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

Climate Change Science Institute, Environmental Sciences Division, Biological Sciences Division
Oak Ridge National Laboratory

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Abstract

Understanding responses of ecosystem carbon (C) cycles to climatic and atmospheric change is the aim of the Terrestrial Ecosystem Science Scientific Focus Area (TES SFA). Improved predictive understanding of terrestrial ecosystems is the long-term motivation guiding our research. Overarching science questions are: (1) How will atmospheric and climate change affect the structure and functioning of terrestrial ecosystems at scales from local to global and from decadal to centuries? (2) How will fossil fuel emissions and terrestrial ecosystem processes, mechanisms, interactions and feedbacks control the magnitude and rate of change of atmospheric CO_2 and other greenhouse gases? (3) What are the climate change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of climate change impacts on ecosystem services and society? The proposed science includes large manipulations, C-Cycle observations, database compilation, and process studies integrated and iterated with modeling activities. The centerpiece of our climate change manipulations is the SPRUCE experiment testing multiple levels of warming at ambient and elevated CO_2 on the C feedbacks from a black spruce–*Sphagnum* ecosystem. Other TES SFA efforts aim to improve mechanistic representation of processes within terrestrial biosphere models by furthering our understanding of fundamental ecosystem functions, and their response to environmental change. The TES SFA aims to integrate experimental and observational studies with model building, parameter estimation, and evaluation to yield reliable model projections. This integrated model-experiment approach fosters an enhanced, interactive, and mutually beneficial engagement between models and experiments to further our predictive understanding of the terrestrial biosphere.

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Executive Summary

The TES SFA supports research to understand and predict the interaction of Earth's terrestrial ecosystems and climate, and to assess vulnerability of terrestrial ecosystems to projected changes in climate and atmospheric composition. The research is focused on how terrestrial ecosystems affect atmospheric CO_2 *and other greenhouse gases (e.g.,* CH_4*) and how the responsible ecosystem processes interact with climate and with anthropogenic forcing factors. Targeted experiments are conducted to quantify climate change responses and thus improve prediction of the effects of atmospheric and climatic change on ecosystems, their capacity to deliver ecosystem services, and the feedbacks from ecosystems to the atmosphere and climate. Other process research is targeted at accurately quantifying the exchange of* CO_2*, water vapor and energy between the atmosphere and land ecosystems through processes such as photosynthesis, evapotranspiration, net production and storage pools, autotrophic and heterotrophic respiration, disturbance, and land management practices. TES SFA research also includes efforts to provide community-benefiting analytical tools, to more accurately quantify uncertainty in anthropogenic emissions of* CO_2 *from fossil fuel burning and takes advantage of ongoing efforts to quantify historical, present-day, and anticipated future greenhouse-gas consequences of land use and land cover change. Fundamental processes controlling terrestrial vegetation function and change discovered by TES SFA tasks are used to improve mechanistic representation of ecosystem processes within terrestrial biosphere models.*

The TES SFA is developing capabilities for quantitative projection of future atmospheric greenhouse gas concentrations and ecological effects from environmental change, incorporating complex feedbacks and responses among terrestrial ecosystems, human activities, and Earth's climate system. Spatial and temporal analyses of terrestrial ecosystem responses through the use of tightly integrated engagement between models, manipulative experiments, and observations will provide robust and fundamental scientific results, syntheses and analyses to advance predictive understanding. This advance in quantitative scientific understanding is used to improve the representation of terrestrial ecosystems in advanced Earth System Models (ESM). The breadth and complexity of this undertaking requires the scientific and technical expertise of multidisciplinary scientists from a range of institutions, and is focused on delivering timely answers to questions of national importance. Quantitative, transparent and accessible science products produced by the TES SFA are available to decision-makers and stakeholders to evaluate and address climate change consequences. The TES SFA team's unique strengths in modeling, experimentation, and measurement are synergistically combined to answer pressing global change science questions. ORNL's powerful computation and informatics capabilities are available to support this vision of Earth System analysis. The TES SFA group focuses on interactions among the climate system, terrestrial ecosystem dynamics, biogeochemical dynamics, and land use change that are most suited to the team's current strengths and potential for near and long-term impact.

Overarching Science Questions

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

1. How will atmospheric and climate change affect the structure and functioning of terrestrial ecosystems at scales from local to global and from decadal to centuries?
2. How will fossil fuel emissions and terrestrial ecosystem processes, mechanisms, interactions and feedbacks control the magnitude and rate of change of atmospheric CO_2 and other greenhouse gases?
3. What are the climate change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of climate change impacts on ecosystem services and society?

Goals and Milestones

The TES SFA Science Plan addresses the following five research goals and associated long-term (5 to 10 year) milestones. Progress on recent (3-year) milestones is summarized in Section 2.

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

- 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 a key understudied ecosystem).

Goal 3: Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in terrestrial 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 ESMs.

Goal 4: Incorporate new findings on interannual and seasonal C and water dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and ESMs 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 focused on terrestrial ecosystem responses to environmental and atmospheric change and to climate change forcing modifications driven by terrestrial C-Cycle processes or influenced by structural features. Tasks included in TES SFA efforts to date are listed below with parenthetical identification of the goals that each addresses.

Task 1: Spruce and Peatland Responses Under Climatic and Environmental Change – SPRUCE (Goals 1 and 2).
Task 2: Synthesis of Walker Branch Watershed long-term monitoring (Goal 4).
Task 3abc: Mechanistic C-Cycle modeling (Goals 1, 2, 3, 4, & 5).
Task 4a: Synthesis of the Partitioning in trees and soils studies (PiTS; Goals 4 & 5).
Task 4bc: Root traits, root function and modeling – New Tasks (Goals 3, 4 & 5)
Task 5: Representing soil C in terrestrial C-Cycle models (Goal 3).
Task 6: Terrestrial impacts and feedbacks of climate variability, events, and disturbances (Goal 4).
Task 7: Fossil C emissions (Goals 1 & 5).
Task 8: LeafWeb data assimilation tool –New Task (Goals 2 & 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 ESMs of future climate and terrestrial response.

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

Approach

Developing robust parameter estimation procedures and reducing uncertainty through identifying and improving structural deficiencies in terrestrial C-Cycle models are accomplished through organized interactions among data collection, experimental manipulation, and model development at all temporal and spatial scales. Experiments and field observations are employed to better understand organismal responses to environmental and atmospheric changes from molecular through whole-plant responses to the integrated function of entire ecosystems. Our efforts are focused on unresolved ecosystem processes and understudied ecosystems subject to greater rates of change under projected climate futures. We use model-data assimilation and multivariate model benchmark evaluation in all aspects of the TES SFA's research program. The SFA uses a multi-model approach in all analyses since multiple models provide richer interpretations and more robust findings than analyses of any single model. Because CO_2 is the dominant forcing factor, we include research to quantify fossil fuel emissions, including their spatial and temporal distributions and associated uncertainties. Products of the TES SFA include primary research publications, synthesis activities (e.g., critical review papers, model-data intercomparisons, and international workshops), archived experimental and modeling data sets, and multi-scale model-data assimilation systems delivering analyses of climate change forcing and terrestrial organism responses appropriate for local-to-global analyses.

Highlights for the period January 2012 through February 2015

- We have produced 132 published, accepted or in press papers since January 2012 (Appendix A). Ten additional papers are being actively reviewed at the submission of this report.
- Initiated the SPRUCE Deep Peatland Heating treatments in June of 2014 for in situ evaluations of the impact of a variety of warming levels on deep peats ranging in age from 4000 to 7000 years. Whole-ecosystem warming and elevated CO_2 treatments for SPRUCE are projected to be underway in June 2015.
- Published or prepared manuscripts for publication on a number of important pre-treatment characterization studies of the *Picea*-*Sphagnum* peatland (Tfaily *et al.* 2014, Lin *et al.* 2014ab, Jensen *et al.* 2015, Hanson *et al.* 2015).
- Modified the hydrologic components of the Community Land Model (CLM 4.5) model to produce a viable wetlands form of CLM (Shi *et al.* 2015).
- Developed spatially explicit datasets and maps of soil phosphorus for initialization of global biogeochemistry models and a representation of phosphorus cycle dynamics for CLM, which is now being integrated into the Accelerated Climate Model for Energy (ACME) land model (Yang *et al.* 2013, 2014**).**
- Completed three Partitioning in Trees and Soils (PiTS) field experiments for which modeling is underway to improve representation of C flow through ecosystems.
- Tested Microbial ENzyme Decomposition (MEND) Model against lab-scale incubation data (Jagadamma *et al.* 2014a,b), and developed new formulations to account for microbial physiological changes as a function of time (Wang G *et al.* 2014a,b).
- Published a high impact *New Phytologist Tansley Review* article on the representation of root functional dynamics in models (Warren *et al.* 2015), and initiated new Root Traits and Root Function Tasks to address gaps in root knowledge and their representation in models.
- A new eddy covariance theory based on ecosystem oxidative ratio was developed (Gu 2013).

