tissue respiration and DOC losses from the bog will be needed to fully characterize the uncertainty and magnitude of S1 Bog net C flux.

The process of calculating C budgets for the S1 bog ecosystem using simple interpolative methods provide a testing ground for fully mechanistic and probabilistic models. The CLM-SPRUCE model effort described in the next section will take advantage of this effort to produce a fully integrated C model of generic wetland function that will have benefited from model-experiment-observation interactions.

SPRUCE Deliverable Progress

The SPRUCE project continues infrastructure development and pretreatment biological process observations in FY2012 with an anticipated transition to full-time experimental treatment applications in spring of 2013. The following deliverables outline major SPRUCE activities anticipated for FY2012 and FY 2013. SPRUCE treatments will be operated, and responses measured and interpreted over a full decade. Such a time period should allow time for interannual variation effects on treatments to be observed and for long-term nutrient cycle alterations to develop in response to the warming and CO_2 treatments.

Table 2. SPRUCE Deliverables and Progress To Date.

Proposed Date	Deliverables in abbreviated form	Status
FY2012 Deliverables		
Mar/Apr 2012	Hire ORNL staff technologist to reside in Minnesota	Completed November 2012
May 2012	Complete specifications for data service to experimental plots, scope specifications for data systems for data acquisition, storage, and transfer to ORNL, and scope specification for site telecommunications.	Completed June 2013
May 2012	Complete engineering and drawings for field facilities including temporary office buildings, data system office space, storage, sample prep space, telecommunications.	Completed 2012
May 2012	Complete construction of field facilities including temporary office buildings, data system office space, storage, sample prep space, telecommunications.	Completed July 2013
May 2012	Complete installation of boardwalks	Completed August 2012
May 2012	Submit a manuscript describing the influence of N on *Sphagnum* growth and photosynthesis at elevated temperature.	In Progress
Apr to Oct 2012	Conduct pretreatment measurements and archiving of time-zero samples for the full range of disciplinary tasks at all defined experimental plots.	Completed
Jun 2012	Complete engineering and drawings for final aboveground warming	Completed

	chambers	December 2012
Jul 2012	Complete the addition of electric, CO_2, propane and data service to all experimental plots.	Electrical and Data lines July 2013 CO_2 and Propane 2014
Sep 2012	Complete the addition of environmental and observational monitoring systems to all planned treatment plots.	
Sep 2012	Begin testing of data acquisition system.	June 2013
Sep 2012	Submit manuscripts on full-scale warming prototype performance, and on seasonal CH_4/CO_2 flux observations using new methods.	In progress
FY 2013 Deliverables		
Oct 2012	Prepare pads for CO_2 tanks.	Delayed to 2013
Mar 2013	Produce manuscripts on baseline plant water relations and woody plant foliar physiology for the S1 Bog.	In progress
Mar 2013	Data system fully operational.	Completed July 2013
April/May 2013	Complete construction of all above- and belowground infrastructures, and initiate treatments.	Delayed to 2014
June 2013	Complete a manuscript on the influence of species and seasonal patterns on *Sphagnum* photosynthesis as a function of temperature, CO_2, relative water content, and PAR	In progress
Summer of 2013	Conduct measurements for the full range of disciplinary SPRUCE tasks for all defined experimental plots employing any refined methods indicated by pretreatment studies.	Underway
July 2013	Submit manuscript on fine-root production in relation to topography and tree density	In progress
Sep 2013	Manuscript on seasonal and depth variation of microbial populations and activity in peat	In progress
Dec 2013	Production of manuscripts dealing with 1) plant water relations and 2) woody plant physiology and T response for the S1 Bog.	In progress

Task 2: Walker Branch Watershed Long-Term Monitoring (Formerly Task R2)

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. DOE-BER funded WBW research is being phased out, and the WBW footprint on the Oak Ridge Reservation will be developed as a core wild land site in the National Ecological Observatory Network (NEON) funded by the National Science Foundation, with construction of the WBW NEON site to begin in the fall of 2013. Recent research projects conducted in WBW have concluded. Recent data were presented at various scientific conferences, and are being written up for publication. These recent projects include studies on stream nutrient cycling, decomposition, and metabolism.

Table 3. Walker Branch Deliverables (expressed in abbreviated form).

Date	Deliverable	Status
April 2012	Analysis for annual hydrology and stream chemistry for calendar year 2011 is ongoing and will be completed by April 2012.	Completed
Summer 2012	Dual nutrient releases will be conducted again in the spring to characterize nutrient uptake during the period of high autochthonous (i.e., algal) production.	Completed
Fall 2013	Papers on the seasonal nutrient pulses to characterize uptake kinetics, and stream litter decomposition	Manuscripts in preparation

Spring 2014	Papers on dual N and phosphorus uptake in streams and a paper on the controls on stream metabolism (determined using a structural equation model)	Manuscipt in preparation

Task 3: Mechanistic Carbon Cycle modeling (Formerly Task F1)

This task incorporates model-data integration and model development across multiple spatial and temporal scales to identify process contributions to the global climate-C cycle forcing from terrestrial ecosystems. This report summarizes key progress under the TES SFA since our January 2012 report in the areas of site scale model-data integration (Task 3a), regional and global land ecosystem modeling (Task 3b), coupled Earth System Modeling (Task 3c), and integrating land-surface model constraints with inverse modeling (Tasks 3d). Brief summaries of progress are presented along with tabular summaries of progress on proposed deliverables or adjustments to those plans.

Task 3a – Improve ecosystem process models with site-level observations and experimental data

Point model development for MODEX activities - A core capability for modeling under this project is the point version of CLM-CN (PTCLM), which maintains the same code base and is compatible with CESM. We are coordinating model developments under the TES SFA and flux tower and experimental sites with other DOE-funded projects at ORNL. While this provides the capability to leverage work from other projects, coordinating the software development and products is a major challenge and time commitment. We expect that major new investments from BER for software support for a new DOE climate model will facilitate these efforts beginning in FY2014 and accelerate model development. PTCLM is currently under development to support simulations at the FACE, PiTS, EBIS and SPRUCE sites. PTCLM is also being used as a model development test bed for CLM-MEND (Task 5) and CLM-CNP (Task 3c). This capability is also benefiting NGEE-Arctic modeling efforts.

We have also identified a critical need for a robust unit-testing framework to support development and integration of new process representations in CLM. By unit-testing, we mean the ability to isolate small functional units of model code (e.g. individual subroutines) and exercise those code units in isolation from the rest of the CLM software environment. The model is currently quite modular, in that mechanistic functionality tends to be gathered within coherent subroutines, with clearly articulated interfaces between the subroutines and the CLM data structures. What is currently lacking is the independent testing framework that can take advantage of this modularity to evaluate the output response to a range of carefully controlled inputs for individual functional units. We have initiated a new task prototyping this unit testing framework, using the photosynthesis subroutine as a starting point. A capable unit-testing package has been developed and tested, including the ability to specify input ranges and plot results, without making any modifications to core model code.

CLM_SPRUCE modeling - Peter E. Thornton (ORNL), Xiaoying Shi (ORNL), Daniel M. Ricciuto (ORNL), Paul J. Hanson, and Jiafu Mao (ORNL) are in the process of incorporating key structural and process changes in a point version of the CLM-CN land surface model (Thornton et al. 2007). This new effort is applied to the SPRUCE high carbon bog ecosystem. Initial efforts focused on model modifications needed to represent the isolated hydrologic cycle of the bog environment with raised hummocks and sunken hollows having distinct hydrologic dynamics and vegetation communities. The preliminary results of the hydrologic efforts show that the simulated water table heights for hummocks and hollows are consistent with observations, and the projected seasonal water table heights for the hummock/hollow topography are reasonable (Figure 14 and 15). We have coupled the new hydrology treatment with vertically structured soil organic matter pools, and the components of a methane model recently developed for CLM (Riley et al. 2011). Next steps for CLM-SPRUCE modeling are to calibrate the new hydrology treatment with vertically structured soil and CH_4 sub-model, and to introduce *Sphagnum* hydrology and carbon cycle physiology.

The progress related to this effort has been presented during the SFA PI Meeting (May, 2013) and the Community Earth System Model (CESM) workshop (June, 2013).

