FY2014 PROGRESS REPORT OAK RIDGE NATIONAL LABORATORY'S TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA (TES SFA)

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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 model-experiment-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 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 (Fig. 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.

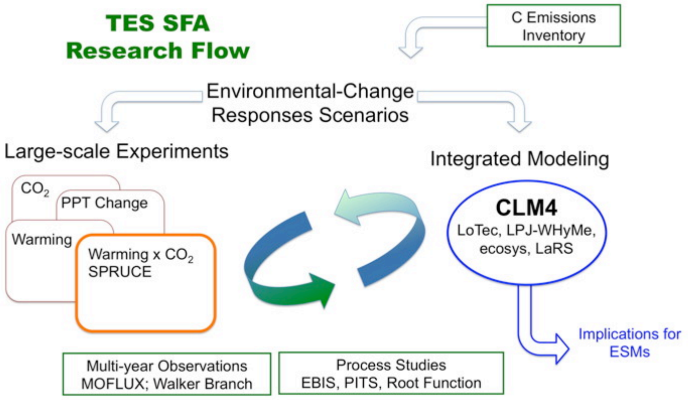


Fig. 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development, and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

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. FY2014 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 (Fig. 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.

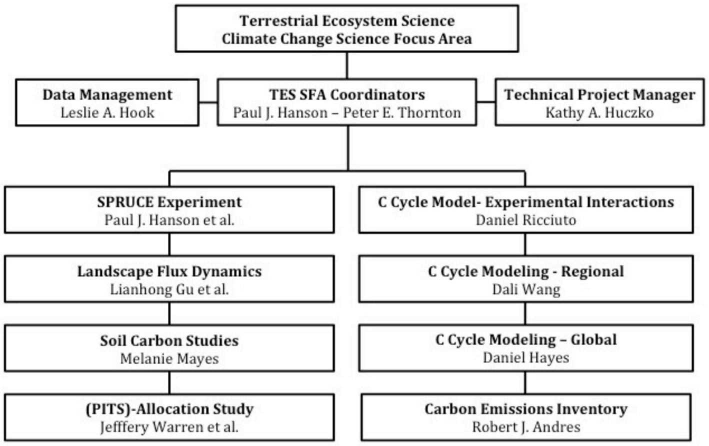


Fig. 2. Organizational chart for the TES SFA effective July 2014.

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 member 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 of the USDA Forest Service 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 FY2014, many initial activities established under our iterative model-experiment-observation interaction are continuing, and some have concluded in the current fiscal cycle with funding 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 FY2013 and FY2014 deliverables is provided showing progress. The deliverables tables include changes made since they were proposed in January 2012.

4AI. REVIEW OF SCIENTIFIC PROGRESS BY TASK

Task 1: SPRUCE Experiment

As of June 2014 the project is approximately two-thirds through the development of infrastructure for the SPRUCE experiment. Full function of the experimental treatments is being planned for the spring of 2015. 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 July 10, 2013.

SPRUCE Infrastructure

Since July 2013, instrumentation monitoring for all experimental plots has been brought online and is being actively logged and managed as we build out the remaining aboveground infrastructure for the SPRUCE experiment in 2014. Planned initiation of full warming treatments is now scheduled for the spring of 2015 (late-May to early June).

While we finish the aboveground construction steps for whole-ecosystem warming, the research group is proceeding with a belowground deep-only warming exercise in 2014 to both test the deep soil warming electrical infrastructure and evaluate rapid responses of microbial systems to all warming levels. This exercise which we are calling the *Deep Peat Heat Study (DPH),* will give us an initial look at the temperature sensitivity of microbial communities and processes and seek to capture signals of DPH effects in surface-evolved CO_2 and CH_4 and their respective isotopic signatures. University and National Laboratory cooperators are actively engaged in DPH and were present for time-zero sampling at the S1-Bog the week of June 2, 2014. DPH Treatments are being initiated throughout the month of June. Aboveground environmental monitoring instruments and data streams will be automated and will come on line in the summer of 2014 in time for intensive use in 2015.

The final construction contract for the installation of aboveground enclosures, subsurface corrals and associated air handling and measurement systems was vetted and approved by ORNL Procurement in spring of 2014 and is currently being actively managed for completion by January 2015 if weather and construction logistics allow such a schedule to be maintained.

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. Initial descriptions of these activities were summarized in the FY2013 annual report and are supplemented here with new information collected since July 10, 2013.

Peat Characterization of the S1-Bog – Full analysis of the pretreatment peat characterization collections obtained in August of 2012 across the S1-Bog experimental area (described in the 2013 annual report), were completed since July 2013. Characterizations of the peat samples were completed for a full range of depths to a maximum of 3 m and included: bulk density, ash content, pH, and elemental levels of C, N, CN ratio, S, P, K, Ca, Mg, Al, B, Cd, Cr, Cu, Fe, Mn, Mo, Na, Ni, Pb, Si and Zn.

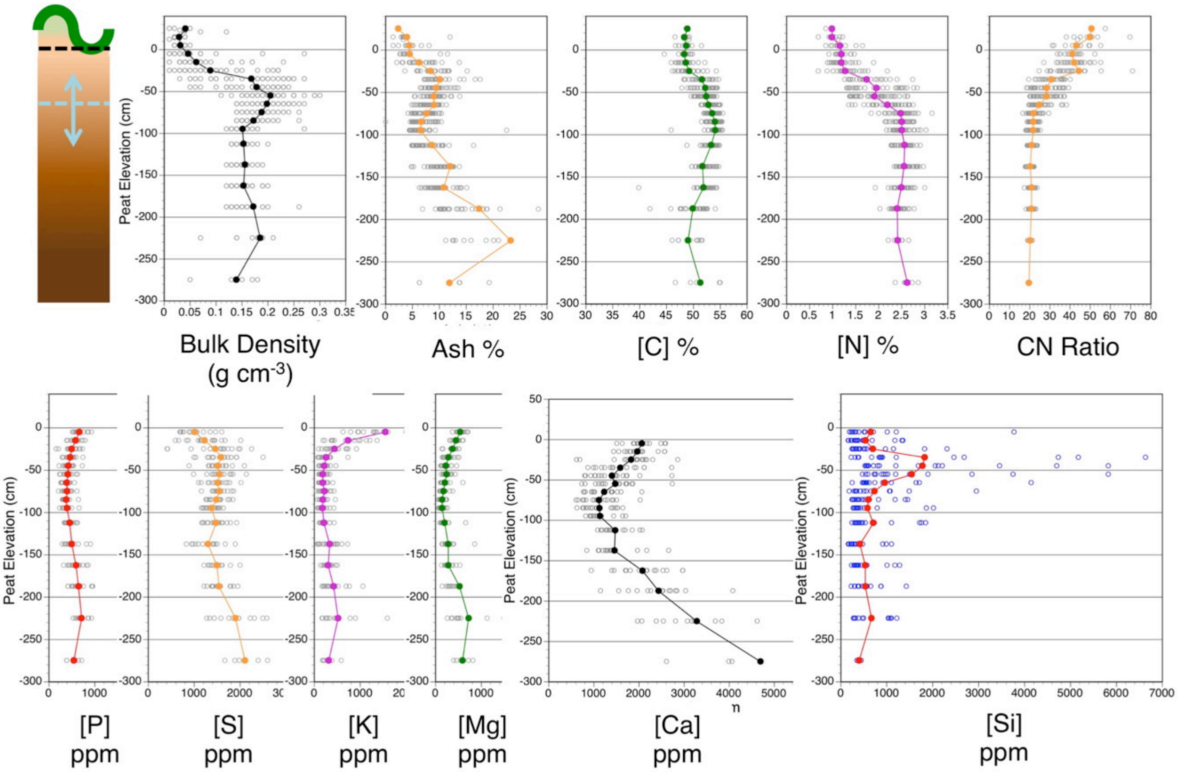


Fig. 3. Depth distributions of peat bulk density, ash content and a range of element concentrations for the S1-Bog SPRUCE experimental plots. Mean characteristics for a given variable are plotted over the full data set obtained from the entire SPRUCE study area. The diagram (upper left) provides a visual representation of hummocks over the hollow (zero depth by definition) above the acrotelm transitioning into the catotelm zone.

Fig. 3 provides a summary of the depth distribution of key peat characteristics and element concentrations at the beginning of the SPRUCE study. Although not shown in a figure, pre-treatment characterization of the S1-Bog site showed few gradients across the plots suggesting that we have been successful in establishing appropriate plot centers for random distribution among our target treatments. Variations with depth as shown in Fig. 3 are key biogeochemical cycling benchmarks against which experimentally induced changes of other variables will be observed. A manuscript (Tfaily et al. 2014) describing organic matter transformation in the peat column of the S1-Bog was recently published that takes advantage of the extensive pretreatment peat characterization conducted since 2012.

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 (Fig. 4). The ^{14}C data reflect the source-age of peat samples with depth and will allow tracking of the mineralization of shallow vs. deep C pools. Calibrated dates for bulk peat from 35-300 cm deep were determined using a Bayesian age-depth model (Bacon v2.2). The mean net C accumulation rate throughout this 10,000-year period was 21 g C m^{-2} y^{-1}. Variation through time may correlate to vegetation change, but the near-surface peats are heavily influenced by root growth and turnover activity, with fire history a possible reason for a key shift in peat age with depth trajectories at the acrotelm to catotelm transition. Karis McFarlane at Lawrence Livermore National Laboratory (LLNL-CAMS) is taking the lead on a manuscript summarizing the age accumulation of peat within the S1-Bog. Tfaily et al. (2014) have also reported that depth-specific DOC & DIC ^{14}C-signatures were distinct from bulk peat. This observation suggests downward migration of DOC as a source of available labile C with depth. Data for ^{13}C isotopic signatures were assayed and are also available for future use in the interpretation of depth-specific changes in C stocks and decomposition activity with depth.

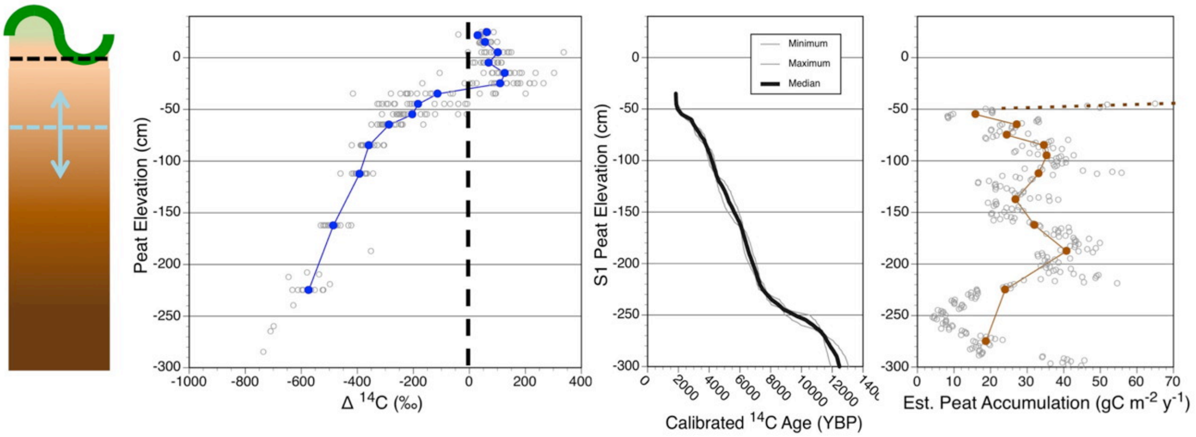


Fig. 4. Depth distributions of bulk peat ^{14}C-signatures, calibrated peat ages, and historical peat accumulation rates. Mean characteristics for a given variable are plotted over the full data set obtained from the entire SPRUCE study area. The diagram (left) provides a visual representation of hummocks over the hollow (zero depth by definition) above the acrotelm transitioning into the catotelm zone.

<u>Aboveground production</u> - Annual assessments of C stocks and accumulation in tree tissues (*Picea* and *Larix*) are being done through annual measurement of tree diameters combined with allometric data for these species collected in 2010 and 2011. Tree dbh and height observations to use these allometric data have been collected since 2011. Standing stocks and 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, 2012, and 2013. Total aboveground standing stock for the non-tree vegetation above the *Sphagnum* surface of the S1-Bog ranges from 180 to 200 g C m^{-2}. Anecdotal site observations between 2012 and 2013 suggesting that shrub production was greater in 2013 have been confirmed by this limited destructive approach. Areas of the experimental plot supporting the destructive measures for shrub-level growth will be dedicated and used for future tissue decomposition studies.

Sphagnum production - *Sphagnum* production was measured again in 2013 using the approach developed in 2012 as described in the FY2013 annual report. Total site production was calculated to be 325 g DM m^{-2}. Standing crop, based on the top 5 cm was 526 g DM m^{-2}, or 226 g C m^{-2}. The 2012 estimate was similar at 277 g C m^{-2}.

Root and Rhizosphere Processes – We are using established and novel methodology to determine the distribution and dynamics of ephemeral roots, and their links with soil nutrient cycling, in the SPRUCE experiment in an ombrotrophic peat bog. Our methods range from manual and automated minirhizotrons to in-growth cores, peat coring, and ion-exchange resins. Colleen Iversen leads the Root and Rhizosphere processes team, which includes Joanne Childs, Rich Norby, Deanne Brice, and Randy Kolka.

Manual minirhizotrons – A manuscript on a 2-year preliminary investigation of fine-root dynamics in the S1-Bog using minirhizotron technology is being prepared. Building upon the methodology and scientific knowledge gained from the preliminary minirhizotron work, four minirhizotron tubes were installed in each of 16 SPRUCE experimental 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 images are being collected approximately weekly throughout the growing season and digitized to obtain root length and diameter (image collection in 2014 is focused on ten SPRUCE experimental plots and two ambient, unchambered plots).

Automated minirhizotrons – Novel, automated minirhizotron (AMR) technology is also being used to track the dynamics of ephemeral roots in the SPRUCE experimental plots. While weekly measurements made with the manual minirhizotrons focus on measurements of annual root production, the AMR systems facilitate high-resolution measurements of root and fungal dynamics. The AMRs capture root and hyphal dynamics at greater temporal resolution (hourly or daily, if desired), and at much higher magnification (100×) than manual minirhizotrons, allowing quantification of the dynamics of mycorrhizal hyphae. The 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 in October 2012. In order to direct the movements of each AMR, the central processing unit associated with each unit must be in contact with an active server. The communications lines associated with each SPRUCE experimental plot were progressively installed over the winter and spring and full communication with all AMR systems was established in June 2014.