- Predictors and mechanisms of drought-influenced tree mortality were proposed and tested at the Missouri Ozark AmeriFlux (MOFLUX) site (Gu *et al.* 2015a).
- A series of three papers in PNAS and PCE established the importance and enabled the modeling of mesophyll conductance for global C-Cycle; the Farquhar photosynthetic C isotope discrimination equation has been updated (Sun *et al.* 2014a and b; Gu and Sun 2014).
- Published a new evaluation of the global fossil fuel emissions uncertainty (Andres *et al.* 2014), the first substantial work in this area in 30 years.
- Archived numerous data sets for continued use by TES SFA researchers and for ultimate distribution to open public access.
- The SPRUCE project infrastructure and institutional support have attracted 14 investigator-initiated projects with their own funding to expand the utility of this significant science investment.
- TES SFA investigators and research contributed to the successful completion of the IPCC AR5 and US Assessment process as authors and technical reviewers.

Table E1 – **Terrestrial Ecosystem Science SFA and USDA Forest Service Funded Participants for the period from January 2012 through February 2015.**

Robert J. Andres	ORNL Senior Research Staff Member
Deanne J. Brice	ORNL Technical Staff
Kelsey Carter	ORNL SPRUCE and PiTS technician (2013 to 2015)
Joanne Childs	ORNL Technical Staff
Ranjeet Devarakonda	ORNL Computer Technologist
Natalie A. Griffiths,	ORNL Associate Research Staff Member
Lianhong Gu,	ORNL Senior Research Staff Member
Paul J. Hanson,	ORNL Corporate Fellow
Daniel J. Hayes,	ORNL Associate Research Staff Member
Leslie A. Hook,	ORNL Associate Research Staff Member
Kevin Hosman,	Technical Staff – University of Missouri – Columbia
Jason Hubbart,	Professor – University of Missouri–Columbia
Kathy Huczko	ORNL Technical Project Manager
Colleen M. Iversen	ORNL Research Staff Member
Anna Jensen	ORNL Postdoctoral Research Associate
Anthony W. King	ORNL Senior Research Staff Member
Laurel Kluber	ORNL Postdoctoral Research Associate
Randall K. Kolka	USDA Forest Service Researcher
Misha Krassovski	ORNL Research Staff Member
John Latimer	ORNL SPRUCE Part-time field technician (2014 to present
Jiafu Mao	ORNL Associate Research Staff Member
Melanie A. Mayes	ORNL Research Staff Member
Karis J. McFarlane	Lawrence Livermore National Laboratory - Scientist
William Robert Nettles	ORNL SPRUCE Site Manager and Technologist
Richard J. Norby	ORNL Corporate Fellow
Keith Oleheiser	ORAU SPRUCE Full-time field & lab technician (2013-2015)
Todd Ontl	ORNL SPRUCE Part-time field data collection technician (2012)
Cassandra Ott	University of Tennessee Graduate Student
Brian Palik	USDA Forest Service Researcher
Stephen G. Pallardy	Professor, University of Missouri – Columbia
Jana R. Phillips	ORNL Technical Staff
Wilfred M. Post	ORNL Distinguished Research Staff Member
Daniel M. Ricciuto	ORNL Research Staff Member
Christopher W. Schadt	ORNL Senior Research Staff Member
Stephen D. Sebestyen	USDA Forest Service Researcher
Xiaoying Shi	ORNL Associate Research Staff Member
Jessica M. Steinweg	ORNL Postdoctoral Researcher
Peter E. Thornton	ORNL Senior Research Staff Member

Anthony Walker	ORNL Postdoctoral Researcher and Associate Research Staff Member
Dali Wang	ORNL Research Staff Member
Jeffrey M. Warren	ORNL Research Staff Member
David J. Weston	ORNL Research Staff Member
Stan D. Wullschleger	ORNL Corporate Fellow
Xiaojuan Yang	ORNL Postdoctoral Researcher and Associate Research Staff Member

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LIST OF ABBREVIATIONS AND ACRONYMS

ACME	Accelerated Climate Model for Energy
AmeriFlux	DOE's organization of America's landscape-scale eddy covariance observations
AMR	Automated Minirhizotron System
ANL	Argonne National Laboratory
ANPP	Aboveground Net Primary Production (in mass or carbon units)
BER	DOE Biological and Environmental Research Program
BNPP	Belowground Net Primary Production
C	Carbon
C3	Plants exhibiting the C3 photosynthetic pathway
C4	Plants exhibiting the C4 photosynthetic pathway
CAM	Crassulacean Acid Metabolism plant photosynthetic pathway
CCSI	Climate Change Science Institute
CDIAC	Carbon Dioxide Information Analysis Center
CESM	Community Earth System Model
CFE	CO_2 Fertilization Effect
CH_4	Methane
CLM-XXX	Community Land Model and designated versions (XXX)
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon Dioxide
CRM	Community Root Module
CSIRO	Commonwealth Scientific and Industrial Research Organization
CUE	Carbon Use Efficiency (microbial context)
DA	Data Assimilation
D&A	Detection and Attribution
DIC	Dissolved Inorganic Carbon
DOC	Dissolved organic carbon
DOE	United States Department of Energy
DOM	Dissolved Organic Matter
DPH	Deep Peatland Heating experiment – a SPRUCE project Effort
EBIS	Enriched Background Isotope Study
EC	Eddy Covariance
ESM	Earth System Model
FACE	Free-Air CO_2 Enrichment experiments
FLEX	Fluorescence Explorer
Fluxnet	International network of landscape eddy covariance sites
FRED	Fine-Root Ecology Database
GCB	Global Change Biology - Journal
GOME-2	Global Ozone Monitoring Experiment–2
GOSAT	Global Greenhouse Gas Observation Project
GPP	Gross Primary Production (typically in C units)
GPR	Ground Penetrating Radar
GTEC	Global Terrestrial Ecosystem Carbon model
GUI	Graphical User Interface
JGI	Joint Genome Institute
Jmax	Maximum rate of electron transport
LAI	Leaf Area Index (m^2 leaf area per m^2 ground area)
LLNL-CAMS	Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry
LTER	NSF's Long Term Ecological Research Program or Sites
MADDPRS	MOFLUX Automated Daily Data Processing and Reporting System
MBC	Microbial Biomass Carbon
MGE	Microbial Growth Efficiency
MEND	Microbial ENzyme Decomposition Model
MIPs	Multi-model Intercomparison Projects

MOC	Mineral-associated Organic Carbon
MODEX	Model Experiment Interaction Activity
MOFLUX	Missouri Ozark AmeriFlux Site
MsTMIP	Multiscale Terrestrial Model Intercomparison
N	Nitrogen
NACP	North American Carbon Program
NASA-DAAC	NASA Distributed Active Archive Center
NDVI	Normalized Difference Vegetation Index
NEE	Net Ecosystem Exchange of C
NGEE	Next Generation Ecosystem Experiments
NH_4-N	Ammonium nitrogen
NIMBios	National Institute for Mathematical and Biological Synthesis
NMR	Nuclear Magnetic Resonance
NOM	Natural Organic Matter
NO_3-N	Nitrate Nitrogen
NPP	Net Primary Production (typically in C units)
OCO-2	Orbital Carbon Observatory - 2
ORNL	Oak Ridge National Laboratory
ORNL-DAAC	ORNL Distributed Active Archive Center
P	Phosphorus
PAR	Photosynthetically Active Radiation
PCE	Plant, Cell & Environment - Journal
PFLOTRAN	Open source, state-of-the-art massively parallel subsurface flow and reactive transport code
PFTs	Plant Functional Types
PiTS	Partitioning in Trees and Soils (PiTS) field experiments
PLFA	Phospholipid fatty Acid
PNAS	Proceedings of the National Academy of Science - Journal
POC	Particulate Organic Matter
PSII	Photosystem II
PTCLM	Point version of CLM
QEPRO	High-sensitivity spectrometer for low light level applications
QPCR	Quantitative polymerase chain reaction
REL	Rhizosphere Ecology Laboratory
rRNA	ribosomal ribonucleic acid (RNA)
SCIAMACHY	SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY
SIF	Sun-Induced Chlorophyll Fluorescence
SOC	Soil Organic Carbon
SPRUCE	**S**pruce and **P**eatland **R**esponses **U**nder **C**limatic and **E**nvironmental change experiment
TBMs	Terrestrial Biosphere Models
TEM	Terrestrial Ecosystem Model
TES SFA	ORNL's Terrestrial Ecosystem Science Scientific Focus Area
TOC	Total Organic Carbon (similar to DOC)
TPU	Triose Phosphate Utilization rate
UNFCCC COP	United Nations Framework Convention on Climate Change
UQ	Uncertainty Quantification
USDA	United States Department of Agriculture
Vcmax	Maximal rate of carboxylation
VOC	Volatile Organic Carbon
VWC	Volumetric Water Content
WBW	Walker Branch Watershed
Y_G	Growth Yield (microbial context)