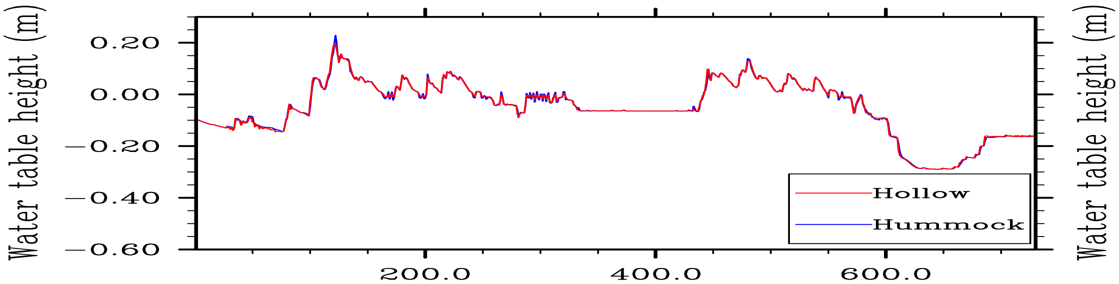

Figure 14. CLM simulated hummock and hollow water table heights for year 2011 and 2012.

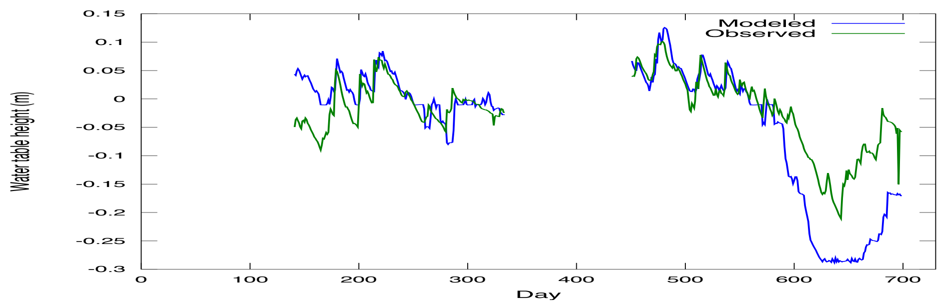

Figure 15. The comparison of CLM simulated and observed water table heights for year 2011 and 2012

<u>*CLM_PITS*</u> - The Partitioning in Trees and Soil (PiTS) project was established to improve the parameterization of C partitioning routines existing in the Community Land Model (CLM) by exploring mechanistic model representations of partitioning tested against field observations and manipulations. Our objective has been to understand and simulate the C partitioning and flux within plants and into soil under dynamic environmental conditions and manipulations of gross primary production. The ORNL CLM-PiTS team (Peter E. Thornton, Jiafu Mao, Daniel M. Ricciuto and Anthony W. King) has succeeded in parameterizing and updating the recently developed single-point version of CLM (PiTCLM) for the PiTS1-loblolly pine shading site. We replicated the PiTS experimental manipulations including the shade treatment and $^{13}CO_2$ labeling. We have carried out sensitivity simulations of CLM by adjusting environmental inputs, internal model parameters and root distributions (Figure 16). Furthermore, to optimize use of observed A/Ci curve and light response data sets, we developed a unit test capability for the photosynthesis-stomatal conductance module in CLM-CN. We've reported our progress for this project at meetings: "the CLM Workshop" (Feb. 2013), "the 4th NACP Meeting" (Feb. 2013), the CCSI Annual SAB Meeting (Mar. 2013) and the SFA PI Meeting. Also, a manuscript related to this modeling effort is being prepared. Priorities for next fiscal year are submitting the first CLM modeling paper for this project and moving this phase-1 work to phase-2 at the PiTS experimental site in a dogwood plantation.

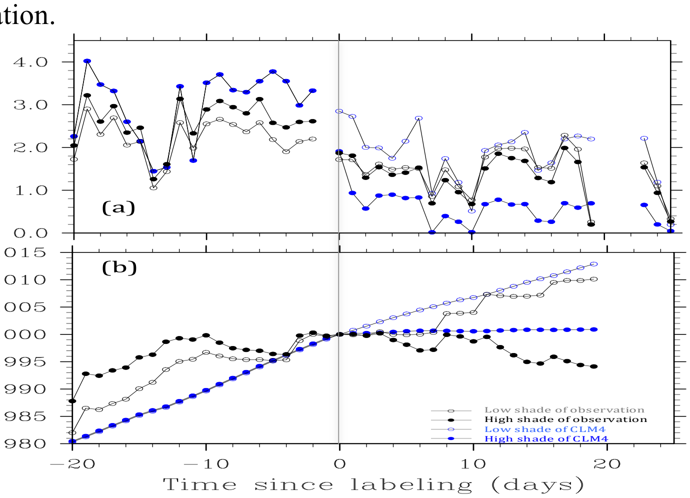

Figure 16. (a) Canopy transpiration (mm/day). (b) Stem carbon relative change.

Site-Level Interim Syntheses Contributions - The North American Carbon Program (NACP) site-level interim synthesis project is concluding, and datasets are being archived through the ORNL DAAC and provided with DOIs for citation purposes. These datasets will continue to serve as valuable benchmarks for future model evaluation. More than 20 modeling groups participated including two participating under SFA funding (CLM-CN and LoTEC). This activity produced 12 publications and provided useful insights into the model structure of CLM-CN, resulting in model improvements currently being used in other TES SFA activities. An evaluation of CLM-CN at 15 AmeriFlux sites was recently performed and a manuscript detailing the results is in progress. We are also exploring the impacts of site-specific input data, the choice of site vs. reanalysis meteorology and model parameters.

Table 4. Task 3a Deliverables

Date	Deliverable	Status
2012	Site-level emulator approach complete and documented. Submit manuscript on LoTEC PFT-level optimization. Submit manuscript on FACE model-data intercomparison.	- Completed - included in regional optimization MS (task 3b) - Completed
2013	- Complete development of CLM-PiTS and CLM-SPRUCE and integrate structural changes into main CLM-CN code. - Submit manuscript detailing CLM-CN parameter sensitivity analysis for 20 tower sites. - Perform model-data comparison for PiTS experiments 1-3	- CLM-PiTS completed; CLM-SPRUCE underway - Initial simulations completed; MS Underway - Experiment 1 complete; others ongoing
2013	- Prototype of CLM unit test for critical model subroutines	- Underway

Task 3b – Improve ecosystem process models with regional observations

Simulations to date have focused primarily on the Global Terrestrial Ecosystem Carbon (GTEC) model, which serves as a computationally efficient methodological test bed for eventual efforts with CLM-CN. Simulations using the regional parameter optimization framework took longer than expected due to technical challenges and limited availability of the Titan supercomputer. Initial results show that the GTEC is improved considerably by optimizing parameters against FLUXNET GPP (Figure 17). We are continuing to provide model output and work on manuscripts related to the Multiscale Terrestrial Model Intercomparison Project (MsTMIP). Global simulations have been submitted for CLM-CN and GTEC and manuscripts detailing the protocol, driver data, and initial results have been submitted by the project PIs (Huntzinger et al., 2013; Wei et al., 2013). We are participating in PalEON, which will provide valuable information to the treatment of century-scale vegetation dynamics in CLM-CN. The second phase of this activity was recently funded by NSF and we expect to begin simulations early in FY2014.

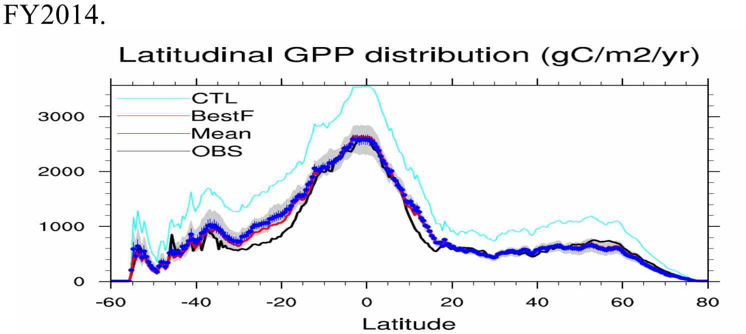

Figure 17. Latitudinal dependence of annual GPP (gC m^{-2} yr^{-1}) simulated by GTEC over the period 1982-2008 for the control run, best fit (optimized parameters), ensemble mean with uncertainty (shaded area), and the upscaled FLUXNET product.