Images collected from one AMR over-winter indicated that fungal hyphae occurred in ~10% of the images captured from the surface 30 cm of peat; no hyphae were present in images taken below 30 cm peat depth (Fig. 5). Weekly scans during the winter months (made possible by the sealed nature of the AMR system) showed little root or hyphal growth between November 2013, and March 2014. However, the abundance of external hyphae of the ericoid mycorrhizal fungi associated with ericoid shrub roots in the AMR images captured from the bog was unexpected and will provide new information to the

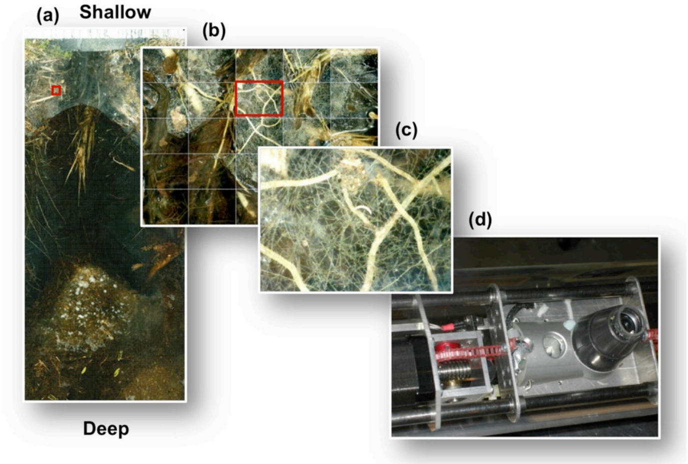


Fig. 5 (a) mosaic of 35,000 individual automated minirhizotron (AMR) images obtained during a single full-tube scan. (b) A 5 by 5 grid of individual AMR images. (c) A single AMR image (~ 2.5 mm by 3 mm at a magnification of 100×) containing ericaceous shrub roots and fungal hyphae. (d) The AMR digital imaging microscope. Twelve AMR robots were installed within their casings in the bog in October 2013; one in each of the SPRUCE experimental plots (and one in each of two ambient, unchambered plots).

community of mycorrhizal ecologists (Mike Allen, University of California, Riverside, *personal communication*). During the spring and summer of 2014, prior to SPRUCE experimental treatment initiation, we will track the phenology of fungal production and mortality with a goal of publishing a high-impact paper prior to the SPRUCE experimental treatments.

***Root in-growth cores* -** Root in-growth cores will be used to determine SPRUCE experimental treatment effects on the chemistry and morphology of newly produced roots. We deployed preliminary root in-growth cores at the S1-Bog in June 2013, in order to test the 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 installed in hollow microtopography were 30-cm deep, based on minirhizotron measurements that indicated that most of root growth was in surface soils (above the average summer water table level). The hummock-hollow differential in each location was determined, and the length of the hummock core was adjusted so that the bottom 10-cm of the hummock core overlapped with the top 10-cm of the hollow core in each location, for comparison of microtopographic differences in rooting dynamics. The preliminary in-growth cores were collected at the end of the growing season (October 2013), and replaced with new, root-free cores, which were collected the following spring (June 2014).

The preliminary in-growth cores captured multiple orders of new roots and associated hyphae for morphological and chemical analyses. As expected, it does not appear that many roots grew into the cores incubated over winter months. Previous work by our group in the S1-Bog has shown that the most common vascular plant species encompassed a range of root morphology and diameter distributions, as well as mycorrhizal colonization (e.g., Fig. 6). Across a range of root orders, root diameter was strongly related with root mass per length and root nitrogen (N) concentration, which has allowed scaling of minirhizotron data to ecosystem carbon and N fluxes. Given this, the biomass and chemistry of newly grown roots from in-growth cores are currently being assessed on an order-specific basis from 10-cm depth increments in each microtopographic position. Preliminary data indicate species-specific preferences for hummock-hollow microtopography and peat depth.

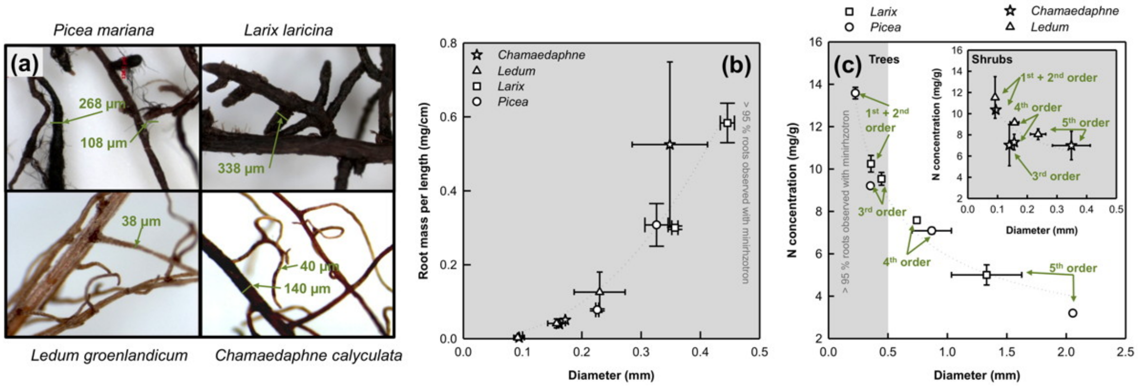


Fig. 6 (a) Images of the first few root orders (small, distal tips which have the highest turnover rate are low order as in stream systems) of dominant plant species in the S1 bog. (b) Root mass per length was positively correlated with root diameter across all major bog species (R^2 = 0.90) in the diameter range where more than 95% of roots were observed with minirhizotrons (~2900 of about 3000 roots were less than 0.5 mm; grey shaded areas). (c) Root N concentration was negatively correlated with root diameter (R^2 = 0.96). Within a functional type (trees, shrubs), root diameter and N concentration changed predictably as root order changed.

Using the same experimental design, root in-growth cores were deployed in hummock-hollow microtopography in two locations in the SPRUCE experimental plots in June 2014. The in-growth cores were installed adjacent to fungal in-growth cores (Hofmockel research group) in each location in order to facilitate comparisons of root and mycorrhizal responses to the SPRUCE experimental treatments. In-growth cores will be collected seasonally (fall, spring) as in the preliminary experiment.

***Fine-root standing crop* –** Fine-root standing crop ($g\ m^{-2}$) is being determined from the peat cores sampled from the SPRUCE experimental plots in August 2012. This is an on-going process due to the time-consuming nature of disentangling roots that are as narrow as 40-µm diameter from a soil matrix that consists in large part of decaying *Sphagnum* moss. Surprisingly, we found intact, well-preserved shrub roots in peat increments as deep as 2 m. We assumed these roots were dead, but well preserved in the anoxic environment in deep peat. Radiocarbon analysis (KJ McFarlane, LLNL-CAMS) confirmed this hypothesis—the ^{14}C signature of intact shrub roots removed from peat samples as deep as 2-m indicated that these roots had a calibrated age of more than 5000 years (Fig. 7). Living roots were confined to the aerobic zone above the average water table depth in the bog, and we will focus our continuing efforts to quantify root standing crop on this zone.

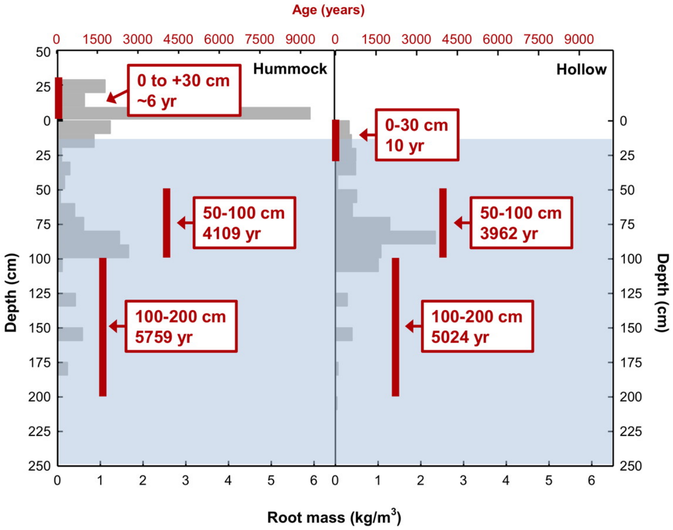


Fig. 7 Peat cores to 2.5-m depth were sampled from the SPRUCE experimental plots in August 2012 and sectioned by depth. Intact, well-preserved shrub roots (biomass shown in grey) were found in peat increments as deep as 2 m. Root samples were bulked into three depth increments for radiocarbon analysis (indicated by red lines and red boxes). Blue shaded area indicates average summer water table.

***Plant-available nutrients* -** Ion-exchange resin capsules (WECSA, LLC, Saint Ignatius, MT, USA) are being 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. Resin access tubes were installed in the SPRUCE experimental plots in June 2013. The access tubes were distributed across paired hummock-hollow microtopography at the peat surface (i.e., focused on the rooting zone) near the water-sampling piezometers in each plot in order to capture differences in peat nutrient availability. A second array of six tubes was installed near plant community composition subplot (for a total of twelve access tubes per plot). Resin capsules were exchanged every 30 days during the 2013 growing season.

The ion-exchange resins indicated that NH_4-N was by far the most available N source, with NO_3-N making up a negligible fraction of N (NO_3-N not shown; the seasonal availability of PO_4-P is still being analyzed). Surprisingly, the overlapping depth increments in the deeper hummock and shallow hollow indicate that NH_4-N availability was somewhat less in the hollow surface than the same absolute depth in the adjacent hummock (Fig. 8). This could be for a few different reasons: (1) greater root uptake in shallower hollow soils compared with deeper hummock soils, or (2) decreased decomposition and N mineralization in hollows, potentially because of differences in the species composition of *Sphagnum* moss, or the fact that living moss predominates in shallow hollows, but dead and decaying moss predominates in deeper hummock peat. These potential differences will continue to be investigated. The availability of NH_4-N declined over the course of the growing season (Fig. 8).

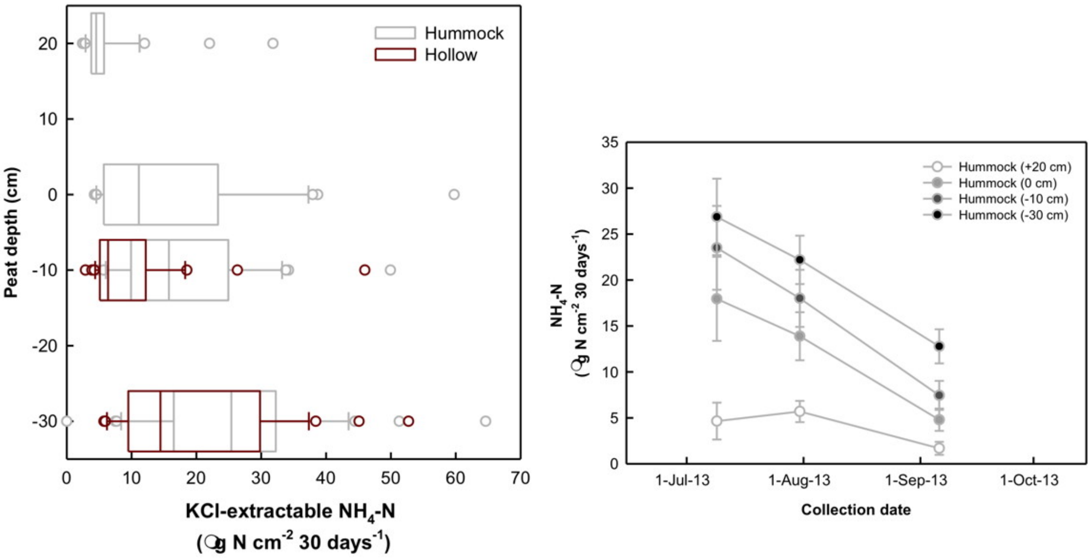


Fig. 8 (Left) Plant-available NH4-N adsorbed to ion exchange resin capsules during a 30-day increment in mid-summer, 2013. (Right) A seasonal pattern of NH4-N availability in raised hummock microtopography across the growing season in 2013.

SPRUCE Plant Physiology **–** The overarching 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* sp. Linkages between the vegetation and environmental conditions dictate photosynthetic and respiratory contributions to site C balance, albedo and hydrological impacts on the surface energy balance, and consequential impacts on soil biogeochemistry. Measurements to date 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.

The SPRUCE physiology team is led by Jeff Warren, with the support of Stan Wullschleger and a post-doctoral physiologist (Anna Jensen – previously of the Swedish University of Agricultural Sciences). In FY13-14 we continued to characterize the plant carbon and water relations of the bog vegetation. Particular effort was given to establishing photosynthetic and respiratory temperature response curves, as well as testing various sensors and measurement techniques to be deployed as treatments are initiated.

Based on our past work at the site, the *Granier*-style heat dissipation probe will be able to provide long-term monitoring of sap flow through the dominant *Picea* and *Larix* trees (seasonal pattern of sap flow Fig. 9). The probes are robust, and they appear to be useable for at least 2 years, after which they will need to be replaced due to tree growth. Calibration of these probes is essential to calculate accurate values of tree transpiration at the site. As such, during summer and fall 2013, several trees containing functioning probes were secured with ropes, and then cut in place, with the cut end immediately placed into a container of water. Over the next several days, water use from the container was monitored simultaneously with the sap flow signal to produce calibration curves. The curves will allow sap flow data from individual trees to be scaled to whole plot tree transpiration, which is a key process represented in CLM. The group continues to explore use of the delicate heat balance sensors to monitor sap flow through the two dominate shrubs, *Ledum* and *Chamaedaphne,* which contribute significantly to total plant transpiration.

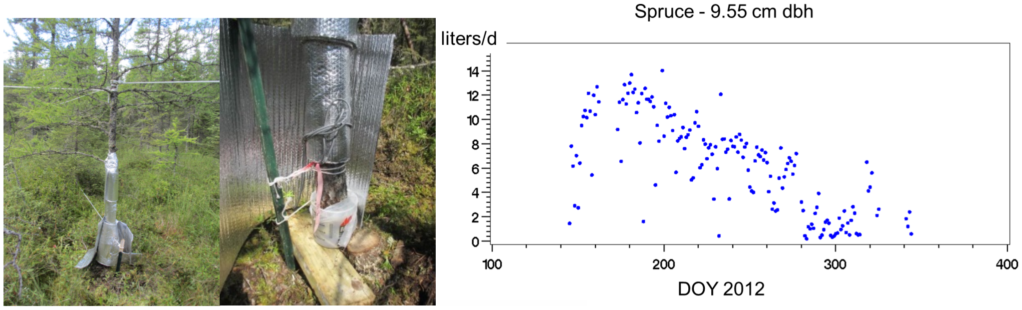


Fig. 9. Seasonal transpiration pattern of a mature *Picea mariana* tree in 2012 (dbh = 9.55 cm). The photos illustrate how sap flow sensors were calibrated in field.