Narrative (Sections 1 Through 6)

1. BACKGROUND AND PROGRAM OVERVIEW

ORNL's TES SFA provides fundamental research in support of the DOE BER Climate and Environmental Sciences Division Strategic Plan (US DOE 2012) specifically addressing Goal 2, which emphasizes process-level understanding of terrestrial ecosystems from bedrock to the canopy. The TES SFA strives to expand fundamental knowledge of terrestrial systems and translate that understanding into predictive models appropriate for regional and global applications. The TES SFA also contributes to grand challenges identified in the 2010 BERAC Grand Challenges Report (BERAC 2010). For example, the TES SFA contributes to understanding biological and ecological systems as complex systems, with a particular emphasis on understanding the translation of information through the scales and levels of ecosystem organization connecting complex fine-scale biological systems with very large-scale climate-biosphere feedbacks. The TES SFA data management and data access activities also contribute real world practice to identified grand challenges in computing.

1.1 ORNL TES SFA Vision

Improved integrative understanding of terrestrial ecosystem processes to advance Earth System predictions through experiment-model-observation synergy

The TES SFA is guided by the vision that sensitivities, uncertainties and recognized weaknesses of Earth System Model (ESM) predictions inform observations, laboratory and field experiments and the development of ecosystem process modeling. In turn, predictive understanding and findings from the field and laboratory and improved process modeling are incorporated, with the associated uncertainties, into ESMs as explicitly and expeditiously as possible. TES SFA research integrates laboratory and field experiments across a range of scales, observations from greenhouse gas inventories, field sites and remote sensing, and multiple process models. This integration is realized through the development and application of empirically driven process model development, model-data fusion, model-data inter-comparison, model performance benchmarking, and uncertainty characterization and quantification. The integration occurs within the context of predictive Earth System modeling and within a framework of earth system simulation using high-performance leadership-class computing.

1.2 TES SFA Philosophy and Research Overview

TES SFA research is an iterative process (Fig. 1.1) translating mechanisms to ecosystem models with a quantitative understanding of model uncertainties. This process informs priorities for future measurements. Our paradigm is to identify and target critical uncertainties in coupled climate and

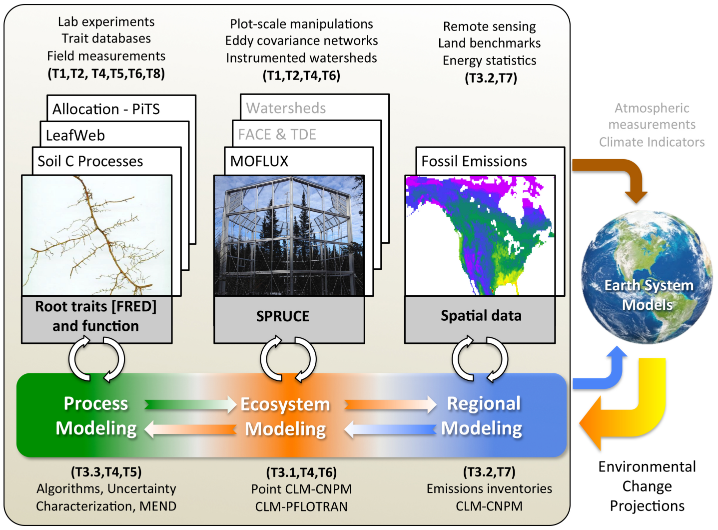

Fig. 1.1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems

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terrestrial ecosystem processes and feedbacks, prioritized by their influence over global change predictions on decadal and century timescales. New measurements and experiments are employed to obtain new knowledge required to characterize, quantify, and reduce these uncertainties.

Terrestrial ecosystem research requires the integration of biophysical, biochemical, physiological, and ecological process understanding. Terrestrial ecosystem models integrate these processes in a mathematically consistent, meta-hypothesis on the coupled operation of the C, hydrological, and energy cycles at hourly to multi-annual timescales and at ecosystem to landscape spatial scales. Terrestrial ecosystem models are built upon, validated by, and constrained by historical and contemporary observations and experiments. Nevertheless, the future of terrestrial ecosystems remains highly uncertain. Further integration of models and experimental manipulations are required to enable reliable projections of ecosystem responses and feedbacks to future climate and other atmospheric forcing.

ORNL's current high-profile environmental change study the Spruce and Peatland Under Climate and Environmental change experiment (SPRUCE) focuses on the combined response of multiple levels of warming at ambient or elevated CO_2 levels in a *Picea mariana–Sphagnum* peat bog in northern Minnesota. The experiment provides a platform for testing mechanisms controlling vulnerability of organisms and ecosystem processes to important climate change variables providing data for model development.

The TES SFA also supports smaller-scale, process-level manipulations to quantify C partitioning in trees and soil (PiTS, Root Trait and Function research, and mechanistic studies of soil C-Cycles). The TES SFA continues its support of long-term monitoring of landscape flux measurements at the MOFLUX site while expanding measurements to better interpret responses. Support for the characterization of the fundamental driver of global C emissions is being supplemented. Limited support for summarizing long-term data from Walker Branch Watershed (WBW) to inter-annual climatic variations is provided.

TES SFA research is ambitious in its scope, effort, and fiscal requirements. It represents a challenge that is fully utilizing, testing and extending the broad interdisciplinary facilities of a DOE National Laboratory. ORNL's SFA research plans and philosophy attempt to eliminate an artificial distinction between experimental or observational studies and modeling (including model construction, parameter estimation, evaluation, and prediction).

1.3 Overarching Questions, Goals and Deliverables

The following overarching science questions and the subsequent description of key goals and milestones acknowledge significant uncertainties in climate change prediction regarding terrestrial ecosystem response. These questions have been modified from their original form to suit changes in emphasis over the previous years of TES SFA support.

1. How will atmospheric and climate change affect the structure and functioning of terrestrial ecosystems at scales from local to global and from decadal to centuries?
2. How will fossil fuel emissions and terrestrial ecosystem processes, mechanisms, interactions and feedbacks control the magnitude and rate of change of atmospheric CO_2 and other greenhouse gases?
3. What are the climate change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of climate change impacts on ecosystem services and society?

The TES SFA goals and long-term (5 to 10 year) milestones are briefly summarized below. Details on progress are documented in the balance of Section 2. Near term (1-3 year) milestones are described in the Research Plans of Section 3. Deliverables for the TES SFA were originally described and justified in the earlier SFA plans (http://tes-sfa.ornl.gov/node/17), and revised in the first triennial review (January 2012). They have been modified slightly to reflect changes in emphasis that have developed over time.

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

- 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 a key understudied ecosystem).

Goal 3: Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in terrestrial 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 ESMs.

Goal 4: Incorporate new findings on interannual and seasonal C and water dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and ESMs 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.

2. PROGRESS SINCE JANUARY 2012

For the performance period from January 2012 to the time of completing this document, the ORNL TES SFA, through seven coordinated ***Tasks***, has made considerable strides in its mission to understand and simulate the interactions of Earth's terrestrial ecosystems and climate, and to assess vulnerability of terrestrial ecosystems to projected changes in climate and atmospheric composition. These strides are evidenced not only by 130+ peer-reviewed papers in leading national and international scientific journals but also by development of large-scale comprehensive research infrastructures, improvement of process-based predictive models from local to regional to global scales, development of publicly available datasets of global importance, development of community support research tools, leadership in national and international ecological and climate change-related workshops, meetings, and by interactions with the public. A brief summary is provided here, followed by a more detailed description for individual tasks.

Task 1 – We initiated SPRUCE experimental treatments for deep peatland heating in June 2014 and anticipate whole-ecosystem warming and elevated CO_2 in June 2015. Early findings indicate differential sensitivity to warming between surface and ancient deep peat C stores. We also completed multi-year, pre-treatment observations for the full range of tree, woody shrubs, forb, *Sphagnum* moss, and microbial communities in the SPRUCE bog and have quantified peat characteristics, biogeochemical cycling, and environmental conditions throughout the soil profile. These observations of ecosystem C, water, and nutrient cycling have informed CLM model development (Task 3), and will serve as a foundation for understanding atmospheric and climatic change effects on peatland processes.