We have also recently extended PTCLM (Task 3a) for multi-cell unstructured grid capability, allowing for computationally efficient simulation of discontinuous points (e.g. the FLUXNET network), or contiguous regions (e.g. North America). This also allows for focused high-resolution simulations, comparisons to gridded remote sensing products, and ensemble simulations for parameter optimization and uncertainty quantification.

Table 5. Task 3b Deliverables

Date	Deliverable	Status
2012	- Global LoTEC, TEM and CLM-CN MsTMIP simulations completed - Submit manuscript on GTEC North American simulations evaluating sensitivity of continental-scale flux to parameters	- Completed - Initial simulations submitted; Sensitivity simulations to be submitted.
2013	- Document emulator approach for regional and global model-data assimilation - Perform LoTEC global simulations with assimilation of point and gridded observations, estimate global C flux and uncertainty - PalEON simulations and data assimilation framework complete	- Completed (Sargsyan et al., 2013) - Initial simulations completed - Underway

Task 3c – Earth system model process integration and evaluation

Multiple studies were carried out to quantify the performance of the Community Land Model at the global scale, with a focus on diagnosing large-scale patterns in model output and evaluating model predictions against large-scale observations. In one series of studies, the vegetation component of CLM was evaluated against multiple remotely sensed datasets. These studies first investigated model predictions of visible and shortwave radiation reflectance from vegetated surfaces, and evaluated against Normalized Difference Vegetation Index (NDVI) data compiled from MODIS and AVHRR sources (Mao et al. 2012a). By analyzing a series of single- and multiple-forcing experiments, this study identified the independent influences of climate variability and increasing CO_2 concentration on trends in springtime growth at northern mid-high latitudes. A second study looked in more depth at the model predictions of leaf area index (LAI), and evaluated predictions against MODIS-based estimates of LAI. Multi-factor simulations suggest that latitudinal variation in LAI trends, while overall global trends are best explained by increasing CO_2 concentration (Mao et al. 2013). A third study went beyond canopy structure to investigate the CLM-predicted rate of gross primary production (GPP), in comparison to MODIS-derived estimates of GPP. This showed overall strong agreement between model and observation-based estimates in terms of spatial and temporal patterns at the global scale, but also highlighted some systematic biases in the CLM photosynthesis algorithm (Mao et al. 2012b). This work has been supported by both the ORNL TES SFA and the C-Climate Feedbacks Project.

Patterns of model-predicted evapotranspiration (ET) were also analyzed and evaluated against a global gridded product based on site-level observations (Shi et al. 2013). This study found that climate variability dominates the predicted variability in ET, with rising CO_2 providing a strong modulation of the climate-induced trends over most land areas. Other factors such as nitrogen deposition and land use change play a much smaller role at the global scale, but can be important locally.

A major effort is underway to integrate the dynamics of the phosphorus cycle into the existing structure of CLM. Currently CLM includes tightly-coupled carbon and nitrogen cycles, one of only a few global-scale models to do so. Early investigations with this model suggested that the introduction of phosphorus dynamics might also be necessary to mechanistically predict model mean state and climate change feedbacks over tropical forests and possibly other regions. Two critical steps toward a mechanistic C-N-P model have now been accomplished. First, an analysis of phosphorus transformations as a function of soil order and age was carried out, demonstrating that reasonable predictions of phosphorus pools could be made on the basis of available soil data (reported previously). These relationships have now been applied to generate global-scale maps of multiple soil phosphorus pools, a requirement for any global-scale model application (Yang et al. 2013). Development of CLM-CNP is now quite advanced, and we expect to publish site-level and global-scale results from the model in the coming year. This work has been supported by both the ORNL TES SFA and the C-Climate Feedbacks Project.

Table 6. Task 3c Deliverables

Date	Deliverable	Status
2012	Literature review on current evaluation metrics, satellite products, global offline ecosystem model outputs and earth system model simulations. Collect and re-map 30-	Completed

	year of NDVI, fPAR and LAI (1981-2010).	
2013	Compare offline historical simulations of CLM4 with the standardized remotely sensed products at various spatial-temporal scales. Submission of related manuscripts.	Completed

Task 3d – Integrating land-surface model constraints with inverse modeling

The CarbonTracker code was obtained from NOAA. Dr. Dali Wang participated in a training session to become familiarized with the code and to learn details about the underlying atmospheric transport model. In conjunction with the Climate Science for Sustainable Energy Future (CSSEF) project, an ensemble capability using high end computing was developed for global CLM-CN simulations, which is expected to benefit Tasks 3b and 3c.

Because of the technical challenges associated with porting CarbonTracker, its extreme computational demands, and a known lack of mechanistic insight from inverse modeling, the carbon cycle modeling team determined that there were other, more urgent, research priorities that should be pursued, and efforts associated with Task 3d has been stopped. Redirection of this effort was done to accommodate an increased emphasis on development of a robust unit-testing framework for CLM (see Task 3a).

Table 7. Future Task 3d Deliverables

Date	Deliverable	Status
Spring 2012	Community engagement and on-site training at NOAA	Completed
FY2012	Develop capability, in collaboration with CT researchers, to run CT adapting the parallelization strategy to fully utilize high end computing at ORNL.	Completed
FY2013	Replace CASA with CLM-CN and/or LoTEC – develop capability to perform land-surface model parameter sensitivity and parameter optimization using the CT methodology.	Effort redirected to Task 3a

Task 4: Partitioning in Trees and Soil (PiTS; Formerly Task F2)

The Partitioning in Trees and Soil (PiTS) task was established with the objective of improving the C partitioning routines in existing ecosystem models by exploring mechanistic model representations of C partitioning tested against field observations. We used short-term field manipulations of C flow, through $^{13}CO_2$ labeling, canopy shading and stem girdling, to dramatically alter C partitioning for measurements evaluations. The data are used to test 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, collection of data, and the analysis of results.

PiTS-1 (loblolly pine shading) has been completed and a data manuscript has been published in a special issue of *Tree Physiology* (Warren et al. 2012). A paired modeling effort has used data from PiTS-1, as well as regular and ongoing meetings between modelers and experimentalists, to assess CLM4 model performance, discuss potential issues of model failure, deal with conversion of data into appropriate form and units, and ameliorate the lack of appropriate experimental data. These interactions have proved serendipitous, and have improved model performance and insight into model structure. Among other successes, the model was modified to include a ^{13}C module, and successfully simulated the ^{13}C pulse moving through the ecosystem. A modeling manuscript is nearly ready for submission.

Following the success of "PiTS-1 – loblolly pine shading," two other experiments are winding down in FY2013 – "PiTS-2 – girdling sweetgum," onsite at the former free air CO_2 enrichment study (ORNL FACE), and "PiTS-3 – seasonal shaded dogwood," offsite at the University of Tennessee Arboretum in Oak Ridge. Both experiments are focused on fate of stored and recently fixed C belowground to roots and symbiotic fungi, where there is known dearth of data.

At PiTS-2, periodic root growth and soil respiration measurements will continue through this final growing season. Anthony Walker, a post-doctoral modeler hired to work on PiTS and the Root Functioning Task, has been modeling the PiTS2 – sweetgum girdling site. He has begun to explore how to reduce C flow belowground while maintaining significant, albeit less, water extraction from the girdled trees. Initial field results are enticing, and suggest a strong and multi-year dependence on C stored in woody tissue, a substantial reduction in plant demand for N, reduced soil CO_2 efflux, and minimal initial change in root production – all are mechanistic components present in CLM4.

At PiTS-3, the site has been decommissioned and restored (including replanting cut trees), and final samples are being processed in the lab. A large amount of automated data has been collected including sap flow, tree basal area, soil moisture, soil $^{13}CO_2$ and $^{12}CO_2$ efflux, with and without roots or mycorrhizae. Destructive sampling has also yielded a large number of samples to process for biomass and ^{13}C content (foliage, seeds, phloem, roots, soil, fungi), including whole tree harvests to determine allometric relationships (the harvests and total leaf area measurements were not planned initially, but added subsequently through discussions between modelers and experimentalists). Initial results show strong seasonal dependence of C partitioning to the various components, including new leaves and fruits, as well as a substantial and rapid transfer of new C belowground to arbuscular mycorrhizal fungi (Figure 18). These results provide data of mechanistic processes not well refined in the models and will lead to improvements in model representation of C partitioning processes.