We anticipate the experimental treatments will increase atmospheric vapor pressure deficit, lead to drier soil and increase water table depth – all of which would increase the potential for drought stress and affect sap flow. We assessed the mechanisms of drought stress by measurement of root, branch and leaf hydraulic conductivity of *Picea* trees. Roots were collected from the cut trees. Results provide estimates of water potential (drought) thresholds for catastrophic xylem cavitation and failure. The turgor loss point (TLP) is based on pressure-volume curves, and indicates a potential threshold for drought stress. *P. mariana* TLP was -24.4 bars (-21.1 to -30.0 bars) while *L. laricina* TLP was lower -18.6 bars (-14.4 to -22.1 bars), indicating the *Larix* may be more susceptible to excess drought stress under hot and drying conditions. A baseline SPRUCE plant water relations manuscript is under preparation.

Seasonal C dynamics (photosynthesis, respiration and carbohydrate storage) of the woody vegetation and their responses to changing temperature and CO_2 continues to be a central focus of the group. During 2013-14, photosynthetic capacity and respiration was assessed using gas exchange, including light, CO_2, and temperature response curves on detached plant material. We have identified and quantified seasonal, canopy and cohort C assimilation patterns of the dominant tree *P. mariana*, using seasonal- and cohort-specific temperature response functions (Fig. 10). In FY2014 we are collecting seasonal temperature, light and CO_2 responses (LCR and A/Ci curves) for *L. laricina* and the two dominating shrub species (*Rhododendron groenlandicum* and *Chamaedaphne calyculata*) to complete seasonal assessment of the photosynthetic capacity of the woody species in the bog. We are also continuing measurement of the temperature respiratory responses of foliar and woody tissues that will be used to improve model estimates of net C balance. Data have been prepared and a manuscript draft is written and currently under revision.

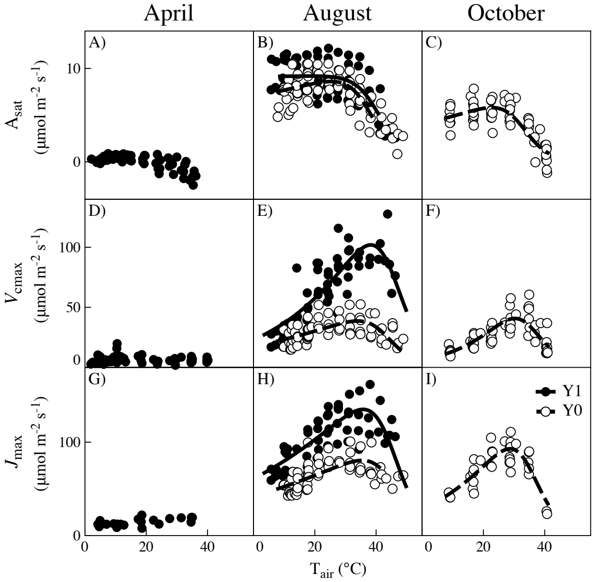


Fig. 10. Seasonal temperature response of (A-C) maximum photosynthesis (Asat), and photosynthetic parameters (D-F) Vcmax and (G-I) Jmax in one-year old (Y1) and current year (Y0) *P. mariana* needles at the S1-Bog. The scatter is individual values of Asat, Vcmax and Jmax and solid lines denote the curve fittings. Such data are essential to accurate modeling of spruce C uptake.

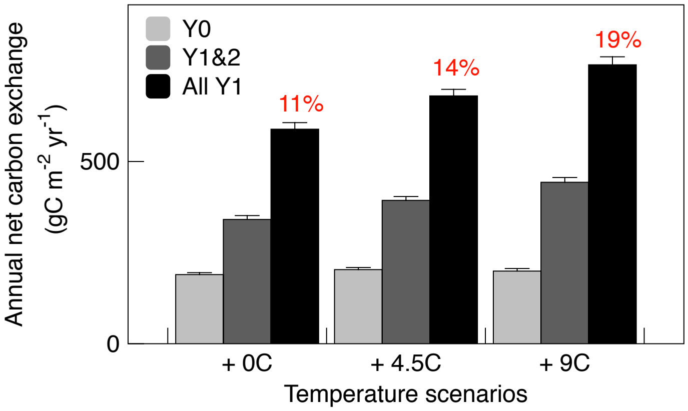


Fig. 11. Extrapolated mean annual net carbon exchange for *Picea mariana* needle cohorts for three temperature assumptions (+0, +4.5 and +9 °C) between 2011 and 2013. Positive values of carbon exchange indicate net uptake into the foliage from the atmosphere, with (Y0 and Y1&2) and without (all Y1) considering cohort-specific differences in the model. The percent values above the All Y1 bar indicate C uptake overestimations when foliar cohort differencs are ignored.

As we anticipate the experimental treatments will increase atmospheric vapor pressure deficit, resulting in drier soils, we designed and carried out a drought stress experiment (the spruce bud break experiment (SBBE)) to evaluate the impact of temporary drought and re-hydration on shoot development and carbon investment in *Picea mariana* trees. We monitored changes in morphological, biochemical (osmolality, chlorophyll nitrogen, and [non-structural carbohydrates (NSC)]) and physiological (rates of respiration (R_d) and light-saturated photosynthesis (A_{sat})) processes during shoot development. Further, to study functional compartmentalization and use of new assimilates, we ^{13}C-pulse labeled shoots at multiple development stages, and measured isotopic signatures of leaf respiration, NSC pools and structural biomass. Results indicate that temporary periods of water deficit inhibits C translocation from older organs to new shoots, delaying their spring development, and shifting internal C partitioning patterns that altered substrate availability for growth and maintenance respiration. Laboratory sample processing is continuing and a manuscript is under preparation.

To study functional compartmentalization and use of new assimilates during leaf and shoot development, we are pursuing ^{13}C-pulse labeling of shrub communities three times during the 2014 growing season (May, June and July). The label will be tracked through the isotopic signatures of leaf respiration, the NSC pool and total structural biomass. We have already carried out two successful labeling events and these samples are currently being processed. Results from the seasonal labeling experiment will be developed into a manuscript in 2015.

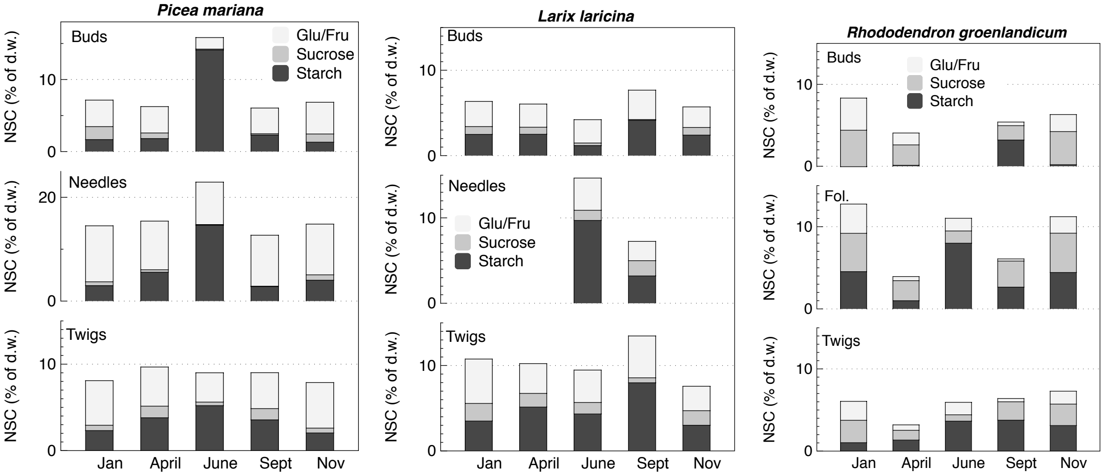


Fig. 12. Seasonal patterns of individual nonstructural carbohydrates; glucose/fructose, sucrose, and starch (%DW) concentrations in buds, foliar and twigs of *Picea mariana*, *Larix laricina*, and *Rhodendron groenlandicum* at the S1-Bog during 2013.

We have continued following the seasonal and dial dynamics of NSCs pools within plant tissue at the SPRUCE site (pre-treatment), with a specific focus on bud and shoot development. Samples (foliar, twigs and stem material from *Picea mariana, Larix laricina, Rhododendron groenlandicum* and *Chamaedaphne calyculata*) have been collected and analyzed. Results will be combined with site-specific climatic information to analyze contrasting supply/demand ratios (relative changes in NSC pools) to better understand the seasonal C-supply status/dynamics in the S1-bog. Sample collection continues through 2014 and into 2015 in anticipation of treatment initiation at the site. A baseline manuscript is under preparation. A new collaboration with Andrew Richardson (Harvard University) and his PhD student (Morgan Furze) will continue focus on NSC analysis at the site and will include long-term post treatment analyses.

Sphagnum Physiology – The goal for the *Sphagnum* moss physiology activities in FY2014 was the extension of our modeled response surfaces to multiple species of *Sphagnum* subjected to several levels of CO_2 and light, development of a *Sphagnum*-specific net photosynthesis and NPP model, and initial testing for the implementation of a highly instrumented net ecosystem exchange (NEE) using clear top automated gas exchange equipment (Li-COR 8100s). Through collaboration with Jon Shaw (Duke University) it was determined that plants we had previously referred to as *S. angustifolium* were actually *S. fallax* and that *S. fallax* and *S. magellanicum* together account for 88% of the total moss cover at the S1 bog site. Our results support the claim that wet-site hollow dominating species had greater assimilation rates under light-saturating conditions and at temperature optimum relative to the hummock prominent.

Using our *Sphagnum* net photosynthesis and NPP model, elemental stoichiometry, and measured *Sphagnum* GPP, we determined the amount of nitrogen needed to support the observed *Sphagnum* production. This modeling exercise led to the need for an initial assessment of dinitrogen fixation associated with *Sphagnum* in preliminary trials with greenhouse-grown specimens. *S. fallax* and *S. magellanicum* stems were incubated in 50-ml tubes in which 5 ml of air was replaced with 5 ml $^{15}N_2$. The tubes were incubated for 24 hours in the greenhouse. Stems were then oven dried, ground and analyzed for ^{14}N and ^{15}N content. Based on the gain in atom percent ^{15}N, N fixation rate was calculated to be 0.0193 $\mu g\ mg^{-1}\ d^{-1}$. Assuming 150 days per year and a *Sphagnum* standing crop (top 5 cm) of 370 $g\ m^{-2}$, annual N fixation would be 1.07 $g\ m^{-2}$, or about 26% of the total *Sphagnum* N pool. Hence, N fixation is a potentially important process in the bog. Field measurements will begin in 2014. This potentially critical component of the S1 N cycle was recently explored in a modeling study that linked our *Sphagnum* net photosynthesis model with a metabolic flux balance analysis model for a N fixing cyanobacterium (Weston et al. 2014). Field and laboratory measurements to test these model predictions will begin in 2014.

Microbial Communities and Processes – SPRUCE project work in collaboration with the Kostka lab shows that microbial communities in the S1 peatland are spatially variable but largely structured by depth and correlated with organic matter decomposition properties. Results of these works were reported last year and subsequently published this past year in three papers in *Applied and Environmental Microbiology* and the *Journal of Geophysical Research: Biogeochemistry* (Lin et al. 2014a, Lin et al. 2014b, Tfaily et al 2014).

The SPRUCE experiment is expected to lead to various changes in ecosystem properties, both due to the direct effects of warming and indirect effects such as drying, that may alter biogeochemical processes mediated by microbial communities. As a consequence and prior to the onset of treatments, we completed two lab-scale experiments at ORNL this past year to scope effects of warming and drying on peat microbial responses. First, we examined temperature effects on peat enzyme metrics and how these vary with depth and season. We hypothesized winter and summer communities in near surface peat would show differential enzyme activities and increased temperature response compared to deeper depths where community optima would be narrowly constrained. We measured activity of three enzymes involved in C, N and P cycling using a custom aluminum heat block to obtain highly resolved curves from 2-65 °C in ~3 °C intervals. Enzyme activity, temperature sensitivity, and C:N enzyme stoichiometry decreased with depth, but showed no seasonal response. Peat N increases with depth whereas C is constant; these trends are reflected in a concomitant decline in the enzyme C:N mineralization ratio. Proteases were less responsive to temperature (Ea<20) compared to enzymes for C and P depolymerization (Ea=20-60). The stable temperatures in deep peat may result in communities and enzymes specialized for narrow temperature ranges, reflected by a decreased temperature response compared to surface peat that experiences large temperature swings. The small response in protease activity indicates a possibility for decoupling of N, from C and P cycling in the peat with warming. The results for this work are in prep for publication in *Soil Biology and Biochemistry*.

Warming will also likely lower water levels in the SPRUCE chambers, causing strong declines in hummock moisture and moderate declines in hollow moisture. Using laboratory incubations, we compared effects of 75 and 50% of ambient moisture on near surface hollow and hummock peat. We measured enzyme activity, microbial and invertebrate community abundance and composition, microbial biomass, and DOC 2, 13, 42, 91, and 112 days post drying. CO_2 was measured cumulatively. Hummock and hollow peat responded differentially to drying, with hollow communities most affected. Hollow samples at 50% moisture resulted in declines in 6 of 7 enzyme activities within two days that was maintained throughout the experiment. In hollow peat, there was a decline in fungal abundance with drought within 13 days. In hummock samples, two peptidase activities increased with drought, while other enzymes were unaffected. CO_2 respiration in general declined with reduced moisture treatments in hummock and hollows, but was 2X higher and more variable from hummock than hollow samples (Fig. 13). Overall, hummock microbial communities/processes were largely unaffected by moisture stress, perhaps reflecting the variable moisture levels experienced in native bogs. We recently finished data collection on the remaining time points of this experiment and validated our approach to quantification of invertebrate populations using QPCR. The results of these experiments will constitute the core of a paper planned for publication in *Applied and Environmental Microbiology*.