Task 2 – Since January 2012, efforts characterizing the responses of stream nutrient and organic C cycling to varying environmental conditions have been summarized. In addition, a 4-decade history of long-term monitoring activities on WBW is being finalized. Those data provide multi-year context of environmental and atmospheric drivers of long-term change that can be contrasted with projected effects of future anthropogenic climate change.

Task 3 – Leveraging results from the SPRUCE and PiTS experiments of Tasks 1 and 4a, the Enriched Background Isotope Study (EBIS) experiment (e.g., Fröberg *et al.* 2009), and results from MOFLUX (Task 6) and other AmeriFlux sites, we have improved models at the point scale as well as regional to global scales by identifying mechanistic process-level contributions to forcing of the coupled global climate-C-Cycle by changes in terrestrial ecosystems. At the point scale, our model-experiment interaction (MODEX) approach has led to better representation of several C and nutrient cycling processes. At the regional and global scales, we are participating in a series of model intercomparison projects using spatially resolved data sets to evaluate the sensitivity of and uncertainty in a number of key model processes. The integration and testing of individual processes in CLM benefits from a newly-developed functional testing framework that allows for systematic analysis and visualization of processes.

Task 4 – We used model-inspired, short-term field manipulations of C flow to alter C partitioning within trees and soils. Integrating with activities of Task 3, experimental results were used to test model representation of C partitioning processes in CLM. This test highlighted missing model processes and pointed to the need for a broader range of data collection that encompasses environmental extremes. These experiments, a series of community-wide workshops, and a synthesis of existing work that highlights the lack of mechanistic root function in models, all lay the foundation to propose mechanistic links between root traits and root function in models spanning multiple scales.

Task 5 – We completed and synthesized a series of experiments on the forms, fate, and transport of soil C, and incorporated these mechanistic processes into a mechanistic enzyme-based C and N cycling model. This MODEX approach yielded information on critical uncertainties in microbial-mediated decomposition of soil organic C, including parameterization of both active and dormant microbial biomass pools and observed microbial community changes through time, paving the way for improvements to CLM.

Task 6 – We leveraged the Missouri Ozark AmeriFlux (MOFLUX) site and the SFA's interactions with the broader AmeriFlux, Fluxnet and global change research communities to advance an integrated understanding of ecosystem responses to atmospheric and climate variability and to incorporate such understanding into terrestrial C and ESMs. Measurements at MOFLUX were crucial to the reformulation of the fundamental eddy covariance (EC) equation, the development of novel EC theories, regional and global syntheses, validation of innovative remote sensing products, and quantification of ecological impacts of drought. Key findings from Task 6 were that the contemporary terrestrial biosphere is more CO_2-limited than previously thought, and that explicit consideration of mesophyll diffusion can explain the persistent overestimation of historical atmospheric CO_2 growth by ESMs. Model investigations were supported by the LeafWeb (http://leafweb.ornl.gov), which has analyzed and compiled worldwide leaf gas exchange measurements from nearly 130 C3 species covering all major plant functional types.

Task 7 – We improved understanding of fossil fuel C dioxide emissions, especially in terms of their temporal distribution, spatial distribution, and uncertainties associated with those emissions. Fossil emissions are a primary driver of the atmospheric disequilibrium impacting and changing terrestrial ecosystems as investigated in Tasks 1-6.

Tables summarizing progress on deliverables established in 2012 are presented in Appendix C.

2.1 SPRUCE Experiment (Task 1)

The SPRUCE experiment is being operated as the first whole-ecosystem, forest-scale experiment to increase temperature and CO_2 concentrations from deep soil to tree canopies. The decade-long experiment is being carried out in a black spruce peatland ecosystem of northern Minnesota and consists of 10 specially-designed, enclosed plots that are 12 m in diameter and outfitted with heating infrastructures for air- and deep-soil warming, as well as a range of biological and environmental monitoring sensors.

As of March 2015 the SPRUCE project infrastructure is largely in place for a spring 2015 initiation of whole-ecosystem warming treatments. Deep peat heating was initiated June 2014 to study the sensitivity of deep, ancient peat C stocks to warming independent from more active surface phenomenon. Extensive pretreatment characterization of the peatland being used in manuscripts on peatland processes and incorporated into the development of a wetland model with the capacity to address the C-cycle, nutrient-cycle, water cycle and energy dynamics of peatland systems and wetlands in general. The following text provides succinct descriptions of SPRUCE infrastructure and peatland science accomplished since

January 2012. Initial descriptions of SPRUCE activities are available in a previous proposal and annual reports available at http://mnspruce.ornl.gov/content/spruce-project-documents.

2.1.1 SPRUCE Infrastructure

Roads and extensive boardwalks were added, electrical service installed, storage units and buildings delivered, and instrumentation was installed for long-term monitoring of environmental conditions and organism-ecosystem responses (Fig. 2.1). Final infrastructure for air warming and subsurface hydrologic isolation of the experimental plots is being completed in the winter of 2014-2015.

Deep Peat Heating –We are proceeding with belowground deep warming (the *Deep Peatland Heat (DPH)* study) in 2014-2015 to evaluate rapid responses of deep peat C stocks, microbial communities, and biogeochemical cycling processes to unprecedented temperatures. In June 2014, deep soil heating was initiated at 5 warming levels (+0, +2.25, +4.5, +6.75 and +9 °C; 2 replicate plots). In the absence of the air warming cap, *in situ* deep peat heating is only effective at sustaining full target warming levels in the deep peat layers. Warming levels at depth were achieved over a 25 (+ 2.25 °C) to 60-day (+9 °C) period depending on the target treatment temperatures, in agreement with *a priori* energy balance model simulations. The mild and gradual warming treatments took several months to produce enhanced levels of net CH_4 flux for the treatment plots proportionate to measured levels of deep peat warming. Enhanced fluxes were maintained only during the warm growing season, and dropped to near zero when surface conditions were frozen. Other data suggest that CH_4 generation within the peat column may be limited by reduced photosynthate supplies in the cold portion of the year. University and National Laboratory collaborators are actively engaged in DPH and were present for time-zero sampling (2 June 2014) and after target warming levels were fully achieved (7 September 2014).

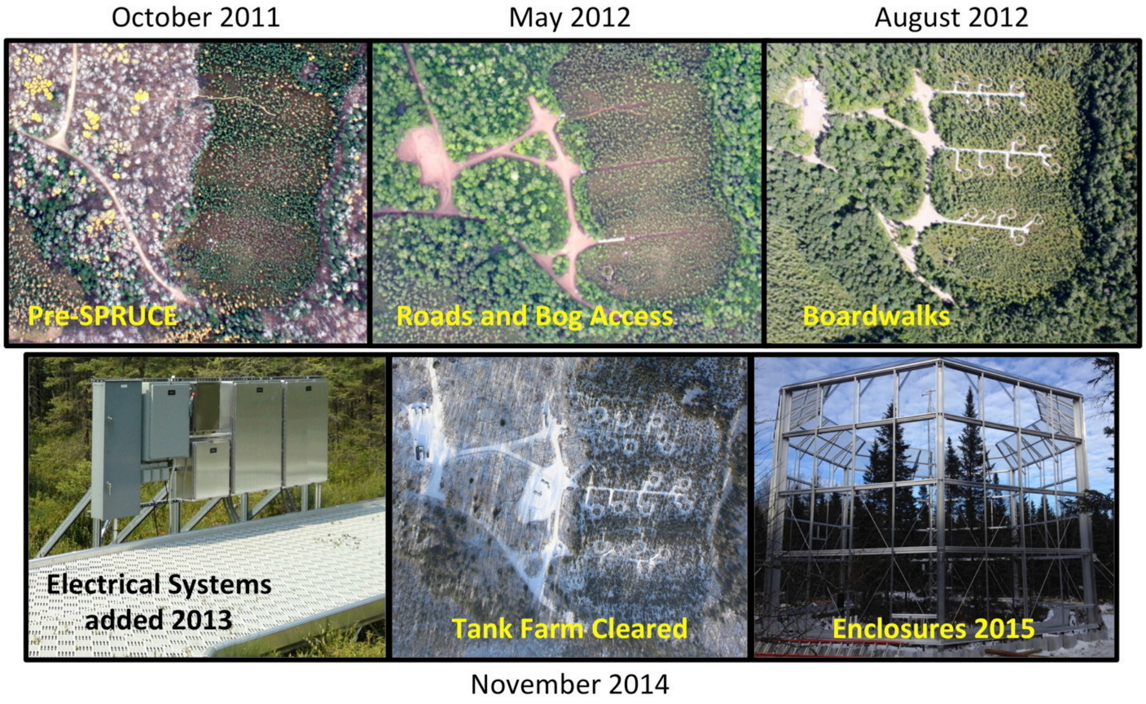


Fig. 2.1 – Development of the SPRUCE experimental site on the southern end of the S1-Bog on the Marcell Experimental Forest through time. Field office and storage facilities were added west of the site in 2013.