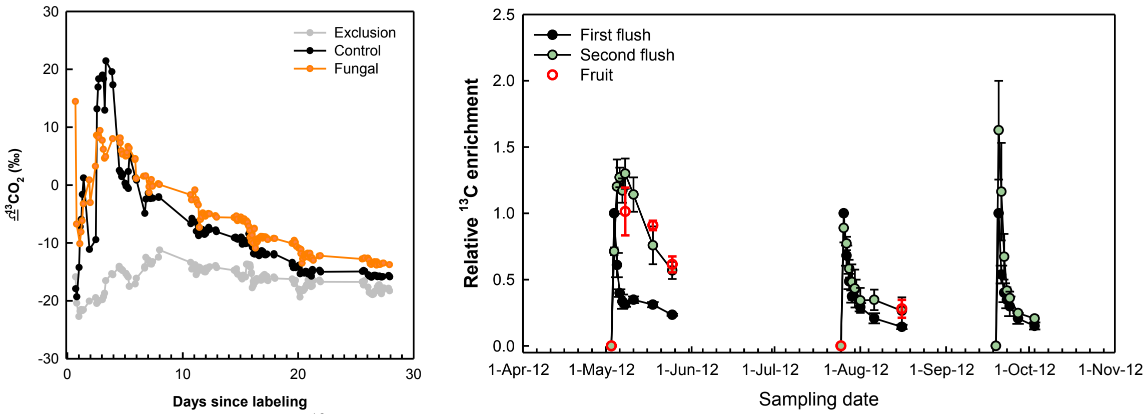

Figure 18. Partitioning of ^{13}C tracer within trees and soil at the PiTS-3 – seasonal shaded dogwood site. (left graph) Evidence of rapid ^{13}C transport from leaves into soil containing mycorrhizal fungi only (fungal), or fungi + roots (control). (right graph). Strong seasonal patterns of 13C flux in young or old leaves (first flush, second flush) or fruit indicating sink dynamics.

Table 8. Updated Progress on Task 4 Deliverables continuing into FY2014.

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

T4a. Integrating Root Functional Dynamics into Models (New Task)

Root functional dynamics remain noticeably absent from the land component of global circulation models such as CLM4, many of which currently have no ability to represent the spatial or temporal resolution of root function. This task was designed to improve representation of root functionality within models (especially CLM4) through a stepwise program that will assess current knowledge, test model sensitivity, and modify or develop novel routines or modules to improve representation of root function as necessary. Model development work will be paired with an empirical research program to provide targeted data for validation and parameterization of the new elements within CLM-CN.

The root functioning team has had several planning meetings since January 2012, refining the scope of the tasks and assessing interest among a diverse group of plant, soil and hydrology modelers, and physiologists and ecosystem ecologists. Work has begun on the first task (*Assess the current representation of roots in models that vary in spatial and temporal resolution*), consisting of a comprehensive literature review and review manuscript. Literature is currently being collected and summarized in tables, the framework and outline for the manuscript is under development. We have also applied for and secured future imaging beam time at the HFIR neutron source, which can be used to assess root functionality *in situ*. With the initial three PiTS studies winding down this year, effort in FY2014 will be shifted to the root functioning task. As such, we expect to have the pending review manuscript submitted and subsequent tasks initiated by January 2014.

Task 5: Fundamental Soil Carbon Cycle Process Studies (Formerly Task F3)

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)

The EBIS-AmeriFlux task 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. All field and laboratory work for the EBIS-AmeriFlux task has now been completed at ORNL and by our subcontractor at Lawrence Livermore National Laboratory (LLNL). Since January 2012 a key paper outlining the soil C cycle dynamics of the EBIS-AmeriFlux sites has been published (McFarlane *et al.* 2013). Paul Hanson will continue to work with colleagues at LLNL, Lawrence Berkeley National Laboratory (LBNL) and Argonne National Laboratory (ANL) to fully archive the EBIS-AmeriFlux data set, and to use it to produce direct quantitative estimates of C transfer rates from litter forms to mineral soil C stocks.

Non-TES SFA funding has been acquired to allow the EBIS-Oak Ridge data (the precursor to EBIS-AmeriFlux) to be used to build a CLM model version capable of tracking ^{14}C isotopes. Jiafu Mao is doing the C cycle modeling, and Paul Hanson is providing guidance and data interpretation with TES SFA support.

Microbial processing of soil C

We are identifying and targeting critical uncertainties in coupled climate and terrestrial ecosystem processes and feedbacks, namely, microbial-mediated decomposition of soil organic matter (SOM), sorption and desorption of depolymerized dissolved organic matter (DOM), and cycling in measurable soil pools. Our goal is to advance understanding and representation of terrestrial ecosystem feedbacks by providing a fully functional, validated, enzyme-based C and N mechanistic cycling model – the Microbial-ENzyme-mediated Decomposition (MEND) model (Wang *et al.* 2013) – as an alternative formulation of SOM dynamics currently in the Community Land Model (CLM-CN).

Testing MEND Against Lab-scale Incubation Data - MEND was parameterized using lab-scale incubations on four soil orders from contrasting eco-regions (Jagadamma *et al*. in review). Soil organic matter (SOM) pools in MEND include particulate, mineral-associated, dissolved organic matter (POM, MOM, and DOM, respectively), microbial biomass (MB), and associated extracellular enzymes (EP and EM), and the adsorbable/desorbable phase of DOM (Q) is differentiated from MOM. Soils were incubated after the addition of ^{14}C-labeled glucose or starch (0.4 mg C g^{-1} soil). Two response variables (cumulative respiration and percentage of ^{14}C respiration from added ^{14}C) were combined into the objective function for model calibration using a stochastic optimization algorithm (Duan *et al.,* 1992; Wang et al. 2009). Parameter uncertainty was quantified by "relatively optimal" parameter sets filtered by a critical objective function value (Wang *et al.* 2013). The parameterization results (Figure 19) indicate that: (1) C use efficiency (E_C) has values of 0.31±0.15 (mean ± standard deviation), which implies that the kinetic and stoichiometric constrains on metabolism are well represented in the model; (2) the turnover (r_{EP}) and production (p_{EP}) rates of POM degrading enzymes are also well-constrained, i.e., r_{EP} = 0.005±0.003 mg C mg^{-1} C h^{-1} and p_{EP} = 0.05±0.03; and (3) specific maintenance rate (m_R) and maximum update rate (V_D) reach the preset upper bound (0.01 mg C mg^{-1} C h^{-1}), which may imply higher growth and maintenance rates in lab vs. field conditions. Uncertainty analysis using a simple statistical method is complete, and MCMC (Markov Chain Monte Carlo) is in progress. Strong agreement between simulated and observed fluxes of $^{14}CO_2$ and total CO_2 were found except for the $^{14}CO_2$ from Andisol with addition of starch. More data points and replicates would improve calibration to MBC and DOM in future experiments.

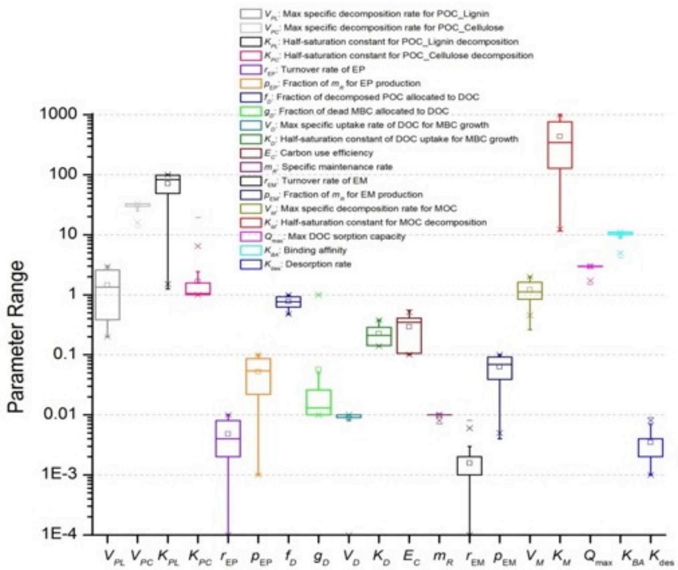

Figure 19. Boxplots of calibrated model parameter values for all soils.