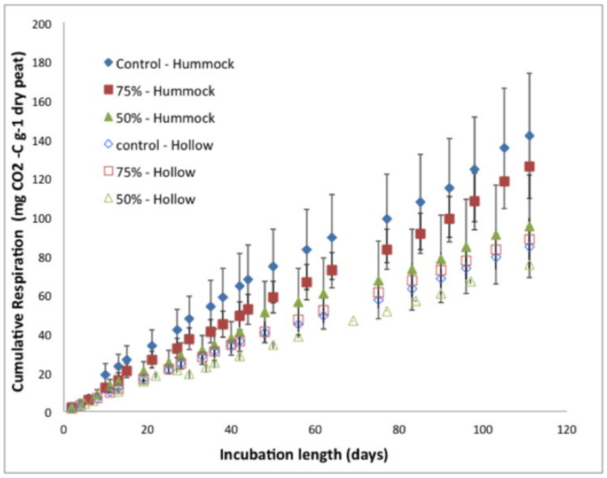


Fig. 13. Hummock communities respired more CO_2 across the moisture levels tested, but are also more variable and more sensitive to reduced moisture levels compared to hollow communities

<u>*SPRUCE Hydrology and Water Chemistry*</u> – Piezometers for depth-specific sampling of peat pore water (0 – 3 m into the peat) were installed in the 16 plot centers at S1 in mid-summer 2013, and sample collection to establish baseline conditions began shortly thereafter. Data collected in 2013 revealed large differences in peat pore water chemistry with depth, with higher pH and ammonium concentrations and lower total organic carbon concentrations in deeper pore water (Fig. 14). The high ammonium concentrations likely reflect the long residence times of deep peat where remineralization and the absence of nitrification produce ammonium. Similar patterns in pore water chemistry with depth were observed over 2 years (2011-2012) of monitoring in one nest of depth-specific piezometers in the south end of S1, illustrating the consistency of chemical conditions with depth across the S1-Bog.

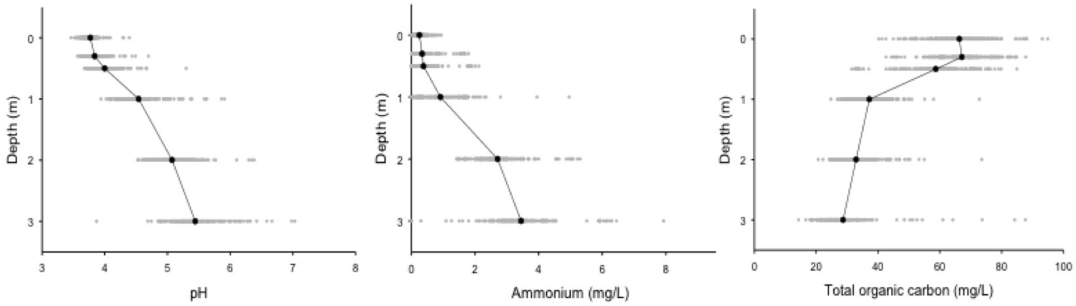


Fig. 14 – Depth profiles (0 – 3 m) of pH, ammonium, and total organic carbon concentrations in peat pore water. Black dots represent the mean value across the 16 plots and 15 sampling periods in 2013, and grey dots show the variation in water chemistry parameters across all plots and sampling periods.

While the largest variation in pore water chemistry was observed with depth, there was some spatial variation across S1, with higher nitrate concentrations in the north vs. the south end of S1, and higher ammonium concentrations in the west vs. the east end of S1 (Fig. 15); however, these gradients were much smaller than those observed with depth in a single location.

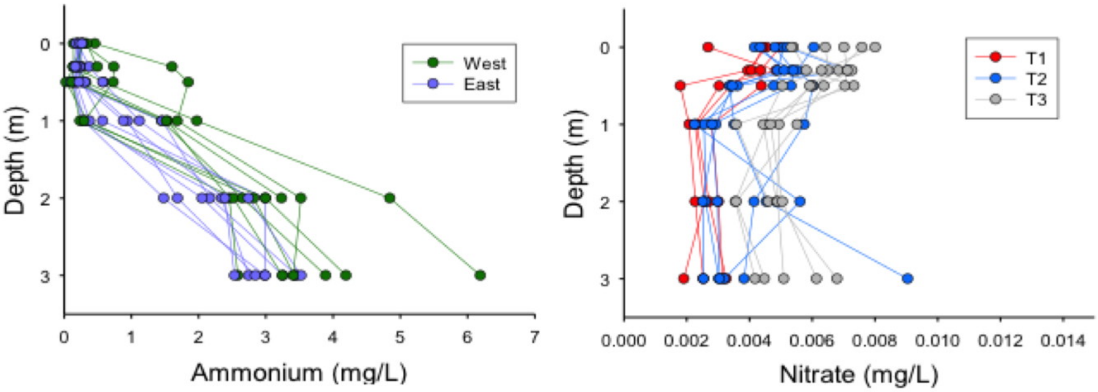


Fig. 15 – Gradients in ammonium concentrations from west to east locations in S1, and in nitrate concentrations from south (transect 1) to north (transect 3). Each line represents the mean chemical profile for one plot across the 2013 sampling season.

In 2014, we are actively conducting biweekly sampling from piezometers in the 10 experimental plots that are being warmed belowground during the 2014 growing season (i.e., the DPH experiment), and we are conducting monthly sampling from the piezometers in the remaining 6 ambient plots. This sampling protocol will continue into 2015 when the full experiment will begin. In 2014, we are also measuring depth-specific pore water chemistry across a wetland gradient from ombrotrophic bogs to minerotrophic fens to examine whether these striking chemical gradients with depth are commonplace in this region or specific to the S1-Bog.

The prototype of the subsurface corral (flow barrier) and drainage collection system continued to be tested in 2013. During a water addition test in 2012, we observed some leakage through corral wall joints, and initiated a test of various sealants and application rates in 2013 to minimize these leaks. We built mini corrals (square of four sheet panels placed into a concrete base) at ORNL and found that the sealant type and application amount did not affect the leakage rate between the wall joints. However, the application of a ‘peel-and-stick’ sealer greatly reduced leakage rates. We applied this ‘peel-and-stick’ sealer to the prototype corral in S1 in late 2013 and observed lower leakage rates. We will continue to assess the performance and functionality of the corral in 2014. Installation of the 10 belowground corrals will commencing in the summer of 2014, and we will instrument each with automated water samplers. These samplers will collect composite samples from the outflow of each plot for analysis of total organic carbon, nutrient, and elemental export.

CO_2/CH_4 flux and model – Simultaneous surface flux measurements of CO_2 and CH_4 have been made since 2011using open-path analyzers and custom-designed chambers that enclose the combined hummock-hollow topography of the bog. This measurement approach enables point-in-time observations of the combined shrub/forb/*Sphagnum*/microbial community for a1.13 m^2 area of the bog. These measurements were expanded to include 16 new collar positions within all 10 target SPRUCE experimental plots and six ambient reference plots.

Hanson et al. (2014) are revising a manuscript following peer review that summarizes this technique and the use of the seasonal and spatial data to characterize CO_2 and CH_4 exchange with the S1-Bog under pretreatment conditions. Maximum net CO_2 flux in midsummer showed similar rates of C uptake and loss: daytime surface uptake was -5 to -6 μmol m^{-2} s^{-1} and dark period loss rates were 4 to 5 μmol m^{-2} s^{-1}. Maximum midsummer CH_4-C flux ranged from 0.4 to 0.5 μmol m^{-2} s^{-1} and was a factor of 10 lower than dark CO_2-C efflux rates. Integrating temperature dependent models across annual periods showed dark CO_2-C and CH_4-C flux to be 997 and 25 g C m^{-2} y^{-1}, respectively. After accounting for daytime CO_2 uptake via photosynthesis, net CO_2-C efflux from the bog was 132 g C m^{-2} y^{-1}. Trimming of vegetation layers showed that the shrub/forb/sedge layer dominated net carbon uptake during the day, but did not change C losses in the dark. This method will enable prediction of CO_2 and CH_4 surface exchange for a range of warming and elevated CO_2 manipulations.

Carbon Budget for the S1-Bog – Since last year's annual report, the physiology task has gathered further information on *Picea, Larix, Ledum* and *Chamaedaphne* tissue C exchange rates and verified that our earlier estimates of woody tissue respiration were too high. Recombining these new woody tissue respiration estimates with other pre-treatment measurements of ecosystem C stocks (trees, shrubs, forbs, peat), foliar gas exchange data, surface CO_2 and CH_4 flux and basin level DOC losses with a simple interpolative model of C flux (Fig. 16). The combined data now indicate a consistent annual uptake of C ranging from 171 to 185 g C m^{-2} y^{-1} by the S1-Bog in its current state of stand succession (i.e., regrowth since 1974). Can we reconcile and explain this level of C accumulation on the short-term (years) with the historical long-term (centuries to millennia) accumulation rates of 21g C m^{-2} y^{-1}? Time and additional observations will tell if the discrepancies are the result of labile C losses and the transition from aerobic to anaerobic storage conditions with peat depth.

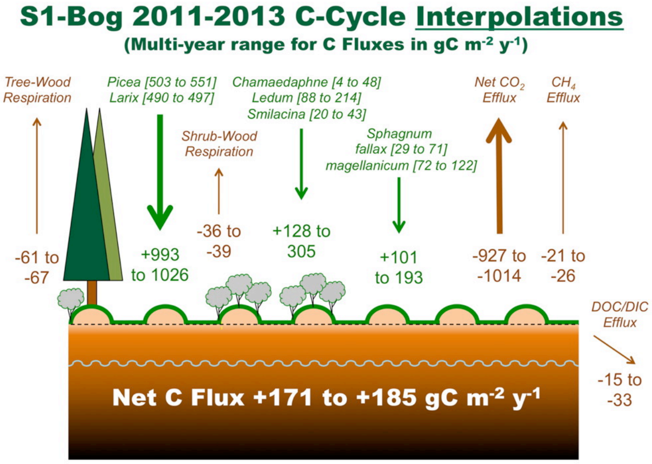


Fig. 16. Interpolated C budget for the S1-Bog for environmental conditions in 2011, 2012 and 2013. Data presented are the multi-year range of data for a given C flux.

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 provide a fully integrated C model of generic wetland function that will use SPRUCE observations to both adjust and benchmark its predictions of wetland C gain.

SPRUCE Deliverable Progress

The SPRUCE project continues final infrastructure development and pretreatment biological process observations in FY2014 with an anticipated transition to full-time experimental treatment applications in spring of 2015. The following deliverables outline major SPRUCE activities anticipated for FY2014 and FY2015. SPRUCE treatments will be operated, and responses measured and interpreted over a full decade. Such a time period should allow 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 1. SPRUCE Deliverables and Progress To Date.

Date	Deliverable	Status
Sep 2013	Manuscript on seasonal and depth variation of microbial populations and activity in peat	Published Lin et al. 2014
Mar 2013	Produce manuscripts on baseline plant water relations and woody plant foliar physiology for the S1-Bog.	Submitted 2014 Jensen et al.
Spring 2014	Submit manuscripts on seasonal CH_4/CO_2 flux observations using new methods.	Submitted 2014 Hanson et al.
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	Still In progress
Summer 2014	Initiate Deep Peat Heating Test and Experiment	June 2014
Summer of 2014	Conduct measurements for the full range of disciplinary SPRUCE tasks for all defined experimental plots employing any refined methods indicated by pretreatment studies.	Underway
2014	Submit manuscript on fine-root production in relation to topography and tree density	In progress Iversen et al.
December 2014	Complete the addition of CO_2, propane and data service capacities to all experimental plots.	Electrical and Data Complete CO_2 and Propane 2014
Spring 2015	Complete construction of all above- and belowground infrastructures, and initiate treatments.	Expected Spring 2015
Spring 2015	Manuscript on the spatial and temporal variation in peat pore water chemistry in the S1-Bog (baseline conditions from the south end of S1)	Being prepared Griffiths et al.
2015	Manuscript on peat age and historical C accumulation rates from 14C data.	McFarlane et al.
Fall 2015	Manuscript on vertical chemistry profiles across a bog-fen gradient (S1, S2, Bog Lake)	Sample collection began in 2014

Task 2: Walker Branch Watershed Long-Term Monitoring

Walker Branch Watershed (WBW) is a long-term forested watershed research site on the Oak Ridge Reservation. DOE-BER funded WBW research is being phased out, and long-term monitoring of WBW ended in 2013. Monitoring will continue through the National Ecological Observatory Network (NEON). Construction of the WBW NEON site began in the fall of 2013 and data collection will begin in 2014/2015. In FY14, manuscripts from recent research projects conducted in WBW were written, and this activity will continue in FY15. One paper on consumer contributions to stream nutrient cycling is in press at *Ecosystems*, one paper on litter decomposition responses to temperature is in review at *Freshwater Science*, and three additional manuscripts are in preparation and will be submitted in FY14 and FY15.

Analysis of a 10-year-long dataset of daily stream metabolism measurements (primary production and ecosystem respiration rates) will occur in FY15 and will include the development of a stream metabolism model to examine effects of climate change on stream carbon cycling.

Table 2. Walker Branch Deliverables and Progress To Date.

Date	Deliverable	Status
Fall 2013	Paper on litter decomposition in response to temperature in streams	Manuscript in review
Fall 2014	Manuscript on quantifying uncertainty in nutrient uptake kinetics	Manuscript in preparation
Summer 2015	Paper on dual N and P uptake in streams	Manuscript in preparation
Fall 2015	Development of a stream metabolism model to examine how climate change will affect stream carbon cycling.	Modeling of stream metabolism in progress

Task 3: Mechanistic Carbon Cycle modeling

This task incorporates model development and MODEX activities at the point scale, including the SPRUCE, PiTS, EBIS, MOFLUX and other AmeriFlux sites, as well as regional to global 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 July 2013 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 a model functional testing framework (Task 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 - We continue to develop and maintain PTCLM, the single-point version of CLM-CN. PTCLM has been integrated into the CLM and CESM code repositories (Oleson et al., 2013), and also plays an important role in the NGEE-Arctic and the newly initiated Accelerated Climate Model for Energy (ACME) project. PTCLM serves as a test bed for most CLM development, providing the ability to quickly test the model against site observations. Within the TES SFA, PTCLM is being used within several CLM development braches: CLM-SPRUCE, CLM-PiTS, CLM-CNP, and CLM-EBIS. These branches are currently being merged into a consistent single version, which will support future SFA modeling activities. Recent work has focused on improving the efficiency of PTCLM simulations, which is more computationally demanding than some other land-surface models due to process complexity and software infrastructure. Through bypassing the model coupler (which is needed for fully coupled simulations), but still using the same CESM code base, the speed of PTCLM simulations was increased by a factor of five, greatly aiding model development and uncertainty quantification efforts.