Subsurface Hydrology – A subsurface corral system to measure water flow and collect water samples from the outflow of each experimental chamber was designed, tested and re-engineered. A new design of the collection basin will allow for more precise measurements of outflowing water, reduce site disturbance during installation, and allow for control of drainage rates if needed.

2.1.2 Peat Characterization of the S1-Bog

Soil characterization (from peat sampled August of 2012 across the S1-Bog experimental area) was completed for all peat depth increments to ~3 m (Fig. 2.2 upper row). Pre-treatment characterizations showed few gradients across the plots, demonstrating successful establishment of appropriate plot centers for random distribution among our target treatments. Variations in peat characteristics and chemistry with depth are key biogeochemical cycling benchmarks against which experimentally induced changes of other variables will be observed (e.g., Tfaily *et al.* 2014).

The ^{14}C isotopic composition and age of the peat profile across the S1-Bog were measured on the 2012 samples (Fig. 2.2 lower row). The ^{14}C data reflect the source-age of peat samples with depth and will allow tracking of the mineralization of shallow compared with deep C pools. Calibrated dates for bulk peat from 35-300 cm depth 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}. Additional observations are needed to reconcile and explain near-term C accumulation (years) with the historical centuries to millennia accumulation rates. Tfaily *et al.* (2014) reported that depth-specific dissolved organic C (DOC) and dissolved inorganic C (DIC) ^{14}C-signatures were distinct from bulk peat, suggesting downward migration of DOC as a source of available labile and relatively young C with depth.

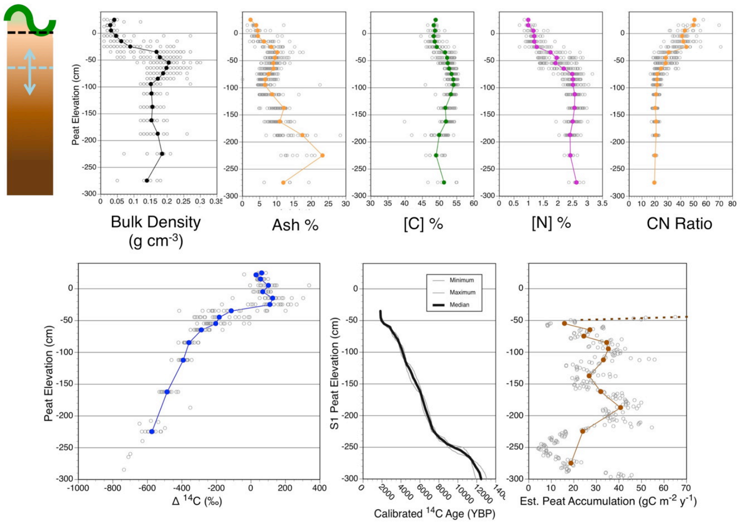


Fig. 2.2 – Upper Row: Depth distributions of peat bulk density, ash content, [C], [N], and CN ration for the S1-Bog experimental plots. Mean characteristics for a given variable are plotted over the full data set obtained from the entire SPRUCE study area. The diagram (upper left) provides a visual representation of hummocks over the hollow (zero depth by definition) above the acrotelm transitioning into the catotelm zone. The entire suite of measurements 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. Lower Row: Depth distributions of bulk peat ^{14}C-signatures, calibrated peat ages (years before present), and historical peat accumulation rates.

Bog elevation measurements – Because warming and CO_2 treatments are hypothesized to have dramatic effects on peat C stocks, it is a possibility that the overall elevation of the treatment plots may change over time. To that end, and based on the recommendations of the review panel at our last triennial review, we have established replicate elevation standards for periodic assessment of peat surface elevations in all treatment plots (*data not shown*). Peat elevations are measured after snow melt in spring and at peak midsummer production to track long-term changes in the peatland surface as an indication of overall peatland C stock changes.

2.1.3 Peatland Phenology and Aboveground Production

S1-Bog Phenology –Phenological observations of tree, shrub and sedge spring growth and flowering (*Picea, Larix, Ledum, Chamaedaphne, Smilacina*, sedges), foliar senescence (*Larix, Smilacina*), and snow cover metrics are being recorded. A daily photographic record of a "tree", "shrub", and "instrument" level monitoring has been compiled into phenology movies (https://mnspruce.ornl.gov/webfm). Phenology images are being incorporated into the Phenocam network operated by Andrew Richardson (http://phenocam.sr.unh.edu/webcam/).

Aboveground production: Trees – Annual assessments of C stocks and accumulation in tree tissues (*Picea* and *Larix*) are estimated with annual measurement of tree circumference and periodic assessments of tree height using allometric relationships. Tree diameter and height measurements were collected mid-winter in 2011, 2012, 2013 and 2014 enabling estimates of annual tree aboveground net primary production (ANPP) for the 2011, 2012, and 2013 growing seasons. The mean pretreatment standing stock of above ground tree biomass (*Picea* and *Larix* combined) at the end of the 2013 growing season was 895±414 gC m^{-2} of which 26 % was foliage. Plot level ANPP based on the whole-tree allometric data in 2014 was 64.3 g C m^{-2}. An independent estimate of foliar only ANPP for both *Larix* and *Picea* (20% of annual foliage stock) provided a higher value of 83 g C m^{-2}. The 2014 assessment of tree standing stocks and ANPP will be done with new data collected in March 2015.

Aboveground Production: Shrubs and Forbs –Standing stocks and ANPP for woody shrubs (*Ledum, Chamaedaphne, Vaccinium*, etc.) sedges (*Eriophorum*) and miscellaneous forbs (e.g., *Smilacina*) were estimated through annual clipping of paired 0.25 m^2 hummock and hollow. Total aboveground standing stock for the non-tree vegetation above the *Sphagnum* surface of the S1-Bog ranges from 183 to 259 g C m^{-2}. Of this total Annual NPP contributions ranged from 72 to 137 g C m^{-2} y^{-1}of which 75 to 90 % was contributed by foliage which cycles approximately annually. The areas used for destructive ANPP assessments will be used for future tissue decomposition studies.

Sphagnum community assessment – Initial assessments of the community composition in the bog indicated dominance by two species: *S. angustifolium/fallax (*77 ± 9% of the surface area) and *S. magellanicum* (17 ± 9 %) and no pretreatment biases. Other *Sphagnum* species (e.g., *S. fuscum* and *S. capiliifolium*) are rare; feather mosses and *Polytrichum* are present, with the *Polytrichum* tolerating the drier sites and conditions. A protocol for *Sphagnum* community composition assessment was established to enable annual tacking of changes in the community in relation to temperature and CO_2 treatments.

Aboveground Production: Sphagnum – *Sphagnum* production and standing crop for the top 5 cm of the peatland surface was measured in each plot through a combination of bundles in hollows and brush wires on hummocks. Across all plots in 2014, annual production was 479 ± 41 g m^{-2} (205 ± 18 g C m^{-2}) and standing crop (top 5 cm) was 635.6 ± 51 g m^{-2} (273 ± 22 g C m^{-2}). Interannual variation in *Sphagnum* production varied by 149 g C m^{-2} for the three years evaluated (2012 = 288; 2013 = 139; 2014 = 205). Standing crop showed less interannual range of 56 g C m^{-2} for the three years evaluated (2012 = 282; 2013 = 226; 2014 = 273). Contrasting the mean annual *Sphagnum* production rate of 205 g C m^{-2} y^{-1}with the current standing crop of 273 g C m^{-2} suggests annual turnover rate of 1.3 for the 2014 assessment. This turnover rate near 1 suggests that annual *Sphagnum* production is transferred rapidly to peat.

2.1.4 Belowground Production

Belowground net primary production (BNPP) is being evaluated using minirhizotron observation systems (manual and automated), with supplemental measurements of the morphology, chemistry, and distribution of new roots throughout the soil profile using root ingrowth cores. Prior to the initiation of measurements, we gathered a community of experts on root dynamics in wetlands, and also in the use of minirhizotron technology, and concluded that the use of minirhizotrons in wetlands presents new challenges but also great opportunities (Iversen *et al.* 2012).