<u>*Lab-scale Measurements: Microbial Biomass Carbon and Carbon Use Efficiency*</u> - Accurate soil microbial biomass C (MBC) estimates are difficult to obtain, but their importance is increasing with the incorporation of more microbial parameters in ecosystem models. Currently, most estimates of MBC come from chloroform fumigation-extraction, substrate induced respiration, and direct cell counts, however these are time consuming and accuracy depends on the soil type. We hypothesized that gene copy number derived from quantitative PCR could be a proxy for MBC, and would provide a better estimate of the relative size of the major soil MBC components (bacteria, fungi, archaea) within the microbial community. Soils were evaluated from 15 locations covering five tropical, eight temperate, and two arctic locations that include seven different soil orders. DNA extraction and qPCR for 16S rRNA genes (bacteria and archaea) and18S rRNA genes (fungi) was used to determine gene copy numbers for each of the three groups and their relationship to chloroform fumigation extraction MBC estimates. In the A horizon, the strongest relationship exists between bacteria gene copy and MBC (r^2 = 0.45), whereas in the B horizon the strongest relationship exists between archaea and MBC (r^2 = 0.86), and good relationships are found for both bacteria (r^2 = 0.52) and fungi (r^2 = 0.31) when A and B horizons are combined. We are continuing to test additional soils and plan to incorporate direct cell counts as another estimate of microbial abundance.

Model simulations found that microbial C-use efficiency (CUE) is a critical parameter (Wang *et al.* 2013), and when allowed to fluctuate according to temperature, substantial differences are observed compared to simulations using a constant CUE. We have worked to optimize a recently published approach for short duration CUE measurements (Wang *et al.* 2013) and are planning a round of CUE measurements in soils from tropical, temperate, and arctic systems to better understand model behavior given variation in this critical parameter. Our original plan was to focus on temperature sensitivity of sorption of DOC, but because the model shows the much greater importance of CUE, our first year deliverables have been adjusted accordingly.

CLM-MEND **-** We are incorporating MEND into the CLM4 two-layer biogeochemistry model thusly: (1) MB and DOM are explicitly expressed in the model. An MB-derived enzyme pool is also included. It consists of the enzymes driving the decomposition, nitrification and denitrification processes. (2) Replace the four aboveground (AG) SOM pools with 5 new pools: AG_Lignin, AG_Cellulose, AG_DOM, AG_MB, and AG_ENZYMES. (3) Belowground SOM is divided into 2 categories: particulate organic matter (POM) and mineral-associated organic matter (MOM). Replace the four belowground (BG) SOM pools with 6 new pools: BG_POM_Lignin, BG_POM_Cellulose, BG_MOM, BG_DOM, BG_MB, and BG_ENZYMES. (4) Add nitrification and denitrification processes into the model. Two pathways are considered to produce N gases (NO, N_2O, N_2): nitrifier denitrification and denitrifier denitrification. (5) Bioturbation: from AG_Lignin to BG_POM_Lignin and from AG_Cellulose to BG_POM_Cellulose. (6) Leaching: DOM, NH_4^+, and NO_3^-. (7) N Uptaking: NH_4^+ and NO_3^-. In addition we have completed a literature review to include P cycling in the model (Hui *et al.* 2013).

Table 9. Soil Carbon Cycle Process Studies Future Deliverables

Date	**Deliverable**	**Status**
FY2012	Finish all laboratory analysis and for the EBIS-AmeriFlux effort.	Complete
FY2013	Temperature dependence of the sorption of common soil substrates – experimental Temperature dependence of the sorption of common soil substrates – modeling	Replaced Complete
Jun 2013	Calibration of MEND model using lab-scale incubation data (Item 1).	Complete
Sep 2013	Temperature dependence of C use efficiency (CUE) of common soil substrates (new deliverable)	In Progress

Task 6: Terrestrial impacts and feedbacks of climate variability, events and disturbances (Formerly Task F4)

The overall goal of Task 6 is to understand responses of ecosystem fluxes of CO_2, water vapor, sensible heat, methane, and isoprene to climate variability and to transfer such understanding to large scale earth system modeling and projections. The task focuses on landscape-scale observations and analyses of climate variability and episodic events as related to ecosystem C and water cycles, energy balance and vegetation dynamics. It serves as a bridge between ORNL TES SFA components in manipulative experiments and fundamental process studies and those in modeling. This is achieved by providing coordinated datasets from belowground to top of canopy and from leaf scale to landscape scale and tools for fundamental process identifications, model representation, parameterization and testing, and demonstration of model performance improvement.

Since January 2012, Task 6 research has resulted in nine peer-reviewed journal publications and one book chapter.

MOFLUX site operations

MOFLUX data have been submitted to AmeriFlux data management on a regular and timely basis. Data for the previous full-year data are typically submitted in the spring of the following year. Data are quality-controlled and flux measurements are gap-filled and ready for use by users. MOFLUX is located strategically in a biome ecotone and has frequent summer droughts and large unseasonable temperature fluctuations, and external demands for the comprehensive MOFLUX measurements have been increasing.

To provide better data support for belowground modeling within the TES SFA, and by the general earth system modeling community, we installed minirhizotron root observation systems at the MOFLUX site in September 2012. In May, 2013, we also installed a new Li-Cor soil respiration system (16 chambers) that replaces the aging 8-chamber system operating since 2004. The new soil chambers are paired with minirhizotron observing tubes so that soil respiration data can be coupled with root growth images. The coupled root – soil respiration observation system will provide one-of-a-kind datasets for belowground process studies and modeling.

Community support **-** We have provided community support for cross-site synthesis efforts by users of Fluxnet and AmeriFlux data (e.g. Ryu et al. 2012; Schaefer et al. 2012, Niu et al. 2012, Barr et al. 2013). Task 6 supports the operation of LeafWeb, which continues serving the world-wide community of leaf photosynthesis for data analysis and provides comprehensive parameter support for regional and global terrestrial C cycle models (leafweb.ornl.gov). The first synthesis paper based on data gathered through LeafWeb is now under review in *Plant Cell and Environment* (Sun et al. 2013).

MOFLUX Science

Interannual variability in MOFLUX carbon and water budgets - The MOFLUX forest ecosystem is a consistent C sink (Table 10). However, the interannual variability is large and mostly controlled by water availability. We found that annual integrated pre-dawn leaf water potential predicts annual net C uptake and water use at the MOFLUX site well (Figure 20). Maximum summer C uptake occurs when summer precipitation equals summer evapotranspiration at a threshold value of 500mm. Below this threshold precipitation strongly controls C uptake. Above it, other factors may limit C uptake. We are now planning to test CLM with these observations.

Improving the theoretical foundation of eddy flux measurements - We have continued the effort initiated in Gu et al (2012) to make the theoretical foundation of eddy covariance technique self-consistent and thus to ensure that the measured fluxes and budgets of C and water are accurate. Recently, we propose a new eddy covariance theory that constrains NEE measurements of any atmospheric gas species with the ecosystem O_2 to CO_2 exchange ratio (g), also known as oxidative ratio (Gu et al. 2013). The fundamental equation of the new theory is derived. It is show if O_2 + g CO_2 is treated as a virtual bi-molecular gas species, denoted as gCO_4, then the fundamental equation of the new theory is identical in form to the fundamental equation of eddy covariance when the ecosystem budget of a single atmospheric constituent (e.g. N_2 or Ar) or dry air is used to constrain net ecosystem C exchange (NEE) measurements of atmospheric gas species.

A convenient, yet still hypothetical, method for measuring g with existing O_2 technologies is also described by Gu et al. (2013). Compared with the current, dry air-based assumptions for eddy covariance calculations, the proposed gCO_4-based approach uses less restrictive assumptions, avoids indirect calculations of multiple variables, and thus prevents losses of flux covariances. The adoption of the gCO_4-based approach will enhance the scientific and societal values of flux sites and networks by eliminating measurement biases and by providing value-added datasets to enable understanding the oxidation state of the biosphere. These improvements will in turn lead to better prediction of terrestrial and oceanic C sinks in response to climate change.