Even with these improvements, PTCLM remains computationally expensive, especially in the context of uncertainty quantification (UQ) where large ensembles are required. When doing model development, it is also often difficult to isolate the effects of a new process when running the full model. Therefore, Dali Wang and Anthony King are leading efforts to build a functional testing framework to support development and integration of individual processes in CLM (e.g., photosynthesis). This approach benefits from the already modular nature of CLM, which we are using to isolate code units and evaluate the output response to a range of carefully controlled inputs for individual functional units. A capable functional testing package has been demonstrated (Wang et al., 2014), 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), Xiaofeng Xu (ORNL), Paul J. Hanson (ORNL), and Jiafu Mao (ORNL) completed model modifications needed to represent the isolated hydrologic cycle of the bog environment with raised hummocks and sunken hollows. Current efforts focus on representing bog biogeochemistry, and we are in the process of incorporating a new microbial functional-group based methane module into a point version of the CLM4.5 model. The new CH_4 module considers dissolved organic carbon dynamic, CH_4 production from acetic acid and CO_2/H_2, and two mechanisms of CH_4 oxidation, aerobic oxidation of methane and anaerobic oxidation of methane (Xu et al., under review). All these biogeochemical processes for CH_4 are simulated in a vertically structured modeling framework within CLM4.5. The new model has been merged with the CLM-SPRUCE model for the hydrology treatment and applied for preliminary estimates of CH_4 flux. Recent work confirmed the importance of vertical and horizontal transport of dissolved organic matter, acetic acid, CO_2 and CH_4 underneath the surface of the SPRUCE peatland; therefore, an effort has been initialized to implement the 3-D transport of these biogeochemical variables in the merged model. The next steps for the modeling effort are to further integrate field observational data from ORNL scientists and university partners with the new merged CLM-SPRUCE model that considers the specific hydrological and CH_4 processes and parameterize the models. The model will be used for projecting the effects of warming and elevated CO_2 on carbon cycling in the peat land, particularly CO_2 and CH_4 processes and surface fluxes. The development of CH_4 model has been partially sponsored by NGEE-Arctic project. Preliminary results on this effort were presented during the AGU fall meeting (December 2013) and DOE TES/SFA PI meeting (May 2014) and are represented in the following figures.

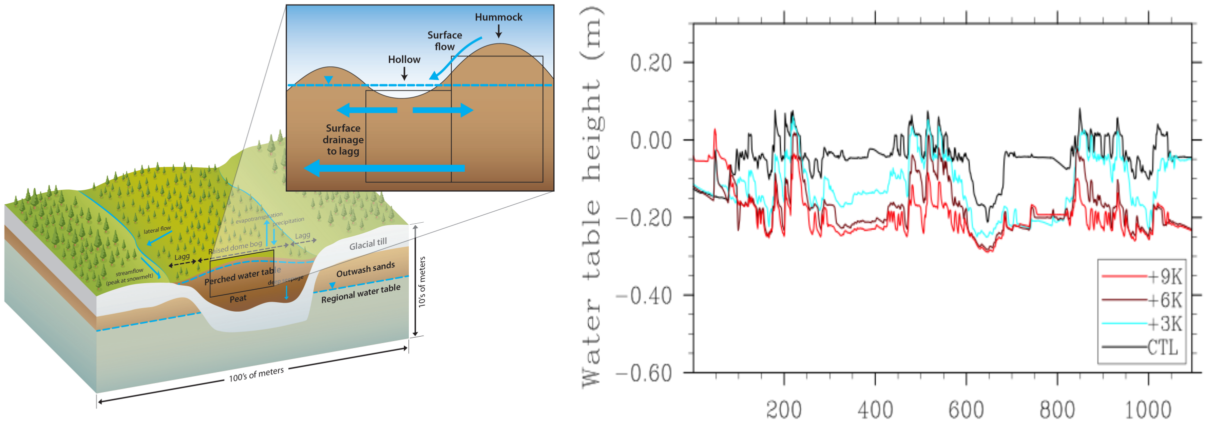
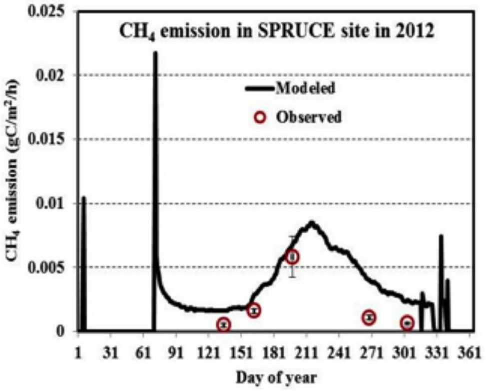


Fig. 17: CLM-SPRUCE representation of S1-Bog hydrology (left panel). CLM-SPRUCE prediction of S1-Bog water table heights (relative to the hollow surface) with different levels of warming (right panel).



Variables	Observed	Modeled
Soil CO_2 efflux (g C m^{-2} y^{-1})	~1000	850
CH_4 emission (g C m^{-2} y^{-1})	24~26	24.5

Fig. 18. Comparison between observed and simulated surface CH_4 flux in 2012. Simulations use CLM-MICROBE, which is currently being merged with the CLM-SPRUCE hydrology model.

Other site-level CLM MODEX activities: 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. Progress in FY14 to date has involved preparation of a manuscript detailing a CLM modeling study at the PiTS phase 1 site. Modeling of PiTS phase 2 and 3 sites is being initiated. In addition, we have extended the functional testing framework to apply the CLM photosynthesis routine to simulate observed light response and A-Ci curves at PiTS (see below).

In cooperation with the C-Climate feedbacks project, Xiaojuan Yang is leading the development of CLM-CNP, which introduces phosphorous dynamics into CLM. CLM-CNP has been evaluated using the PTCLM framework at a number of tropical sites, and these evaluations have been published (Yang et al., 2014). Model experiments using CLM-CNP also identified current knowledge gaps related to processes controlling soil P availability in tropical forests, providing guidance for future field observations of carbon and nutrient cycling.

Additional work, initiated in the CSSEF project but now supported by the TES SFA, is simulating the ORNL Enriched Background Isotope Study (EBIS) in a version of CLM (CLM-EBIS) that contains two litter layers. Initial results compare favorably to simulations, and a manuscript is in preparation. We are collaborating with Ram Oren (Duke University), to make changes to the nutrient GPP downregulation and belowground allocation schemes CLM-CN 4.5 using data from a closed-chamber CO_2 manipulation experiment. Finally, PTCLM is being used to test CLM at a number of eddy covariance sites, including 15 sites in North America evaluated in the North American Carbon Program (NACP) interim synthesis. A detailed parameter sensitivity of CLM-CN that extends previous work at the Niwot Ridge site (Sargsyan et al., 2014) is underway, and will improve understanding of which processes control specific model predicted variables and how these controls vary temporally and spatially. We are also performing a structural intercomparison to evaluate the CLM4.5 vs. CLM4.0, and various options within CLM4.5 including vertically resolved soil carbon, and ORNL modifications.

Functional testing for CLM

Working with National Center for Computational Science (www.nccs.gov), Dali Wang (ORNL) has developed a systematic approach to analyze CLM software system (Wang et al., 2014a, Wang et al., 2014b), a preliminary web-based, interactive CLM Software Structure Analysis and Visualization System (www.ornl.gov/~7xw/Overview.html), which provides useful information for future CLM model development.

We have developed a software platform (Wang et al., 2014c, Wang et al., 2013) to support comprehensive CLM Ecosystem Function Testing using site-based measurements and observational datasets. A photosynthesis testing module has been implemented and verified using leaf web datasets (leaf-web.ornl.gov). Also in collaboration with universities, we have developed new methodologies to analyze climatic and terrestrial ecosystem observational datasets (Zhao et al., 2013; Shi et al., 2014a; Shi et al., 2014b). This functional testing development is also supported by the newly initiated DOE-BER ACME project. We envision the TES SFA to continue to assist in the development of this framework, most importantly for the application of the functional testing software to site-level model-data comparisons that are beyond the scope of ACME.

Anthony King, Daniel Ricciuto, and Dali Wang are also working to extend parameter optimization and UQ techniques to the functional testing framework. This allows for CLM functional units to be parameterized by data across a range of scales.

Table 3. Task 3a Deliverables

Date	Deliverable	Status
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	- Completed - MS Underway - Ongoing
2013	- Prototype of CLM unit test for critical model subroutines	- Completed
2014	- Complete evaluation of CLM-CN at FACE, PiTS, EBIS and other experiment sites using parameter optimization and comparison of multiple model structures - Evaluate CLM-SPRUCE with initial SPRUCE treatment data including evaluation of prognostic methane model against measurements.	- Underway - Initial simulations complete

Task 3b – Improve ecosystem process models with regional observations

Although site observations are extremely useful to evaluate CLM, scaling of model parameters and processes for regional and global relevance requires spatially resolved datasets. TES investigators Mao, Ricciuto and Shi recently initiated participation in UQ-focused MIP led by Ying-Ping Wang (CSIRO) that is especially relevant for this task. We are performing 200 global 2x2 degree 50-year simulations of CLM-SP (satellite phenology) in which we are varying 24 biogeophysical parameters. We will use this model ensemble to determine the optimal parameters for best simulating FLUXNET synthesized GPP and evapotranspiration (ET). The optimized model will then be run in full CLM-CN mode (with biogeochemistry turned on) and evaluated against biomass, soil carbon, and other independent datasets. This effort should improve CLM simulations and provide useful information about how controlling parameters vary across space and as a function of environmental conditions. Results will be submitted in late FY2014 with a manuscript planned in FY2015.

We are continuing to participate in PalEON, which will provide valuable information to the treatment of century-scale vegetation dynamics in CLM-CN. The second phase of this activity initiated in FY 2014 and we have completed several point-level simulations from the years 850-2000 and evaluated these simulations against observed vegetation dynamics.

In addition to the MIPs listed above, we are investigating the ability of CLM-CN 4.0 and CLM-CN 4.5 to simulate observed biomass, GPP, evapotranspiration, litterfall, soil respiration and LAI. In conjunction with the DOE-BER C-climate feedbacks project, we are developing a multivariate global benchmarking product that can be used to calibrate and validate TES SFA-inspired model structural developments efficiently. We are also beginning to extend the efficiency improvements implemented in PTCLM to regional simulations, which will expedite these analyses greatly.

Table 4. Task 3b Deliverables

Date	Deliverable	Status
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 - Completed - Completed
2014	- Complete CLM-CN global parameter sensitivity analysis - Document global data assimilation approach for CLM-CN and its integration with high-end computing resources	- Underway - Underway

Task 3c – Earth system model process integration and evaluation

This task is now tightly integrated with the newly initiated ACME project, in which several TES SFA investigators are also participating. There is also a strong connection with the C-climate feedbacks project, focused on benchmarking and evaluation. The purpose of this task is not to duplicate the efforts of these projects, but to engage these efforts to evaluate MODEX-inspired model developments efficiently. We anticipate selected TES SFA model developments will become part of the standard ACME release, and we also expect to integrate ACME changes into the TES SFA on at least an annual cycle. TES SFA efforts will be focused on single point, regional and global offline model UQ and evaluation rather than fully coupled simulations that will be led by ACME. UQ methodology and workflow development are supported by ACME, and in the TES SFA we will focus on applying these methods to evaluate hypotheses about model structure.

We are continuing to provide model output and work on manuscripts related to the NASA-funded Multiscale Terrestrial Model Intercomparison Project (MsTMIP). Participation in MsTMIP has led to important collaborations and model evaluations that have aided other DOE-relevant model development activities. The TES SFA is contributing simulations from three models out of the twenty in the intercomparison. Global simulations have been submitted for CLM-CN 4.0, GTEC, and TEM and several publications coauthored by TES SFA investigators Hayes, King, Mao, Ricciuto, Shi, are in review or accepted (Zscheischler et al., 2014; Wei et al., 2014). In FY2014, we are performing higher-resolution MsTMIP simulations for North America. We are working on manuscripts on evaluating MsTMIP modeled biomass and CO_2 fertilization to be submitted in FY2015. Additionally, patterns of model-predicted evapotranspiration (ET) are also being analyzed and evaluated against a global gridded product being developed at ORNL through the C-climate feedbacks project. Using both MsTMIP and CLM-CN simulations, we are evaluating how model structure affects the attribution of changes in ET to different forcing factors (e.g., climate, land use change, CO_2 fertilization and nitrogen deposition).

A major effort is continuing to integrate the dynamics of the phosphorus cycle into the existing structure of CLM. Development of CLM-CNP is now quite advanced, and we already published site-level results (see task 3a). Regional and global offline CLM-CNP simulations are underway. Results for the application of CLM-CNP in the Amazon region were presented in an invited talk at the AGU Fall meeting in December 2013. A manuscript on this regional application is also being prepared. The global application of CLM-CNP is well underway, and we are expecting to publish the global scale results this year. This work has been supported by both the ORNL TES SFA and the C-Climate Feedbacks Project.

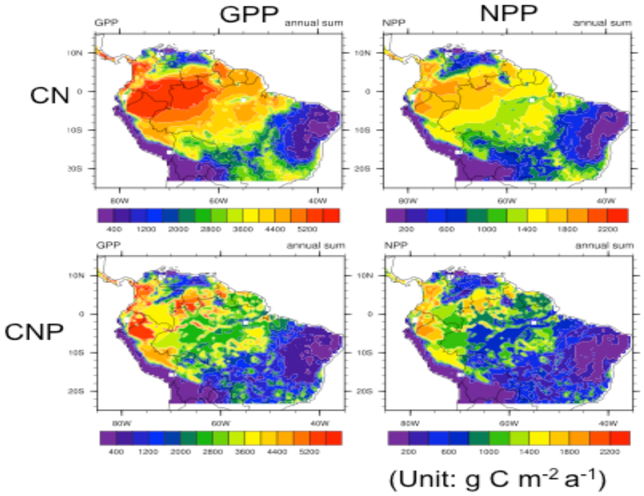


Fig. 19. Comparison of both average annual gross primary productivity (GPP) and net primary productivity (NPP) between CLM-CN and CLM-CNP beteween 2000 and 2009. Both fluxes are highly limited by P in much of the Amazon region.

Table 5. Task 3c Deliverables

Date	Deliverable	Status
2013	Compare offline historical simulations of CLM4 with the standardized remotely sensed products at various spatial-temporal scales. Submission of related manuscripts.	Completed
2014	Evaluate transient simulations of fully coupled CMIP5 models and MsTMIP outputs against remotely sensed products at various spatial-temporal scales. Submission of related manuscripts.	Underway

Note that task 3d (integrating land-surface model constraints with inverse modeling) was redirected in FY2013 to support development of the functional testing framework (now part of task 3a). Details were provided in the FY2013 annual SFA report.