Root growth and morphology–We investigated fine-root dynamics of woody species in the S1 bog using minirhizotron technology, and found that: (1) root production varied across a gradient of tree density (Fig. 2.3), (2) rooting depth was limited to above the average summer water table level, and (3) production associated with raised hummock topography was generally greater than that in hollow depressions (Fig. 2.3). These measurements will be used to parameterize ecosystem and land surface models.

Minirhizotron tubes were then installed in paired hummock-hollow positions in two locations in each SPRUCE experimental plot representing “treed” and “non-treed” vegetation. Image collection began in June 2013 and will continue throughout the experimental duration. Root ingrowth cores, also deployed in hummock-hollow microtopography in the SPRUCE plots, are used to determine treatment effects on the chemistry and morphology of newly produced roots. Biannual ingrowth collections have shown patterns similar to minirhizotrons: roots were shallowly-distributed and commonly located in hummock microtopography. The morphology of roots of the dominant vascular plant species is being used to extrapolate minirhizotron measurements of root length and diameter to root mass, C and nutrient content (as in Iversen *et al.* 2008). Linkages between root form and function are the leading edge in understanding the contribution of roots to ecosystem-scale C and nutrient fluxes (Iversen 2014). Preliminary estimates are that fine roots contribute between 0 and 200 g C m^{-2} and between 0.0 and 2.8 g N m^{-2} in annual production, depending on microtopographic position and nearby tree density. When the fraction of hummock-hollow area is accounted for (60% hummocks, on average), root production at basal areas similar to those observed in the SPRUCE experimental plots averages 39 ± 22 g C m^{-2} $year^{-1}$ (±1 SD).

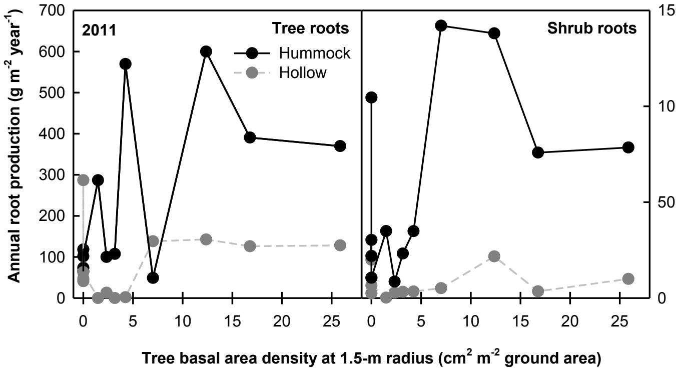


Fig. 2.3 – Root production was generally greatest in hummocks. Tree and shrub root production were differentiated in minirhizotron images based on the very small average diameter of shrub roots (first three root orders less than ~ 200 µm). Note different axes on each graph.

Root-fungal interactions– Novel, automated minirhizotron (AMR) technology is also being used to track the dynamics of ephemeral roots in the SPRUCE experimental plots. AMR systems capture root and hyphal dynamics at greater temporal resolution and at much higher magnification (100×) than manual minirhizotrons, allowing quantification of mycorrhizal hyphae dynamics. Images collected 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. Scans during the winter months showed little root or hyphal growth. The abundance of external hyphae of the ericoid mycorrhizal fungi associated with ericoid shrub roots was unexpected and will provide new information to the community of mycorrhizal ecologists. We are tracking the phenology of fungal production and mortality with a goal of publishing a high-impact paper on root and rhizosphere interactions.

Fine-root standing crop – Fine-root standing crop (g m^{-2}) was determined at multiple depths to -2.5 m from the peat cores sampled in August 2012, to ~2.5-m depth and sectioned into multiple depth increments. Surprisingly, we found intact, well-preserved shrub roots in peat increments as deep as 2 m. Radiocarbon analysis (KJ McFarlane, LLNL-CAMS) confirmed that these roots were dead (>5000 years old), but well preserved in the anoxic deep peat. Roots with modern ^{14}C signatures 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 dynamics in this zone.

2.1.5 Vegetation Physiology

Woody Plant Physiology – A focus on physiological processes allows us 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.* Particular effort has been given to establishing photosynthetic and respiratory temperature response curves, providing pertinent data for model parameterization and testing, and testing various sensors and measurement techniques to be deployed as treatments are initiated.

Granier-style heat dissipation probes provide long-term monitoring of sap flow through the dominant *Picea* and *Larix* trees. Calibration of these probes is essential for the accurate calculations of tree transpiration. As such, on three occasions trees containing sap flow sensors were cut and water uptake directly measured *in situ* using a potometer method. We are also exploring the use of delicate heat balance sensors to monitor sap flow through the two dominate shrubs, *Ledum* and *Chamaedaphne,* which contribute significantly to total plant transpiration.

We hypothesize that warming treatments will increase atmospheric vapor pressure deficit and evapotranspiration, leading to drier soils and increased water table depth, thereby increasing the potential for drought stress. We assessed thresholds of drought stress by measurement of root, branch or leaf hydraulic conductivity of *Picea* and *Larix* trees. The foliar turgor loss point, based on pressure-volume curves, indicates a potential drought threshold for *P. mariana* ranging from -2.1 to -3.0 MPa, while *L. laricina* was lower, ranging from -1.4 to -2.2 MPa, indicating that *Larix* may operate closer to its drought threshold. Indeed, late summer foliar water potential for *Larix* can approach -2.0 MPa, while stomatal control limited *Picea* to <-1.5 MPa). Large root xylem vulnerability curves indicated substantial loss of function began by ~3.5 MPa. Such data will provide mechanistic knowledge of drought-dependent feedback to C assimilation and might be used to refine CLM-SPRUCE parameterization.

Photosynthetic capacity and respiration were assessed on detached plant material, including light, CO_2, and temperature response curves for *Picea, Larix, Rhododendron and Chamaedaphne*. Seasonal, canopy and cohort C assimilation patterns of *P. mariana* were quantified using seasonal- and cohort-specific temperature response functions (Fig. 2.4). Measurement of the temperature respiratory responses of foliar and woody tissues have continued and will be used to parameterize a SPRUCE photosynthetic sub-model.

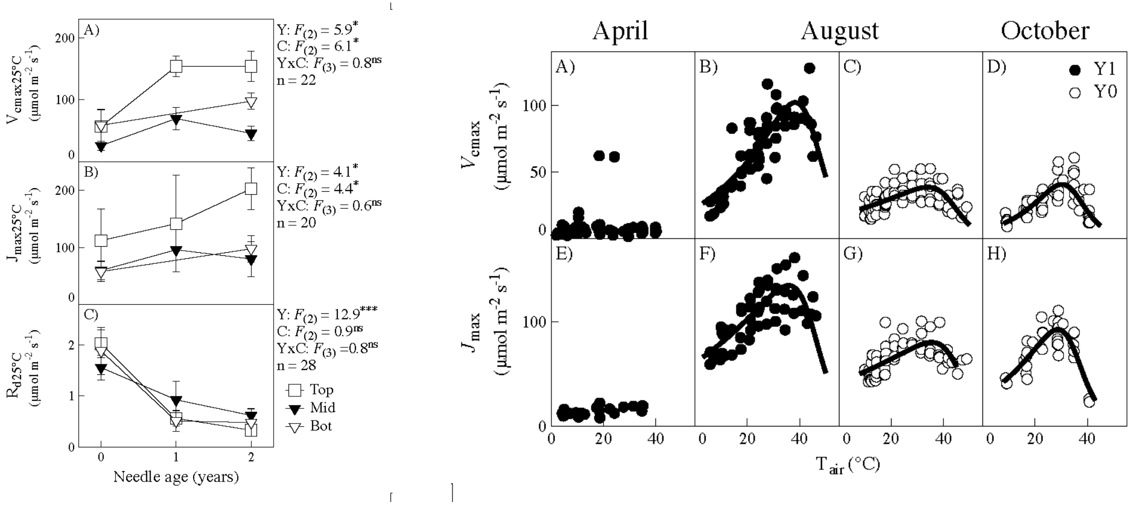


Fig. 2.4 – (Left) Foliar photosynthetic capacity (as V_{cmax} – carboxylation and J_{max} – electron transport) and respiration (R_d) at 25 °C for three different foliar cohorts collected from different canopy positions, (right) Temperature responses of V_{cmax} and J_{max} for developing (Y0) and one-year-old (Y1) spruce foliage.

We quantified chemical and morphological characteristics of the multiple foliar cohorts of *Picea* that will be important for modeling. We have conducted ^{13}C-pulse-labeling and assessment of non-structural carbohydrates of shrubs and *Picea* to track shoot development and seasonal C partitioning responses to changing environmental conditions.