Table 10. Annual carbon and water (evapotranspiration) budgets at the MOFLUX site

Year	2005	2006	2007	2008	2009	2010	2011	2012	Mean±SD
Annual net C uptake(g)	457	320	242	392	418	367	375	193	345±89
Annual ET (mm)	654	603	541	684	689	729	553	470	615±89

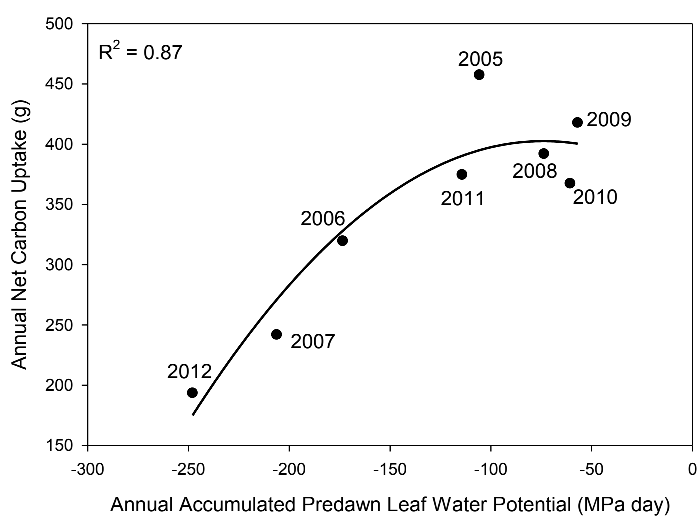

Figure 20. (Left column) Changes of annual net C uptake with annual accumulated predawn leaf water potential at the MOFLUX site.

Mesophyll conductance - Since January 2012, process-level research under Task 6 has been focusing on mesophyll conductance (g_m) because g_m affects photosynthesis at least as strongly as stomatal conductance. We analyzed worldwide measurements of over 100 C_3 species covering all major plant functional types from herbaceous temperate plants to woody tropical species with growth environments ranging from greenhouse to natural vegetation. We found the assumption of infinite g_m results in up to 75% underestimation for maximum carboxylation rate V_{cmax}, 60% for maximum electron transport rate J_{max}, and 40% for triose phosphate utilization rate T_u. V_{cmax} is most sensitive, J_{max} is less sensitive, and T_u has the least sensitivity to the variation of g_m. As a consequence of the differential effects of g_m, the ratios of J_{max} to V_{cmax}, T_u to V_{cmax}, and T_u to J_{max} in commonly used photosynthetic models are all overestimated under the infinite g_m assumption. A nonlinear function can be used to convert the parameters estimated under the infinite g_m assumption to proper values if an estimated g_m is available, which is very useful for large-scale C cycle modeling. Manuscripts are being prepared.

Isoprene emission at MOFLUX - We have collaborated with Mark Potosnak of DePaul University and Alex Guenther of NCAR on isoprene emission measurements at MOFLUX. Measurements from 2011 showed that the MOFLUX site has the largest isoprene emission ever observed in North America. It was also found that current models underestimated isoprene emission under drought conditions. A manuscript on these findings is being prepared.

Improving large-scale models with findings from Task 6 - Modeling work in FY12 has resulted in a major improvement in the coupling between C and water cycles in global models. A key result from Sun et al. (2012), has been applied in the latest release of Community Land Model version 4.5 (http://www.cesm.ucar.edu/models/cesm1.2/clm/CLM45_Tech_Note.pdf). Furthermore, for the first time a mesophyll conductance model has been implemented in a global land model (CLM). Initial simulations show that without representation of mesophyll conductance, models underestimate the responsiveness of terrestrial ecosystems to rising atmospheric CO_2.

Table 11. Task 6 Deliverables

Date	Deliverable	Status
FY2012	Submit MOFLUX data sets to the AmeriFlux data center. Install 8 minirhizotron tubes at the MOFLUX site	Completed
FY2013	Submit MOFLUX data sets to the AmeriFlux data center. Install minirhizotron camera and start taking images. Develop implementation recommendation of mesophyll conductance modeling for CLM.	Completed
FY2013	Complete and test the isoprene-modeling module for FAPIS. Conduct initial observational and modeling analyses on the correlation between CO_2 fluxes and isoprene emissions.	Underway

Task 7: Fossil emissions (Formerly Task F5)

Fiscal year 2013 has seen continuing efforts within the task on fossil emissions toward maintaining and improving a publicly available data base on CO_2 emissions from fossil fuel consumption, examining and confronting the uncertainty in emissions estimates, and utilizing the CO_2 emissions database in terrestrial C budgets. Recent efforts include annual and monthly emissions data by country through 2009 which are available online (processing of 2010 data should begin soon, CDIAC is waiting for final data corrections from the United Nations); compilation of preliminary annual estimates, by country, through 2011; and significant strides in characterizing the uncertainty associated with CO_2 emissions from fossil fuel consumption. A peer-reviewed manuscript on this uncertainty characterization is nearly complete and should be submitted for review later this summer. Dr. Andres continues to play a prominent role in Global Carbon Project (http://www.globalcarbonproject.org) activities, including the forthcoming Global Carbon Atlas (scheduled for release just before the next UNFCCC COP in Warsaw, November 2013).

Activity directed toward the deliverables listed in the 23 January 2012 progress report is summarized in the following table

Table 12. Future Task 7 Deliverables

Date	Deliverable	Status
FY2013	Publication on uncertainty estimates associated with emissions	On schedule.

FY2013-2015	Monthly emission inventories at the scale of states and months at a global scale	On schedule.
FY2013-2015	Generation of annual and monthly distributions of global emissions	On schedule.

For item 1, the current uncertainty focus is on national and global totals. After submission of that uncertainty manuscript, focus will shift to the uncertainty of spatial distributions of emissions. Data from items 2 and 3 will be made freely available to the public by CDIAC. Peer-reviewed publications on these three items are expected to continue (listed below are 11 peer-reviewed publications produced since the January 23, 2012 progress report). Figure 21 shows the results from one study where atmospheric CO_2 concentrations are broken down into fossil, oceanic, and terrestrial biosphere components.

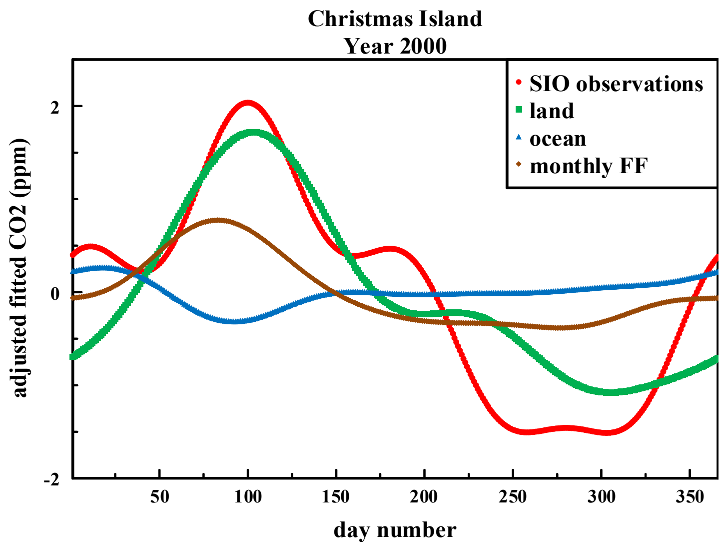

Figure 21. An example of monthly fossil fuel data allowing more knowledge of the global C cycle. An atmospheric chemistry transport model resolves atmospheric CO_2 concentrations into contributory terrestrial biosphere, ocean, and fossil fuel components. Other sites include: American Samoa, Cape Kumukahi, Point Barrow, and South Pole. Across all sites, fossil fuels contribute about 10% to the atmospheric seasonal amplitude (even after filtering to remove local fossil fuel inputs). Fossil fuel peaks usually occurs prior to the biosphere peak which creates implications for interpretation of atmospheric concentrations solely as a function of terrestrial and oceanic processes. SIO=Scripps Institution of Oceanography.

For FY2014 and FY2015, Task F7 plans to continue annual updates of fossil fuel CO_2 emissions and provide high quality input to global C cycle analyses through various applications and refinements of the emissions database.

TES SFA Data Systems, Management, and Archiving Update

Data systems and management are not a separate task, but an integral part of the overall TES SFA concept. The open sharing of all data and results from SFA research and modeling tasks among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE‘s Program of Terrestrial Ecosystem Science.

The SPRUCE task has (1) completed design for data acquisition from experimental plots and for site telecommunications, (2) designed data systems for acquisition, storage, and transfer of data to ORNL for project access and analyses, and (3) has begun implementation and testing of these data systems. Ongoing measurements at the S1 Bog environmental monitoring stations established in 2010 are routinely processed, basic quality control checks performed, and provided for project use. Publically available data products include value-added environmental monitoring data, completed S1 Bog characterization studies including vegetation surveys, vegetation allometric and biomass sampling results, and investigations of peat depth with ground penetrating radar (GPR). Publically and project-only available data, the Data Policy, and Data Management Plans are available on the SPRUCE web site: http://mnspruce.ornl.gov/.