Task 4: Partitioning in Trees and Soil (PiTS)

The Partitioning in Trees and Soil (PiTS) task was established with the objective of improving the C partitioning routines in existing ecosystem models by exploring mechanistic model representations of partitioning tested against field observations. We used short-term field manipulations of C flow, through $^{13}CO_2$ labeling, canopy shading and stem girdling, to dramatically alter C partitioning, and resultant data are being used to test model representation of C partitioning processes. A key feature of this task is the atypical tight MODEX interaction between ORNL modeling (J. Mao, D. Ricciuto, P. Thornton, A. King) and empirical scientists (R. Norby, C. Iversen, J. Warren) 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). Regular and ongoing MODEX meetings are assessing CLM simulation results from PiTS-1 and have included discussion of potential issues related to failure of the model to adequately represent experimental results. One issue that has arisen is related to data collection – the modelers have indicated a desire for additional experimental data replication, and data from conditions that are not normally encountered in the field –

data with extreme endpoints – e.g., photosynthetic light response curves that include radiation values that are much greater than saturated conditions – data that experimentalists typically don't collect. These MODEX interactions have thus led to new field campaigns to collect additional data. J. Mao has led development of a PiTS-1 modeling manuscript (nearing completion), and will begin focus on the similarly structured, yet improved PiTS-3 (dogwood shading) field site upon manuscript submission.

The PiTS-2 (girdling sweetgum) project was conducted at the former free air CO_2 enrichment study (ORNL FACE). PiTS-2 field data have been fully collected, including soil water dynamics, soil CO_2 efflux, root production, $^{13}CO_2$ ratios in fine roots, non-structural carbohydrate (NSC) pools have been quantified across root classes and in trunk phloem. Substantial drawdown of girdled tree root starch reserves was observed especially in larger diameter roots (Fig. 20).

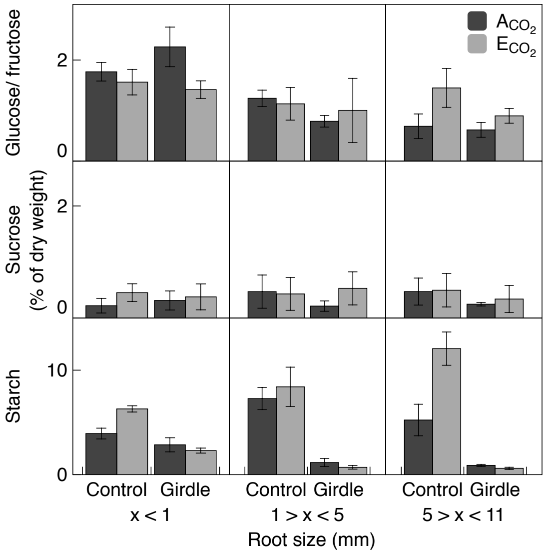


Fig. 20. Concentrations of soluble sugars (glucose, fructose and sucrose) and starch by root size in sweetgum grown under ambient (A_{CO2}) and elevated (E_{CO2}) CO_2 concentrations. Samples were collected 1.5 years after the trees were girdled (mean ± 1SE, n = 3-4).

Field data from PiTS-2 will be incorporated into a manuscript this year in collaboration with PhD. student Doug Lynch at the University of Illinois – Chicago, who had previously been working with ORNL and Argonne National Lab on root respiration and production dynamics following shutdown of the FACE site. Results will be used to simulate observed C partitioning dynamics following girdling by Anthony Walker, a post-doctoral modeler hired to work on PiTS and the Root Functioning Task. As part of his PhD program at University of Sheffield and continued involvement in the FACE Model-Data Synthesis (FACE-MDS) project. Anthony has modeled the ORNL FACE site and compared various earth system model outputs for the site (Walker et al. 2014); thus for this site we are starting from a strong parameterized framework to extend a girdling capacity into CLM4. Initial 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 amenable to MODEX efforts to test mechanistic model performance.

At PiTS-3, the experimentalists have been collecting additional field data in FY13 to fulfill the needs of the modelers – especially increased seasonal replication of foliar gas exchange. A large amount of automated data have 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. 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. Model simulations of C partitioning at PiTS-3 will begin later this year. Results provide insights of mechanistic processes not well refined in the models and will lead to improvements in model representation of C partitioning processes. The PiTS projects have been very successful in developing new relationships within the SFA group and addressing a key limitation in CLM and other terrestrial biosphere models. There is strong continued interest in C partitioning (especially belowground) among the ORNL PiTS group will be bolstered by the Fall 2015 arrival of joint UT-ORNL NIMBios postdoctoral fellow (Caroline Farrior of Princeton) interested in application of game theory to plant allocation dynamics. As such we hope to continue our carbon partitioning focus into the next 3 year funding cycle, as well beginning application of the MODEX framework to our developing belowground/ root function tasks. Future efforts will use knowledge gained from the three PiTS field studies, and the insights into model function and failure from the simulation efforts to determine new MODEX avenues to pursue.

Table 6. Updated Progress on Task F2 Deliverables continuing through FY2015.

Date	Deliverable	Status
May 2013	Simulations of PiTS-1 site using CLM4 completed using observed driver meteorology and ^{13}C data.	Completed
June 2014	Collect additional seasonal experimental data as requested by the modelers during MODEX interactions	Ongoing
Aug 2014	Complete manuscript detailing CLM4 modeling for PiTS-1	Planned
Oct 2014	Finalize data analysis and manuscript preparation for the PiTS-2 field study. Construct model framework for simulating girdling in PiTS-2 and begin PiTS-3 simulations.	Planned
Jan 2015	Finalize data analysis and manuscript preparation for the PiTS-3 field study. Complete PiTS-2 and -3 simulations	Planned
Mar 2015	Submit data to ORNL TES SFA data archive for public release concurrent with publication of PiTS-2 and -3 data manuscripts.	Planned
Jun 2015	Manuscripts from PiTS-2 and -3 modeling studies submitted for publication.	Planned

Task 4a. Integrating Root Functional Dynamics into Models

Root functional dynamics remain noticeably absent from the land component of global circulation models such as CLM, most of which have limited, or no ability to represent spatial or temporal biogeochemical, carbon and water fluxes in context of root traits, such as biomass. Plant nutrient and water uptake and C release to the soils are thus independent of most root traits – often based solely on demand or site characteristics such as soil depth. This task was designed to assess and improve representation of root functionality within terrestrial biosphere models (especially CLM) 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 deemed necessary. Model development work will be used to design and direct a paired empirical research program to provide targeted data for validation and parameterization of the new elements within CLM4.5.

The root functioning team has had periodic meetings since 2012, discussing the state of the science, and considering various pathways forward in context of the broader goal of improved ‘belowground functioning’ in the models. We have a diverse and interested group of plant, soil and hydrological modelers, physiologists and ecosystem ecologists and data managers. A subset of the group has developed a comprehensive manuscript for the distinguished New Phytologist Tansley Review Series entitled: *Incorporation of Root Structure and Function into Models – Review and Recommendations*. The manuscript reviewed well and is currently under revision. Key findings illustrate the lack of mechanistic detail across models (Fig. 21), with few models that consider such essential processes as Michaelis-Menten nutrient uptake kinetics, hydraulic redistribution of soil water, or root mycorrhizal associations – all crucial components that regulate root function. Scaling root function was another central tenant of the review, and describes a path forward to scale mechanistic root functions, through traits, for application in terrestrial biosphere models (Fig. 21).

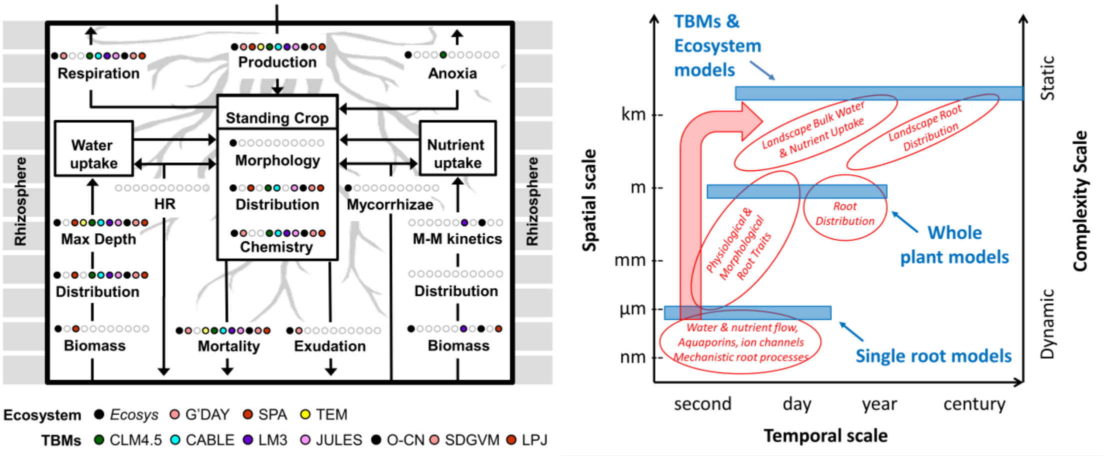


Fig. 21. (Left) Presence or absence of root related functions in ecosystem and terrestrial biosphere models, and (Right) potential to scale mechanistic root process knowledge through root traits to those models.

A variety of different recommendations emerged from the study, including development and utility of functional modules that deal with specific model processes, pairing detailed root data (e.g., minirhizotron-sourced root dimensions and distribution) with soil water extraction patterns in reactive transport models such as PFLOTRAN, and the need for additional sensitivity analysis to determine if inclusion of additional root processes in models would improve the outcome. These three tasks have been initiated with the leadership of modelers A. Walker, D. Wang, J. Kumar and D. Ricciuto, with direct ongoing interactions with empiricists C. Iversen and J. Warren.

The ORNL root functioning group has led and participated in a number of internal ORNL and DOE-sponsored workshops focused on roots and belowground process representation in models. Most recently, C. Iversen organized and hosted a successful workshop on: ‘Improved Representation of Roots in Models’ to engage the broader community of top root ecology scientists in context of how current knowledge of root traits, physiology, distribution and root-soil interactions might be applied to model improvement. Supplemental funding has allowed Colleen Iversen to pursue creation of a much needed root trait database, one of the key discussion points during the workshop, which will provide a tremendous resource to current and future model development efforts that consider the utility of including more mechanistic belowground process representation in the models. We expect to continue and expand our efforts in these arenas during FY15 and for the next 3-year funding cycle.

Task 5: Fundamental Soil Carbon Cycle Process Studies

We identify and target critical uncertainties in coupled climate and terrestrial ecosystem processes and feedbacks, namely, microbial-mediated decomposition of soil organic carbon (SOC), sorption and desorption of depolymerized dissolved organic carbon (DOC), C-cycling rates in measurable soil pools, and updating controls on biochemical recalcitrance. 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 GS 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

We completed the publication of the year-long lab-scale incubation experiments (Jagadamma et al. 2013ab, 2014), and the archiving of the data products on ORNL’s TES-SFA data website. These experiments involved four substrates and five soils, using both bulk soils and separate fractions consisting of particulate carbon (sand-sized) and mineral-associated carbon (silt- and clay-sized). We found that for simple substrates such as glucose and starch, a 3-pool model was needed to model assuming first-order decomposition, while for native SOC and more complex substrates such as cinnamic acid and stearic acid;

a 2-pool first-order model was sufficient. Further, the more complex substrates induced priming of native SOC and also enhanced the proportion of fungi over bacteria. Additional modeling, i.e., beyond first-order assumptions, occurs using the MEND model.

MEND was parameterized using these experiments, where calibration targets included native CO_2 fluxes, $^{14}CO_2$ fluxes from substrate additions, dissolved organic carbon (DOC), and microbial biomass carbon (MBC). Although we started this process last year and initial results were promising, we found that for most soils, calibration of the DOC and MBC pools was difficult beyond 30 days. Over longer time frames, change in CO_2 fluxes as a function of time tended to decrease, and the model was unable to match observations of MBC (Fig. 22). We concluded that large proportions of the microbial community became dormant over time, and we developed a new microbial physiological model to account for dormancy (Wang GS et al. 2014a). This concept is consistent with numerous observations in the literature. Subsequently, the microbial physiology model and the MEND model were united in a new model and tested against the lab-scale incubation data ((Wang GS et al. 2014b; Fig. 22). In addition, another research group tested our original MEND model against other models (Li et al. 2014).

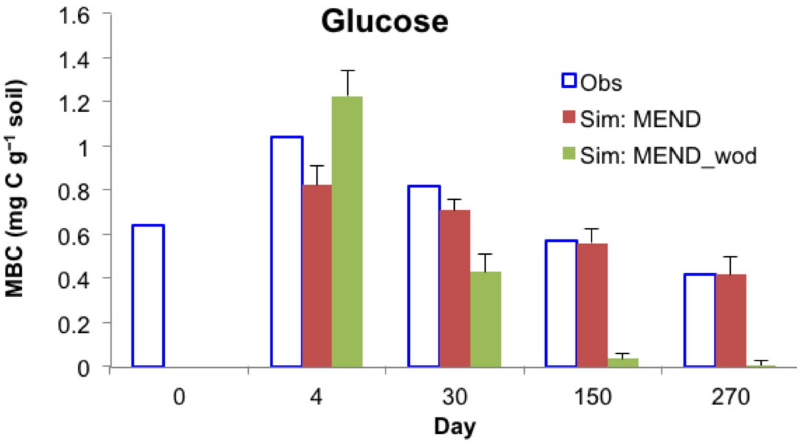


Fig. 22. Microbial biomass carbon (MBC) in the Mollisol incubation experiment, as observed and simulated with MEND and MEND without dormancy (MEND_wod). Source Wang GS et al. (2014b).

Linking MEND with CLM in BER's ACME Model

The MEND model will be included in future development of the CLM model under the aegis of the Accelerated Climate Model for Energy (ACME) funded through BER's Earth System Modeling Program. Postdoctoral researcher Gangsheng Wang, the primary modeler on this project, was hired as ORNL staff and will work approximately 60% of his time for model development and testing, of which MEND will be one part.

Carbon Use Efficiency (CUE) - Model simulations found that CUE is a critical parameter, and when allowed to fluctuate according to temperature, substantial differences are observed compared to simulations using a constant CUE. We conducted preliminary investigations to measure short duration CUE measurements. Two recent open-literature publications caused us to stop working in this area – (Li et al.2014) identified substrate-specific CUE in lab-scale experiments, and (Dijkstra et al. 2011) use a modeling approach to determine that CUE should be calibrated to be around 0.3. Thus, we chose not to use TES resources to duplicate published findings and concepts, which resulted in a re-assignment of this milestone.