Sphagnum Physiology – The *Sphagnum* dominated moss layer is estimated to contribute to approximately 47 to 49% of NPP (NPP; Table 2.1) within the S1 system and is considered a critical component for maintaining low bog pH and N inputs through its associated microbiome. Pre-treatment experimentation evaluated inter-specific variation in moss physiology to variable environmental conditions at intermediate and seasonal temporal scales. Nine *Sphagnum* species were collected and grown under common growth chamber conditions and assayed for net CO_2 exchange using the LiCOR 6400. The trends in net photosynthesis to variable [CO_2] and photosynthetically active radiation (PAR) were similar among species, although there was considerable variation in response curve saturation values (Fig. 2.5). The *S. fallax/S. angustifolium* mix, together with *S. magellanicum,* account for some 94% of the total moss cover at the S1 bog site. Field measurements of clipped tissue placed in the LiCOR 6400 revealed that there was little difference in net photosynthesis responses to [CO_2], PAR and temperature between *S. magellanicum* and *S. fallax* (data not shown). The response of net photosynthesis to CO_2 was influenced by date of collected material suggesting the continued need for seasonal evaluations. We installed six clear-top automated gas exchange chambers (LiCOR 8100s) in hollows to assess *Sphagnum* net ecosystem exchange of C (NEE) from just after snowmelt (late May) until late fall (November). The species composition was manipulated by transplanting *S. fallax* or *S. magellanicum* into the chambers. Mid-day CO_2 uptake values were similar for *S. fallax* and *S. magellanicum* except in early spring when *S. fallax* displayed greater net CO_2 uptake. Field campaigns in 2015 will investigate underlying physiological mechanisms.

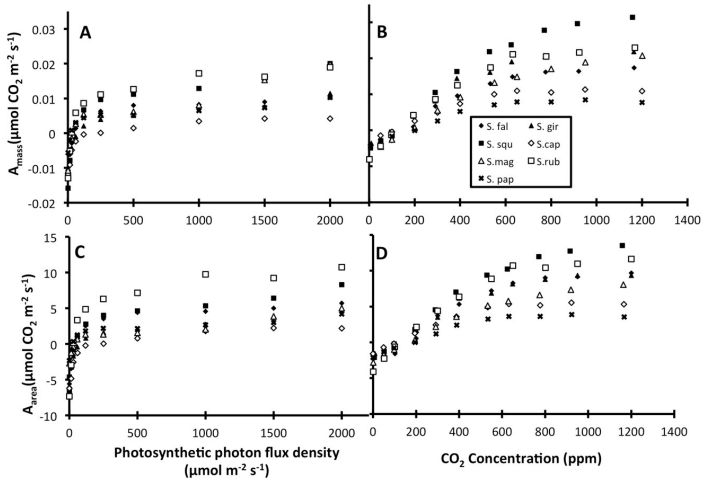


Fig. 2.5 – Net photosynthetic response of various *Sphagnum* species exposed to differing (A, C) photosynthetic photon flux densities, and (B, D) CO_2 concentrations. Each response curve was generated using one sample measurement. (A, B) were plotted on mass based CO_2 assimilation and (C, D) were plotted on area based assimilation rates.

Nitrogen fixation within Sphagnum – Preliminary assessments of N fixation associated with *Sphagnum* were conducted with plants grown in the greenhouse and in the field. *Sphagnum* was incubated for 24-48 hours in culture tubes containing air with 10% $^{15}N_2$, after which the *Sphagnum* was dried and analyzed for ^{15}N content on an isotope ratio mass spectrometer. The mean fixation rate measured on greenhouse samples was 19.3 µg g^{-1} d^{-1}, which is a substantial fraction of the N content of *Sphagnum*. Similar field assays showed large variability, with many samples showing no evidence of N_2 fixation. An objective for 2015 will be to identify the sources of variation. An initial formalization of this critical *Sphagnum* – microbe interaction was recently explored in a modeling study that linked our *Sphagnum* net photosynthesis model with a metabolic flux balance analysis model for an N-fixing cyanobacterium (Weston *et al.* 2014).

2.1.6 Rhizosphere Processes

Plant-available nutrients – Ion-exchange resin capsules (WECSA, LLC, Saint Ignatius, MT, USA) are 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. A series of resin-access tubes installed in hummock-hollow topography in late 2010 indicated that plant-available N was least in the shallow peat profile where most of the fine roots are located. In June 2013, two arrays of six tubes each were installed within all SPRUCE experimental plots (Fig. 2.6, left). Monthly ion-exchange resin collections during 2013 and 2014 confirmed the preliminary findings that NH_4-N increased with soil depth (Fig. 2.6 right), and that NH_4-N was by far the most available N source.

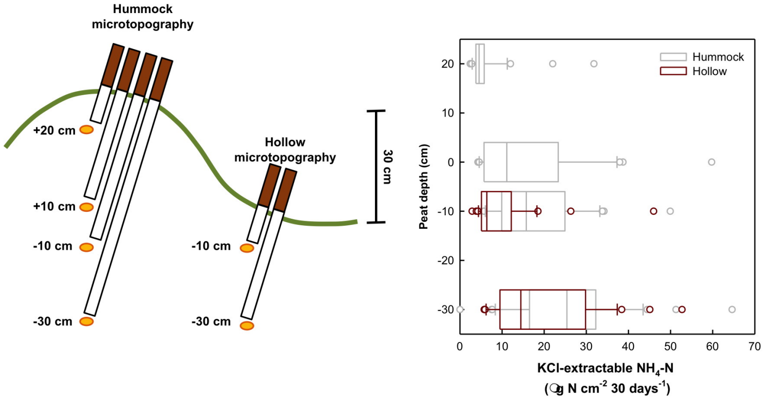


Fig. 2.6 – (Left) An example array of six resin-access tubes installed across paired hummock-hollow microtopography. (Right) Plant-available NH_4-N adsorbed to the surface area (cm^2) of ion exchange resin capsules during a 30-day incubation period in mid-summer, 2013. NO_3-N averaged between 0.03 and 0.10 µg N cm^{-2} 30 $days^{-1}$ during the same time period.

Pretreatment spatial and seasonal variation in microbial communities and processes – Initial work on microbial community composition, structure, and function in the S1-Bog focused on spatial variation throughout the peat profile and across the bog. Core sampling was conducted in 2010-2012 and analyses were done in collaboration with the lab of Joel Kostka at Georgia Tech. We used a combination of rRNA gene sequence analysis and quantitative polymerase chain reaction (QPCR) to look at community composition and structure (Lin *et al.* 2014a), and functional profiles of enzyme activity and stoichiometry with depth and season (Lin *et al.* 2014b). We found that microbial communities across the S1-bog were spatially variable from location to location, but largely consistent in structure of their relative changes with depth across these locations. Fungal abundance decreased dramatically in the acrotelm with depth, to amounts near or below the detection limit of QPCR in the catotelm. Bacterial abundance followed the same trend below approximately 20 cm, while archaeal abundance remained relatively constant with depth, leading to archaeal dominance in the deep peat layers. Changes in microbial composition and function with depth appear correlated with organic matter decomposition properties (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. In late August 2014, sampling of all the plots associated with the DPH experiment was undertaken. Amplicon-based rRNA sequencing of all sample depths/plots is currently being completed at ORNL, and metagenome and metatranscriptome of four peat depths from all cores/plots is being conducted in collaboration with the DOE-Joint Genome Institute (JGI) under a collaborative project in the Community Sequencing Program that was accepted in 2014 (http://jgi.doe.gov/microbial-communities-functions-peatlands/).

We also completed two lab-scale experiments at ORNL in 2013 to scope effects of warming and drying on peat microbial responses. Enzyme activity, temperature sensitivity, and C:N enzyme stoichiometry decreased with depth, but showed no seasonal response. These trends are reflected in a concomitant decline in the microbial enzyme C:N mineralization ratio (Fig. 2.2). Proteases were less responsive to temperature compared with enzymes for C and P depolymerization. The stable temperatures in deep peat may thus 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 diurnally and seasonally.

Warming is expected to lower water levels in the SPRUCE chambers, causing strong declines in hummock moisture and moderate declines in hollow moisture. We used laboratory incubations to assess the impact of moisture availability on enzyme activity, microbial and invertebrate community abundance and composition, microbial biomass, DOC, and CO_2 efflux for hollow and hummock peat. Hollow and hummock peat responded differentially to drying, with hollow communities most affected. Drought decreased 6 of 7 enzyme activities, and led to a decline in fungal abundance in the hollowsCO$_2$ efflux declined with reduced moisture in both hollows and hummocks, but was more variable in hummocks (Fig. 2.7). Respiration from hollow microbial communities were largely unaffected by moisture stress, reflecting the variable moisture levels experienced in hollows in the native bogs.