The Partitioning in Trees and Soil (PiTS) task has archived data from the PiTS-1 study and they are publically available on the ORNL TES-SFA web site: http://ornl.TES-SFA.gov.

Additional SFA task data products have been archived at program-specific archives, Fossil Emissions at Carbon Dioxide Information Analysis Center (CDIAC), MOFlux at AmeriFlux, and North American Carbon Program (NACP) data synthesis products at the ORNL Distributed Active Archive Center (ORNL

DAAC). The TES-SFA web site may not be the first archive for generated data products, but will ensure that products are securely archived, discoverable, and available to the public in a timely manner. The TES-SFA web site provides this discovery and access service: http://ornl.TES-SFA.gov.

4AII. Science Highlights Since January 2012

- ORNL TES SFA staff completed 69 articles and 5 book/proceedings chapters since January 2012.
- Gunderson et al. (2012) used empirical field data from small-scale warming studies to show that warming alone was responsible for extending the growing season in spring and fall for woody plants.
- Parsekian et al. (2012) demonstrated that ground-penetrating radar can be used to characterize peatland C stocks, and we use this analysis to establish treatment plots throughout the S1 Bog.
- Significant infrastructure for SPRUCE treatments and measurements was installed in the S1 Bog throughout FY2012 and these activities continue in FY2013.
- Barbier et al. (2012) reported on the design and optimized performance of enclosures for whole-ecosystem warming manipulation experiments in support of SPRUCE.
- Mao et al. (2012) found a significant positive relationship between annual spring vegetation growth and temperature in most northern ecosystems to be evident both in remote sensing data and in CLM4 transient simulations advancing our knowledge about the nonlinear dynamics of vegetation growth in the northern mid and high latitudes.
- Huntzinger et al. (2012) study revealed large variation in terrestrial biosphere model estimates of long-term mean net ecosystem production and discrepancies in the magnitude and timing of the seasonal cycle from model structural and model driver data differences.
- Hayes et al. (2012) studied the North American C sink and concluded that *Top-down* approaches (i.e., inverse models) produce greater estimated sink strength than do *bottom-up* approaches (biosphere models and inventories).
- Wang et al. (2012) developed kinetic parameters for key ligninolytic and cellulolytic enzyme kinetics essential for modeling the decomposition of plant litter and soil organic matter.
- Sun et al. (2012) identified the cause of numerical instability in the calculated C and water fluxes in land surface models (LSMs), and developed and implemented a new approach to overcome the numerical instability in the Community Land Model (CLM).
- Warren et al. (2012) Evaluated C partitioning within a vegetated ecosystem using canopy shading and subsequent $^{13}CO_2$ fumigation. Shading was found to reduced C uptake, stem and root growth, and site water use. Data are being used to test C partitioning within a point version of the Community Land Model (CLM-CN).
- Tipping et al. (2012) combined model-data analysis using EBIS-Oak Ridge data to provide a powerful approach for defining and resolving important soil C cycling mechanisms.
- A key publication from the completed EBIS-AmeriFlux task (McFarlane et al. 2013) was published demonstrating the nature of climate, edaphic and biotic controls on soil C cycling across a range of eastern deciduous forest sties. These data are important for benchmarking soil C cycle models.
- Wang et al. (2013) published the Microbially-mediated ENzyme Decomposition (MEND) model, which uses the Michaelis-Menton and Arrhenius equations to catalyze the decomposition of soil organic matter via microbial extracellular enzymes.
- Mao et al. (2013) Applied CLM4 and the latest satellite-derived LAI to investigate annual trend changes and controlling factors of global vegetation growth from the period 1982 to 2009. Over the 28-year period, both the remote-sensing estimate and CLM4 simulation show a significant increasing trend in annual vegetation growth.
- Shi et al. (2013) used CLM4 and observation-based evapotranspiration (ET) to quantify the relative contributions of climate and non-climate factors (rising CO_2 concentration, nitrogen deposition, land use / land cover change, and aerosol deposition) to trends in ET. CLM4 dynamics compared well with independent observation-based estimates of ET trends. This analysis provides new quantitative and objective metrics for evaluation of land ecosystem process models.

4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff have produced 74 publications (69 journal articles, 5 book/proceedings chapters) since our last summary report. The journal papers were published in over 40 different journals including one article in the *Proceedings of the National Academy of Sciences* (Bauerle et al. 2012). Journals hosting more than two SFA publications include: *Agricultural and Forest Meteorology* (4), *Biogeosciences* (6), *Global Change Biology* (4), *Journal of Geophysical Research – Biogeosciences* (6), and *Soil Biology and Biochemistry* (3).

Journal selection for pulication of TES SFA work is at the discretion of the senior author. Journals are typically selected to achieve maximum exposure of the research results for the science community. We do tend to focus on journals having high impact factors, but that is not necessarily the primary criteria for the selection of a journal for publication of a given research result. High-profile journals (e.g., *Science*, *Nature*, *PNAS*) are pursued for the publication of results anticipated to be of general interest to a wide audience. We find that solid and well-presented scientific results are well received and cited in all of our chosen journals.

4B. FUTURE SCIENCE GOALS AND PLANS

Many of the goals and milestones established for the TES SFA in FY2010 are still being actively worked. Some activities have been completed and we have redirected effort accordingly. For example, EBIS-AmeriFlux experimental efforts have been completed and that effort has been transferred to the microbial enzyme focused studies of the soil C cycle. After the SPRUCE infrastructure is completed, more TES SFA effort will be placed on model-observations interactions.

We intend to expand our C cycle modeling efforts in the area of functional unit testing, providing test capabilities for all the major model subroutines, and adding new unit-testing capabilities for each new process representation brought into CLM through the SFA efforts. We also will be carefully integrating our development and evaluation efforts with other DOE BER-sponsored model development and analysis projects. Specifically, as the next-generation land model development proceeds under DOE BR support, we will be sharing lessons learned and suggesting candidate architectures and process representations based on the ORNL TES SFA efforts.

Areas where we expect to see early ORNL TES SFA contributions to the new land model development are in representations of soil carbon and other biogeochemical cycles (e.g. CLM-MEND and CLM-CNP). A key near-term deliverable opportunity also exists for using MOFLUX observational data to benchmark the CLM model. Such an interaction will improve that way that CLM captures forest ecosystem drought response. Further efforts underway will also complete manuscripts on the importance of mesophyll conductance to C cycle models.

4C. NEW SCIENCE FOCUS AND IDENTIFIED KNOWLEDGE GAPS

Beyond FY2015, landscape C dynamics observations will be transitioned to new ecosystems. We plan to move the focus of the eddy flux research to the northern peatland ecosystems to better integrate with the flagship SPRUCE experiment and provide critical methane flux data to support CLM-Wetland model development. Fluxes of CO_2, water vapor, sensible heat, and methane at the ecosystem scale (i.e. including trees, *Sphagnum* spp. and the organic soils) will be measured and used to test ecosystem models at the SPRUCE site and identify potential deficiencies. Access and electrical infrastructure for this new eddy covariance site has already been added added to the S1 Bog. Future development will be initiated after the completion of SPRUCE experiment installations. Dr. Lianhong Gu has also begun discussions to begin participation in eddy covariance observations underway at a fen wetland site located several kilometers from the S1 Bog. We will coordinate flux measurements at the two sites so that measurements are optimized for model testing and process understanding. Data will be provided real time to the TES SFA modeling research group for parameterization and benchmarking. We expect that a new wetland eddy covariance site will be able to answer the following example science questions:

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

4D. COLLABORATIVE RESEARCH

We continue to encourage key external groups to develop complementary research tasks for the benefit of TES SFA research tasks. Support for the following independently funded research groups is being provided through the use of SPRUCE leased office/lab facilities and access to the SPRUCE experimental site on the S1 bog:

- Dr. Joel Kostka and colleagues are supported on a DOE BER funded study of microbial ecology within SPRUCE that will extend our capabilities.
- Drs. Scott Bridgham and Jason Keller and colleagues are supported to conduct a DOE BER funded study of mechanisms underlying heterotrophic CO_2 and CH_4 fluxes in a peatland.
- Drs. Kirsten Hofmockel and Eric Hobbie are supported to address the question – Can microbial ecology inform ecosystem level C-N cycling response to climate change? With DOE BER funds.
- Drs. Brandy Toner, Ed Nater and colleagues from the University of Mercury and Sulfur Dynamics in the SPRUCE experiment using funding provided through the USDA Forest Service.
- Dr. Andrew Richardson has also obtained DOE BER funds for the acquisition and installation of phenology cameras at the SPRUCE site. Our electrical infrastructure and data transmission capabilities will facilitate this work once the experimental structures have been installed.
- Dr. Bruce McCune (Oregon State University) and Sarah Jovan (USDA Forest Service) have acquired their own support to study lichen responses to warming and elevated CO_2 within the SPRUCE experimental infrastructure.
- The carbon cycle modeling team is participating in several model intercomparison studies, which provide valuable insight and standardized datasets used for SFA model development tasks. These projects enhance the visibility of TES SFA research and have resulted in numerous publications. TES SFA funds are being used to set up and perform the simulations. Projects include the NACP interim synthesis (Task 3a), NASA- funded MsTMIP (Task 3b), and PalEON (Task 3b)
- Dr. Peter E. Thornton has contributed significant effort in FY2013 to IPCC AR5 Working Group I as an author, and Dr. Paul J. Hanson has served as a reviewer for various drafts of the Working Group I and II reports.