Although we aborted the CUE experiments, we reported the calibrated true growth yield (YG) and its temperature dependence in the ISME paper (G. Wang et al. 2014b). Note that the constant "true growth yield (YG)" is also called "intrinsic CUE" in our study, which is different from the CUE definition of (Dijkstra et al. 2011). The relation between YG and CUE can be described as (Frey et al. 2013):

$$\frac{CUE}{Y_G} = \frac{\mu_m \cdot g(s)}{\mu_m \cdot g(s) + m_R}$$

where μ_m and m_R are the maximum specific growth rate and the specific maintenance rate, respectively; and g(s) is a function of the substrate concentration (s), e.g., $g(s) = s/(s+Ks)$, where Ks is the half-saturation constant.

The above equation indicates that CUE < YG. Dijkstra et al. (2011) suggested that CUE should be around 0.3, and our MEND calibration results showed that YG had a mean value of 0.56 with 95% confidence interval of 0.48–0.64.

Our results showed the dependence of true growth yield (YG) on the changes in temperature (ΔT), where ΔT is the difference between incubation temperature (20 ºC) and the mean annual temperature (MAT). YG decreased with increasing ΔT from 0.7 to 22.9 ºC. The temperature response coefficient for YG (i.e., the regression slope) was approximately −0.01 ºC−1 with 95% CI of (−0.016, −0.005) ºC−1, which comprises previous experimental estimates.

Proxies for Microbial Biomass Carbon

As discussed last year, accurate soil microbial biomass carbon (MBC) estimates are difficult to obtain, but their importance is increasing with the incorporation of more microbial parameters in ecosystem models (Wang GS et al. 2014ab). Currently most estimates of MBC come from chloroform fumigation-extraction, which requires toxic reagents, is time consuming and accuracy depends on the soil type. We hypothesized that gene copy number derived from quantitative PCR (qPCR) 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. Although others have compared methods for estimating soil biomass, the studies occurred prior to the development of qPCR (Bailey et al. 2002), or were focused on a single soil type (Leckie et al. 2004; Buckeridge et al. 2013) or organism type (Baldrain et al. 2013; Landewert et al. 2003). Since last year, we more than doubled the amount of soils involved in this research, from 15 to around 40. DNA extraction and qPCR for 16S bacteria, 18S fungi, and 16S archaea were used to determine gene copy numbers for each of the three groups and their relationship to chloroform fumigation extraction MBC estimates. We also incorporated comparisons of additional microbial abundance measures including direct cell counts of fungi and bacteria and phospholipid fatty acid analyses. Understanding the quantitative relationships between these four measures of microbial abundance in a variety of soil types should prove valuable to expanding data sets that can be modeled. Data collection on this portion is complete and the paper is in prep. New deliverable and new target date is 09/14.

Short-term decomposition experiments for model validation.

During model calibration (Wang GS et al. 2014ab), we found that new experiments should include both much shorter (< 4 days) and much longer (>1 year) timeframes than typically employed to ensure greater accuracy. We also identified the need to have much more replication of MBC and DOC data, and to use more “representative” and more “recalcitrant” substrates such as lignin and cellulose. Finally, we wanted to use soils that are connected to more comprehensive field-scale campaigns that will enable better model calibration in the future. Thus, we planned a new set of experiments using 13C cellulose and glucose, with much greater resolution over both short and long timeframes, using soils from NSF’s NEON or LTER sites. Thus, a new deliverable is planned for 5/15 involving the short-term experiments. We will also initiate work for long-term experiments.

Future work

New activities for the next review cycle will involve the long-term decomposition experiments and model calibration using both short- and long-term decomposition experiments. We will conduct a literature review, and/or use an existing database, to identify additional data that can be used for model calibration. We will conduct a set of lab-scale incubations on SPRUCE site materials using new capabilities for simultaneous detection of CO_2, CH_4, O_2, H_2 and H_2S, which will enable testing of our model (once incorporated with CLM) against field-scale observations in these unique organic and saturated soils in the next review cycle.

Table 7. Task 5 Soil Carbon Cycle Process Studies Future Deliverables

Date	Deliverable	Status
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
May 2015	"Short-term decomposition experiments for model validation"	In Progress
Sep 2015	MEND is linked with CLM and tested against existing CLM model	In Progress

Task 6: Terrestrial impacts and feedbacks of climate variability, events and disturbances (aka MOFLUX and associated activities)

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 carbon 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 for process understanding and model testing,
- new process representation suitable for implementation in Earth System Models, and
- tools for parameterization identification and demonstration of model performance improvement.

Since July 2013, Task 6 research has resulted in seven peer-reviewed papers published in leading national and international journals (including one featured in the cover of *Plant Cell and Environment*), at least two accepted papers, and at least three manuscripts in preparation.

We do not keep track of national or international publications that use Task 6 data. Task 6 scientists do not request to be coauthors of these publications unless significant intellectual contributions have been made, in addition to data contribution.

MOFLUX site operations

MOFLUX data have been submitted to AmeriFlux data management on a regular and timely basis. Data for the previous full year 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. External demands for the comprehensive MOFLUX measurements have continued to increase.

LeafWeb

Task 6 supports the operation of LeafWeb, which continues to serve the worldwide community of leaf photosynthesis for data analysis and provides comprehensive parameter support for regional and global terrestrial C cycle models (leafweb.ornl.gov).

To date LeafWeb has accumulated tens of thousands of A/Ci curves. Collaboration with the TRY plant trait database is now under discussion. Dr. Jens Kattge, the TRY PI, visited ORNL in June 2014 to discuss collaboration between TRY and LeafWeb. The first synthesis paper based on data gathered through LeafWeb is now published in Plant Cell and Environment (Sun et al. 2014). This paper was featured in the cover of the April 2014 issue of this journal.

Task 6 Selected scientific findings

1. LeafWeb global synthesis paper points to major importance of mesophyll conductance for photosynthesis (Sun et al. 2014). The objective of this study was to use the worldwide datasets gathered by LeafWeb to determine the effects of CO_2 diffusion inside leaves, i.e., mesophyll conductance, on photosynthesis across all major plant functional types and climates. Worldwide measurements of nearly 130 C_3 species covering all major plant functional types are analyzed in

conjunction with model simulations to determine the effects of mesophyll conductance (g_m) on photosynthetic parameters and their relationships estimated from A/C_i curves. We find that an 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. Due to this asymmetrical effect of g_m, the ratios of J_{max} to V_{cmax}, T_u to V_{cmax}, and T_u to J_{max} are all overestimated. An infinite g_m assumption also limits the freedom of variation of estimated parameters and artificially constrains parameter relationships to stronger shapes. These findings suggest the importance of quantifying g_m for understanding in-situ photosynthetic machinery functioning. We show that a nonzero resistance to CO_2 movement in chloroplasts has small effects on estimated parameters. A nonlinear function with g_m as input is developed to convert the parameters estimated under an assumption of infinite g_m to proper values. This function will facilitate g_m representation in global carbon cycle models. The findings of this study will lead to better understanding of photosynthetic processes under natural conditions and development of better global carbon cycle models. They show that a virtual laboratory like LeafWeb is a cost effective, efficient tool for promoting international collaboration, collecting spatially distributed datasets of global importance, and conducting synthesis research that would otherwise be difficult to carry out.

2. Improving methods for measuring mesophyll conductance and photosynthesis isotope discrimination equation (Gu and Sun 2014). The objective of this study is to improve key methods for measuring mesophyll conductance and the equation for predicting photosynthesis carbon isotope discrimination. We have identified deficiencies in the chlorophyll fluorescence-based (i.e., variable J) and carbon isotope-based (i.e., online carbon isotope discrimination) methods for measuring mesophyll conductance and proposed effective solutions accordingly. In addition, we have derived a new photosynthesis carbon isotope discrimination equation that considers multiple sources of CO_2 for carboxylation. Studies with the variable J method have reported that mesophyll conductance (g_m) rapidly decreases with increasing intercellular CO_2 partial pressures (C_i) or decreasing irradiance. Similar responses have been suggested with the online isotope discrimination method, although with less consistency. Here we show that even when the true g_m is constant, the variable J method can produce an artifactual dependence of g_m on C_i or irradiance similar to those reported in previous studies for any of the following factors: day respiration and chloroplastic CO_2 photocompensation point are estimated with Laisk method; C_i or electron transport rate is positively biased; net photosynthetic rate is negatively biased; insufficient NADPH is assumed while insufficient ATP limits RuBP regeneration. The isotopic method produces similar artifacts if fractionation of carboxylation or C_i are positively biased or $\Delta 13$ negatively biased. A nonzero chloroplastic resistance to CO_2 movement results in a qualitatively different dependence of g_m on C_i or irradiance and this dependence is only sensitive at low C_i. We thus cannot rule out the possibility that previously reported dependence of g_m on C_i or irradiance is a methodological artifact. Recommendations are made to take advantage of sensitivities of the variable J and isotopic methods for estimating g_m. This study shows that mesophyll conductance is crucial for understanding and predicting responses of photosynthesis to the increase in atmospheric CO_2 concentrations. Our improvement of key methods for measuring mesophyll conductance will improve photosynthesis and carbon cycle modeling. Additionally, photosynthesis carbon isotope discrimination is the foundation for the terrestrial carbon isotope ecology. Our improvement of the photosynthesis carbon isotope discrimination equation will facilitate the application of carbon isotopes in studying ecological processes.

3. Precipitation variability affects species and community water stress in a central US forest. Soil water availability and thus plant water stress in natural conditions are affected by not only precipitation amount but also precipitation variability. Precipitation variability (PV) is determined by the distribution of precipitation intensities among the precipitation events (intensity distribution) and by the spacing of precipitation events along the time axis (event spacing). A major hurdle for the study of the direct effects of precipitation variability on plant water stress has been a lack of a satisfactory measure that can simultaneously capture the characteristics of both intensity distribution and event

spacing of PV. Here we propose a Precipitation Variability Index (PVI) that overcomes this hurdle. We use nearly decade-long measurements of predawn leaf water potential integral (PLWPI) at the Missouri Ozark AmeriFlux site to evaluate the effectiveness of PVI in relating PV to plant species and community water stress. We show that PVI and the mean precipitation rate jointly and sufficiently determine inter-annual variations in PLWP for all species investigated, indicating their effectiveness in quantifying the impacts of precipitation regimes on species and vegetation community water stress. Furthermore, we show that the sensitivities of species water stress to variations in precipitation regimes are reflected more in their responses to PVI than to the mean precipitation rate. We suggest that PVI should be adopted as a key index in quantifying the ecological and physiological impacts of precipitation regimes.

Table 8. Task 6 Deliverables

Date	Deliverable	Status
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.	Completed
FY2014	1. Complete and submit the manuscript ‘The impacts of precipitation variability on species and community water stress in a central US forest’ to Global Change Biology 2. Complete and submit the manuscript ‘The impacts of precipitation variability and drought on ecosystem carbon uptake and water use in a central US forest’ to Global Change Biology	Underway
FY2015	1. Complete and submit the manuscript ‘The impacts of precipitation variability and drought on tree species and community mortality in a central US forest’ to Global Change Biology 2. Complete and submit the manuscript ‘The impacts of precipitation variability and drought on leaf area display in a central US forest’ to Geophysical Research Letters or Environmental Research Letters.	Underway
March 2015	Submit 2014 MOFLUX data to AmeriFlux	Underway
Beyond 2015	Once the USFS completes the installation of the planned tower at the Bog Lake Fen Site in the Marcell Experimental Forest, we will instrument the eddy flux observation system for methane, carbon dioxide, sensible heat and latent heat.	Planned work

Task 7: Fossil emissions

Fiscal year 2014 has seen continuing efforts within Task 7 toward maintaining and improving a publicly available data base on carbon dioxide emissions from fossil fuel consumption, examining and confronting the uncertainty in emissions estimates, and utilizing the carbon dioxide emissions database in terrestrial carbon budgets. Recent efforts include annual and monthly emissions data by country through 2010 which are available online (processing of 2011 data should begin soon, CDIAC is waiting for final data from the United Nations); compilation of preliminary annual estimates, by country, through 2012; and significant strides in characterizing the uncertainty associated with carbon dioxide emissions from fossil fuel consumption.

A peer-reviewed manuscript on global uncertainty characterization is accepted in Tellus B and another manuscript describing the uncertainty with the gridded emissions product is nearing completion. Andres continues to play a prominent role in Global Carbon Project activities, including the Global Carbon Atlas (http://www.globalcarbonatlas.org) released at the November 2013 UNFCCC COP in Warsaw, which had more than 24,000 unique, visits from 164 countries in the first week after release. Andres was a contributing author to the IPCC AR5 WGIII report Chapter 5 on Drivers, Trends and Mitigation that will be published soon. Andres is also contributing to the Carbon Model Intercomparison Project (CMIP6) activities now a being initiated.

Table 9. Future Task 7 Deliverables

Date	Deliverable	Status
FY2013	Publication on uncertainty estimates associated with emissions	On schedule. First manuscript accepted, second manuscript nearly ready for peer-review.
FY2013-2015	Monthly emission inventories at the scale of states and months at a global scale	On schedule. Emission year 2010 complete, 2011 to begin soon.
FY2013-2015	Generation of annual and monthly distributions of global emissions	On schedule. Emission year 2010 complete, 2011 to begin soon.

In Table 9 - Item 1, the current uncertainty focus is in transition from national and global totals (manuscript accepted for publication) to annual 1-degree latitude by1-degree longitude scales (manuscript nearing submission stage). 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 three peer-reviewed publications and nine presentations produced since the 10 July 2013 progress report). Fig. 23 shows the results from one study where uncertainties from fossil fuels are compared to other major components in the global carbon cycle.

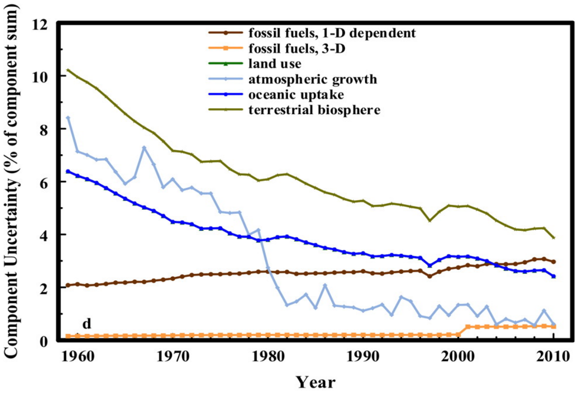


Fig. 23. Fossil fuel carbon dioxide compared to other global carbon cycle components. One σ uncertainty, expressed in percent of total carbon cycle flux and reservoir stock changes. 1-D dependent and 3-D are respectively the maximum and minimum uncertainty analysis results. The land use curve lies directly under the oceanic uptake curve.