5. STAFFING AND BUDGET SUMMARY

5A. FY2013 FUNDING ALLOCATION BY PROGRAM ELEMENT

FY2013 spending is summarized in Table 13. The listed amounts represents costs and commitments incurred through June 17, 2013. Total available funding for ORNL's TES SFA included $2,043K carryover from FY2012 and $8,005K of new budget authorization received in FY2013. We are currently spending at rates consistent with the spending plans outlined in the January, 2012 proposed budgets for the TES SFA.

Table 13. Budget expenditures by TES SFA Program Element through July 8, 2013. Total available funding in FY2013 is $10,048K including $2,043K of FY2012 carryover funds targeted primarily for SPRUCE infrastructure.

Task	Cost Through June 2013 ($K)	Commitments Through June 2013 ($K)	Remaining Funds June 2013 ($K)
SPRUCE Science	$1,826	$184	**$751**
Carbon Cycle Model Interactions	$960	---	**$120**
MOFLUX	$434	$71	**$67**
PITS (C allocation)	$123	$8	**$157**
Soil C Studies	$132	---	**$89**
C Emissions	$59	---	**$47**
Postdoctoral Fellows & Students	$283	$226	**$63**
SPRUCE Infrastructure	$1,509	$697	**$367**
SPRUCE – Planned Construction	---	---	**$1,755**
Reserves	$19	---	**$101**
SFA Totals	**$5,345**	**$1,186**	**$3,517**

5B. FUNDING ALLOCATION TO EXTERNAL COLLABORATORS

A variety of collaborations are being fostered to provide necessary expertise or effort in areas critical to the completion of research tasks. In FY2013 we are directly funding the University of Missouri ($164K) to provide MOFLUX on site execution of the following measurements: stand-level eddy covariance, soil CO_2 efflux, belowground production via repeated minirhizotron image collections, stem allometric increment data, and litter basket net primary production. We provide $40K per year through an Interagency Agreement to allow the USDA Forest Service research group to help with the operation and planning of the SPRUCE experimental infrastructure and science tasks.

Through the Oak Ridge Institute for Science and Engineering (ORISE) we have also developed a number of subcontracts for the support of postdoctoral research associates working on the TES SFA including: Natalie Griffiths, Meg Steinweg, Anthony Walker and Anna Jensen.

Subcontracts in support of the SPRUCE project in FY2012/13 include funds and funding for SPRUCE construction (multiple contracts $800K with nearly $2000K pending), leased space in Minnesota ($45K y^{-1}), a small IAG with the USDA Forest Service ($40K y^{-1}), and new building additions.

5C. PERSONNEL ACTIONS AND PROCEDURES IN FY2013

New Hires – Two new postdoctoral research fellows were brought on staff since January 2012. Dr. Anthony Walker was hired with C cycle modeling expertise to provide specific support to the extrapolation of PITS C allocation experimental results to models. Dr. Anna Jensen was hired to supplement the physiological response work on the SPRUCE experiment. Drs. Meg Steinweg and Natalie Griffiths are completing their respective postdoctoral positions in FY2013, and searches for replacement staff are underway.

Anticipated Future Hires – If funding flexibility allows, we plan to transition Natalie Griffiths to full-time staff status at the beginning of FY2014 to take on internal leadership of the SPRUCE task on hydrologic change and dissolved organic C formation and transport.

Retirements and Releases - Dr. Mac Post retired from ORNL after decades of service at the end of December 2012. His role in aspects of the C cycle modeling group is being filled by Dr. Daniel M. Ricciuto with the support of our recent hires of Daniel Hayes, Xiaoying Shi, Jiafu Mao and XiajuanYang.

Procedures for advancing new and developing investigators - We use various methods to prepare for and replace TES SFA staff to ensure project continuity and productivity through time. Developing TES SFA staff are commonly hired through postdoctoral research associate positions and their performance and contributions to task activities are tracked. Our postdocs are vetted for potential future roles as task leads, and are hired as staff into leadership roles as appropriate for our needs.

Where identified disciplinary needs are established (and for which adequate funding is available) the TES SFA also has the capacity to hire established staff persons directly into a task leadership role. When a need for new staff is identified but funding is insufficient to initiate a hire, ORNL internal funds may be requested through a strategic hire program to bring individuals on board. This internal program allows for a 1 to 2 year transitional period to enable the TES SFA group to establish an appropriate, stable, and fully funded position. For example, Daniel Hayes was brought to ORNL to supplement our C cycle modeling expertise in anticipation of the retirement of established staff.

Within the TES SFA, task accomplishments and budget management is executed at an overarching level by the Principal Investigator with feedback from all Task leads. Individual Task leads are given the responsibility to track scientific progress and the responsibility for managing their fiscal resources within an annual cycle. Training to allow new staff to understand ORNL procedures, accounting systems, and managerial activities is available and provided when appropriate. Such training, in addition to one-on-one mentoring with established staff, provides developing staff with the information and skill sets required to transition into leadership roles. At the institutional level, ORNL has formal programs for mentoring high-potential early career staff, and we use informal mentoring at the personal level to ensure that junior staff who have potential leadership qualities are identified and helped with career development

5D. NATIONAL LABORATORY INVESTMENT IN THE PROGRAM

ORNL has demonsted its commitment to climate and environmental change research through substantial investments over many years in climate change modeling, the development of innovative large-scale experimental infrastructures through the Laboratory Directed Research and Development program (LDRD), and in the construction of other critical infrastructures, including a new field support building (Building 1521), greenhouses, the Joint Institute for Biological Sciences, and renovations in support of molecular ecology. 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, and current LDRD project is funded to build and test integrated belowground measurement probes that may be deployed to better understand subsurface microbial processes in SPRUCE. Initial development of the Microbial Enzyme Mediated Decomposition model (MEND) (Task 5) was initiated through ORNL LDRD funds in FY11-12 ($500K), while testing and incorporation into CLM-CN occurs through the TES SFA.

The Climate Change Science Institute brings together all ORNL Climate Change staff including members of the TES SFA into a single building and fosters day-to-day interactions among modelers, experimentalists and data management specialists.

The TES SFA is supported by world-class capabilities at ORNL. The National Leadership Computing Facility provides an open, unclassified resource that we will use to enable breakthrough discoveries in climate prediction. The Carbon Dioxide Information Analysis Center (CDIAC) is pioneering utilization of infrastructure support for data and model integration that we will use and build upon in the TES SFA. The Atmospheric Radiation Measurement Program data system (ARM Archive), the NASA Distributed Active Archive Center for Biogeochemical Dynamics (NASA-DAAC), and the USGS-funded National Biological Information Infrastructure (NBII) Metadata Clearinghouse provide additional expertise in this emerging research discipline.

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

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. Since that purchase the threshold amount of funds needed to define a capital expenditure has risen to the point that few other capital requests are anticipated. Melanie Mayes is pursuing a request for a multiple isotope, multiple gas (e.g., CO, CO_2, CH_4, H_2O) PICARRO analyzer with potential applications for process level work in both the laboratory and field. Other instrumentation for multi-spectral scanning not rising to the level of capital equipment funds have been purchased among ORNL projects for use on TES SFA tasks.

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.

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