For FY2015 and FY2016, Task 7 plans to continue annual updates of fossil fuel carbon dioxide emissions and provide high quality input to global carbon 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 completed design, installation, and testing of data systems for data acquisition from experimental plots and for site telecommunications and data storage. Design work continues for transferring data to ORNL for project access and analyses. 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. Automated data acquisition, data storage, and remote data access was implemented in 2014 for the environmental monitoring stations. 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). New project-available data are large-collar *in situ* CO_2 and CH_4 flux data, and the physical and chemical characteristics of peat from experimental plot cores collected in 2012. Publically and project-only available data, the Data Policy, and Data Management Plans are available on the SPRUCE web site: http://mnspruce.ornl.gov/.

Results of recent lab-scale experiments conducted to investigate the dynamics of organic carbon (C) decomposition from several soils from temperate, tropical, arctic, and sub-arctic environments

(Jagadamma, et al. 2014) and to test the newly developed soil microbe decomposition C model -- Microbial-ENzyme-mediated Decomposition (MEND) 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 data collection may not be the first archive for generated data products, but the TES-SFA 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 JULY 2013

- ORNL TES SFA staff completed 40 articles and 7 book/proceedings chapters since July 2013.
- Lianhong Gu and colleagues have produced a sequence of manuscripts on the importance of capturing foliar mesophyll conductance correctly in ecosystem and global models to better quantify future C cycles (Gu and Sun 2014, Sun et al. 2014ab).
- Wang et al. (2014b) found that dormancy of the microbial community should be considered in organic C decomposition in lab-scale experiments. They coupled a new microbial physiology model that considers dormancy with the Microbially-mediated ENzyme Decomposition (MEND) model. A coupled physiology-decomposition model was successfully tested against lab-scale incubation experiments from Jagadamma et al. (2013b, 2014).
- Initial pretreatment analysis and characterization papers for SPRUCE are being produced and published (Tfaily et al. 2014, Lin et al. 2014ab, Hanson et al. and Jensen et al. in review).
- Xiaojuan Yang and colleagues parameterized and validated the new CLM-CNP model, which includes phosphorous cycling, at several tropical sites (Yang et al., 2014). The model accurately captures P-limitation along a soil chronosequence and is a significant structural advance over CLM-CN. CLM-CNP is currently being evaluated in regional and global simulations.
- The C-Cycle modeling task iterates closely with the TES SFA experimental groups on SPRUCE and PiTS and has produced an improved CLM hydrologic model (Shi et al. in preparation) and as begun to incorporate fundamental plant carbon allocation improvements from the PiTS studies and relevant external efforts.
- In FY2014, TES SFA staff produced a comprehensive review of the status of root characteristics and function within ecological models (Iversen 2014; Warren et al. 2014) and planned and participated in three different workshops to better define future belowground research (reports pending).
- Robert Andres continues to work with CDIAC and various global C-Cycle working groups to provide quality and spatially explicitly fossil emission data for those efforts (Francey et al. 2013ab; Le Quere et al. 2013; Maksyutov et al. 2013; Nassar et al. 2013; Oda et al. 3013; Potosnak et al. 2014; Saeki et al. 2013ab and archived data sets).
- In June of 2014 we initiated the Deep Heat Peat experimental system to characterize the temperature sensitivity of ancient peatland carbon to warming while conducting pre-whole-ecosystem warming evaluation of belowground infrastructure.
- As of June 2014, the Root and Rhizosphere processes team is able to communicate remotely with all twelve automated minirhizotrons in the SPRUCE bog. Initial observations allowed by this state-of-the-art technology that were not previously possible with manual minirhizotron technology indicate that fungal hyphae are shallowly-distributed in the bog and overwinter with little growth activity, and that there are an unexpected number of external fungal hyphae associated with ericoid shrub roots.
- TES SFA partial support allowed Paul Hanson, Richard Norby, Anthony Walker, Colleen Iversen and Jeff Warren to contribute to three new manuscripts summarizing the ORNL-Duke FACE model-data synthesis project. The papers from the FACE project pioneered the application of the MODEX approach to multi-model intercomparisons, evaluating the underlying model assumptions rather than the models per se. Compensating biases and unintended consequences of

some modeling assumptions were uncovered in process related to nitrogen cycling, allocation and LAI. Papers: DeKauwe et al. 2014, Walker et al. 2014, Zonke et al. 2014.

- Griffiths and Hill (2014) examined the contribution of a dominant consumer to stream nutrient cycling. The consumer was a significant source of N via excretion (contributed >50% of stream water ammonium concentrations) but also a P sink (due to sequestration of P in tissues), suggesting these consumers contribute to ecosystem-scale P limitation.

4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff produced 53 publications since our last summary report (40 published or in press journal articles, 7 book/proceedings chapters, and 4 manuscripts in review). The journal papers target over 30 different journals including one article in review for the *Proceedings of the National Academy of Sciences* (Sun et al. 2012) and one article and a published correspondence in *Nature Climate Change* (Francey et al. 2014ab). Journals hosting more than two SFA publications in this annual cycle include: *Biogeosciences* (3), *Journal of Geophysical Research – Atmospheres (3), Journal of Geophysical Research – Biogeosciences* (3), *New Phytologist* (4) and *Plant, Cell & Environment* (3). Significant additional effort is also being placed on the characterization and archiving of TES SFA data and models and a new listing of such data set is appended at the end of this report.

Journal selection for publication 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

Some of the goals and milestones established for the TES SFA in FY2010 are still an active focus; especially in the area of the flagship SPRUCE experiment. Several activities have been completed and we have redirected effort accordingly. For example, following completion of the EBIS-AmeriFlux fieldwork, effort was transferred to the microbial enzyme focused studies of the soil C cycle. We have recently completed synthesis activities to assess belowground research needs and will be pursuing sensitivity analyses of ecological models to root functional traits as a prelude to additional proposed observational or experimental work in this area. After the SPRUCE infrastructure is completed and additional funds are available, the TES SFA will enhance efforts to leverage knowledge gained from past and ongoing process studies, manipulative experiments and ecosystem observations (e.g., SPRUCE, PiTS, belowground fundamentals, landscape fluxes, EBIS, and TDE) to improve ecosystem models. This enhanced effort will support model developments in the ACME project while we likewise expect software infrastructure improvements in ACME to benefit the TES SFA. The following specific future science goals have been identified and actions have been planned accordingly:

- Improved gross primary production modeling - We will apply new understanding of mesophyll diffusion, and nitrogen and phosphorous limitations on photosynthesis to improve the modeling of gross primary production in CLM.
- Improved terrestrial biosphere root module - We are developing a new terrestrial biosphere root module for CLM to support current and future belowground research activities.
- Improved simulations of hydrology and biogeochemistry at SPRUCE - We will integrate CLM-Wetlands with CLM-PFLOTRAN which is currently being used in the NGEE-Arctic project to produce spatially resolved simulations of the S1 Bog and surrounding uplands, explicitly representing flows within the bog.
- Ecological forecasting at SPRUCE - We will ingest the real-time data streams from SPRUCE with our model optimization framework to make automated, near-term predictions of ecological variables with CLM. These predictions will be used to test model hypotheses and assist in timing fieldwork by suggesting when to observe key variables and predicting transition points.

- Improved tree mortality module - We will test a new mortality prediction approach developed for the MOFLUX site for potential large-scale application with Oregon State scientists.
- MOFLUX observational data will be used to benchmark the CLM model in predicting forest ecosystem responses to drought and climate variability. From 2004 to 2014, the MOFLUX site has experienced a wide range of climate conditions from fairly wet to extreme drought years offering an exceptional opportunity to test CLM against climate extremes.
- Provide a more flexible software infrastructure for broad CLM-related scientific communities, including computer scientist, computational scientists, modelers, experimentalists, as well as observational dataset providers, etc. We will develop an interactive and comprehensive software structure exploration system for CLM components within DOE's new earth system models. We will develop a cloud-based, interactive CLM ecosystem function-testing platform with focus on the verification/ calibration and further mechanistic representations of biogeophyisical and biogeochemical processes. A cloud-based, Interactive CLM ecosystem functional testing platform for broad CLM Communities (with focus on BGC-process calibration and verification using site-based measurements) will be co-funded by ACME.

4C. NEW SCIENCE FOCUS AND IDENTIFIED KNOWLEDGE GAPS

Beyond FY2015, landscape CO_2, water, and energy dynamics observations will be expanded to new ecosystems. We plan to move the focus of the eddy flux research to the northern peatland ecosystems to better integrate with the SPRUCE experiment and provide critical CH_4 flux data to support CLM-Wetland model development. Fluxes of CO_2, water vapor, sensible heat, and CH_4 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 boardwalks and electrical service infrastructure for a new eddy covariance site has already been added to the S1-Bog. Future development will be initiated after the completion of SPRUCE experiment installations. Dr. Lianhong Gu will 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 process understanding, identification, model-component development and testing. Data will be provided real time to the TES SFA modeling research group for parameterization and benchmarking. The expanded landscape flux effort will be able to answer the following example science questions:

- What are the budgets of CO_2, water and CH_4 at daily, weekly, monthly time scales at this peatland site and associated uncertainties?
- How are the CH_4 budgets related to those of CO_2, water and energy at different time scales?
- How do climate variability and biological and ecological processes control the net ecosystem exchanges of CO_2, water and CH_4?

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, Jeff Chanton and colleagues have received new support from DOE BER for a second 3-year to study microbial ecology within SPRUCE. Their work extends our capabilities in this area.
- 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 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 their own support to study lichen responses to warming and elevated CO_2 within the SPRUCE experimental infrastructure.
- Dr. Adrian Finzi obtained DOE BER support to add high temporal resolution measures of CO_2 and CH_4 flux from the experimental plots that will include ^{13}C isotopic capabilities.
- Dr. Karis McFarlane, Tom Guilderson, Jennifer Pett-Ridge and colleagues have obtained LLNL-CAMS internal laboratory directed funds to work with SPRUCE to characterize the ^{14}C isotopic composition of gases emanating from the S1-Bog surface. Such data will help interpret the relative balance between old and new C sources impacted by the SPRUCE warming and CO_2 treatments.
- The carbon cycle modeling team continues to participate 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.
- Dr. Robert Andres was a contributing author to the IPCC AR5 WGIII report Chapter 5 on Drivers, Trends and Mitigation to be published soon.
- Xiaojuan Yang (and Richard Norby and Anthony Walker on FACE grants) have collaborated with the University of Western Sydney and INPA in Brazil on modeling projects which will strengthen ties to the tropics and specialists in P cycling.

5. STAFFING AND BUDGET SUMMARY

5A. FY2014 FUNDING ALLOCATION BY PROGRAM ELEMENT

FY2014 spending is summarized in Table 10. The listed amounts represent costs and commitments incurred through June 24, 2014. Total available funding for ORNL's TES SFA included $2,366K carryover from FY2013 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. Small amounts of new budget authorization provide through the TES SFA are managed as independent efforts and not pooled for management as a part of the total TES SFA budget ($35K through June 24, 2014).

Table 10. Budget expenditures by TES SFA Program Element through June 24, 2014. Total available funding in FY2014 is $10,406K including $2,366K of FY2013 carryover funds targeted primarily for SPRUCE infrastructure.

Task	Cost Through June 24, 2014 ($K)	Commitments Through June 24, 2014 ($K)	Remaining Funds June 24, 2014 ($K)
SPRUCE Science	1840	6	435
Carbon Cycle Model Interactions	597	0	137
MOFLUX	290	74	53
Process Studies (PITS, Root Function)	80	8	3
Soil C Studies	201	0	55
C Emissions	64	0	31
Postdoctoral Fellows & Students	243	151	20
Other Science	39	27	106
SPRUCE Infrastructure	486	58	256
SPRUCE – Construction	328	4425	8
Reserves	67	26	292
SFA Totals	**$4,235**	**$4,775**	**$1,396**

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 FY2014 we are directly funding the University of Missouri ($120K) 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. We are funding two Minnesota residents (John Latimer $51K; Keith Oleheiser, $40K) to provide part time support for ongoing SPRUCE field and laboratory research tasks.

Through the Oak Ridge Institute for Science and Engineering (ORISE) we have two subcontracts for the support of postdoctoral research associates working on the TES SFA including: Anthony Walker and Anna Jensen.

Infrastructure subcontracts in support of the SPRUCE project in FY2014 include funds and funding for SPRUCE electrical wiring ($96K) and final aboveground construction ($4317K), and leased space in Minnesota ($45K y^{-1}). Funding is also allocated to Lake Country Power to pay SPRUCE electrical costs for running experimental systems and computers and to heat and cool the S1-Building located nearby.

5C. PERSONNEL ACTIONS AND PROCEDURES IN FY2014

New Hires – New postdoctoral hires were put off in FY2014 as a consequence of the need to provide full funding for final construction contracts for SPRUCE. As planned, however, Dr. Natalie Griffiths was transitioned to a full-time ORNL staff position to take on leadership of the SPRUCE task on hydrologic change and dissolved organic C formation and transport. We have recently hired John Latimer to collect minirhizotron images seasonally for the duration of the SPRUCE experiment.

Anticipated Future Hires – Looking ahead to FY2015, and as the budget allows, the TES SFA plans to pursue hiring 2 to 4 new postdoctoral fellows to supplement full time staff positions in support of SPRUCE, Carbon Cycle modeling, and other process level work. We are also looking to provide partial support TES SFA support to transition Dr. Anthony Walker into a full time staff position.

Retirements and Releases – Dr. Anna Jensen will complete her postdoctoral appointment at ORNL under FY2014 funding.

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. New TES SFA staff members are commonly first 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 new 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, Dr. 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 staff with potential leadership qualities are identified and helped with career development

5D. NATIONAL LABORATORY INVESTMENT IN THE PROGRAM

ORNL has demonstrated 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.

In FY2014, ORNL provided the equivalent of $1000K staff support from internal funds to allow timely completion of the SPRUCE aboveground infrastructure in FY2014 and FY2015. Without this support that construction process would have been delayed pending the receipt of sufficient funds to cover the associated cost.

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) 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 have previously been 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. In FY2014, Melanie Mayes received funds for a Picarro Model G2508 analyzer for N_2O, CH_4, CO_2, NH_3 and H_2O measurements in air. The analyzer uses Cavity Ring-Down Spectroscopy (CRDS) technology, a time-based near-IR telecom laser measurement that quantifies spectral features of molecules in an optical cavity. The analyzer is coupled with 12 automatic flux chambers. The system has potential applications for process level work in both the laboratory and field for various TES SFA tasks. Melanie Mayes also received funds for the Columbus Instruments Micro-Oxymax respirometer, which is a lab-scale detection system for $O_2/CO_2/CH_4/H_2/H_2S$ measurements in air in up to 20 incubation flasks simultaneously. The system has potential applications for process level work in the laboratory, and in particular for investigating carbon cycling processes with low oxygen content.

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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