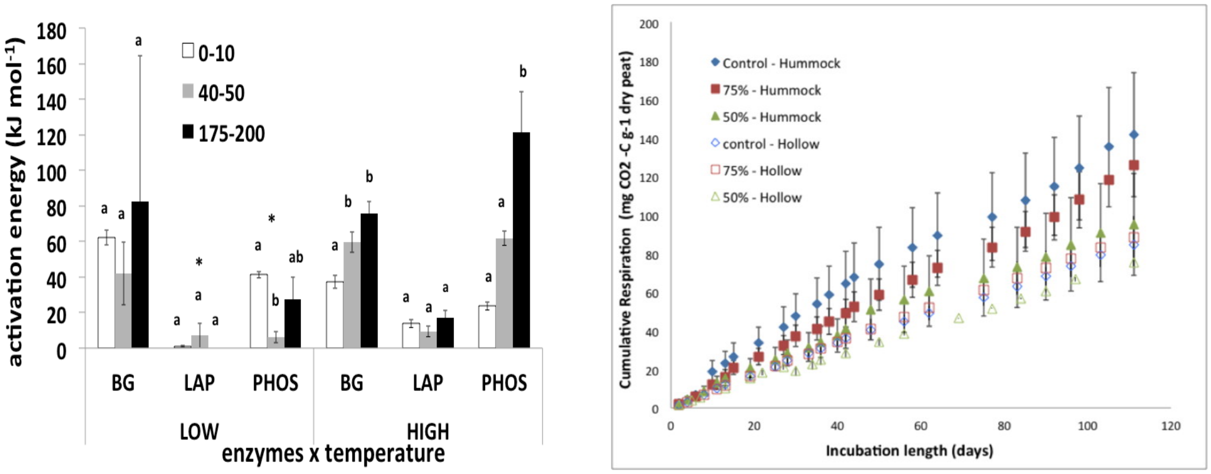


Fig. 2.7 – A) Activation energy for β-glucosidase, leucine amino peptidase, and phosphatase at three depths, & low and high incubation temperature B)Hummock communities respired more CO_2 across the moisture levels tested, but are also more variable and more sensitive to reduced moisture levels compared to hollow communities.

2.1.7 Decomposition and Flux of CO_2 and CH_4

Organic Matter Decomposition –A decomposition experiment will evaluate the effect of temperature and elevated CO_2 on the breakdown of dominant litter types in a peatland ecosystem. Above and belowground litter types include black spruce (*Picea mariana*) needles and fine roots (< 1 mm diameter), Labrador tea (*Ledum groenlandicum*) leaves and fine roots (< 0.5 mm diameter), and *Sphagnum angustifolium/S. fallax* and *S. magellanicum*. Work in 2013 and 2014 focused on collecting, sorting, and air drying litter in preparation for litterbag construction and deployment.

A 3 year moss decomposition experiment was initiated in 2014 to examine the effect of location (hummock, hollow, lawn) and moss species on decomposition rates. Hollow species (*S. angustifolium, S. fallax*), hummock species (*S. magellanicum*), and lawn species (*Polytrichum* sp.) were each placed in hummocks (S1 bog), hollows (S1 bog), and lawns (Bog Lake Fen). Bags will be retrieved after 0, 1, and 3 years, and mass loss and litter chemistry will be measured; time zero litterbags have been processed.

_CO_2/CH_4 flux_ – To evaluate the hypothesis that net CO_2 and CH_4 flux will increase with warming, a technique for simultaneous surface flux measurements of CO_2 and CH_4 was developed using 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 over 1.13 m^2 of the bog. Measurements conducted since 2011 were expanded in 2013 to include new collar positions within all 10 target SPRUCE experimental plots and six ambient reference plots. Maximum net CO_2 flux in midsummer showed similar rates of C uptake and loss: daytime surface uptake was -5 to -6 $\mu mol\ m^{-2}\ s^{-1}$ and dark period loss rates were 4 to 5 $\mu mol\ m^{-2}\ s^{-1}$. Maximum midsummer CH_4-C flux ranged from 0.4 to 0.5 $\mu mol\ m^{-2}\ s^{-1}$ and was 10 times 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 $g\ C\ m^{-2}\ y^{-1}$ (Hanson *et al.* 2014). Trimming of vegetation layers showed that the shrub/forb/sedge layer dominated net C uptake during the day, but did not change C losses in the dark.

2.1.8 Carbon Budget for the S1-Bog and bog NPP

Carbon Budget – A key preliminary activity is to gain an initial understanding of the C stocks and fluxes in the S1-Bog. We combined pre-treatment measurements of ecosystem C stocks (trees, shrubs, forbs, peat), foliar gas exchange data, tissue respiration, surface CO_2 and CH_4 flux and basin level DOC losses within a simple interpolative model of C flux for such an analysis. The combined data indicate a surprisingly high annual uptake of C ranging from 214 to 289 $g\ C\ m^{-2}\ y^{-1}$ (Fig. 2.8) by the S1-Bog in its current state of stand succession (i.e., regrowth since 1974). This estimate provides one indication of the C status of the bog. Similar characterizations will continue with warming treatments and will be compared to measured ANPP.

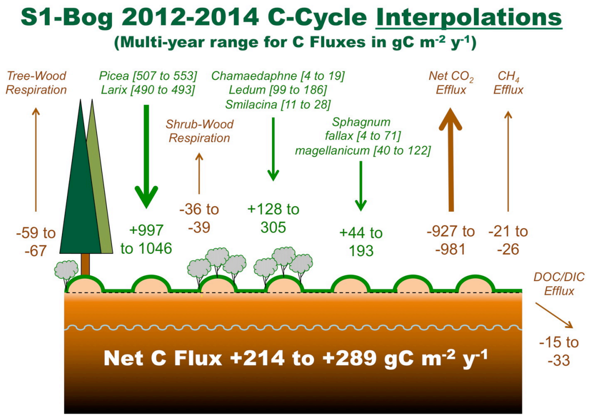


Fig. 2.8 – Interpolated C budget for the S1-Bog for environmental conditions in 2012, 2013 and 2014. Data presented are the multi-year range of data for a given C flux

Bog Net Primary Production – With little or no change in peat C stocks, we expect cumulative NPP estimates to match the range of net CO_2, CH_4, and DOC efflux from the bog (perhaps 1100 $g\ C\ m^{-2}\ y^{-1}$).

Table 2.1 shows that we can only currently account for between 411 to 430 g C m^{-2} y^{-1}. We will reconcile the S1-Bog C budget using more comprehensive model-experiment evaluations (Task 3).

Table 2.1. Annual NPP Contributions within the S1-Bog Peatland for the period from 2011 to 2014.

NPP Component*	Annual Contribution (g C m^{-2} y^{-1})
Tree growth (wood and foliage allometric estimates)	64 to 83
Shrub & Forb Annual Growth	103 (mostly foliage)
Sphagnum Moss Annual Production	205
Belowground Root Production	39
True Total	**>> 411 to 430**

*Common NPP components that remain unmeasured include: tree cone and plant seed production, root rhizosphere C exudation, and variable internal plant carbohydrate pools.

2.1.9 Hydrology and Porewater Chemistry

Porewater chemistry measurements have been used to: (1) establish baseline conditions in the S1 bog, (2) quantify variation among depth profiles across peatland ecosystems (S1 bog, S2 bog, Bog Lake poor fen comparison; 2014), and (3) assess initial responses to deep-peat heating (2014).

Baseline porewater chemistry of the S1-Bog – Porewater chemistry was measured in the S1 bog since 2011 to examine temporal (seasonal and inter-annual) variations in depth-specific chemistry. Depth-specific piezometers (0, 0.3, 0.5, 1, 2, 3 m) were sampled weekly or monthly and revealed large changes in chemistry with depth, including increasing pH and NH_4-N and cation (i.e., calcium) concentrations and decreasing total organic carbon (TOC) concentrations (Fig. 2.9). The higher concentrations of NH_4-N and lower concentrations of TOC at depth reflect the mineralization of older peat or longer water residence times while the higher pH and cation concentrations may reflect interaction of deeper porewater with the surrounding groundwater.

Baseline porewater chemistry for the SPRUCE plots – Depth-specific piezometers, installed in summer 2013, are serving as the depth-specific porewater sampling sites for the SPRUCE experiment. Most porewater solutes showed no differences across space; however, NH_4-N increased from east to west, and NO_3-N increased from north to south. These gradients were typically small relative to the larger changes observed with depth at a given location.

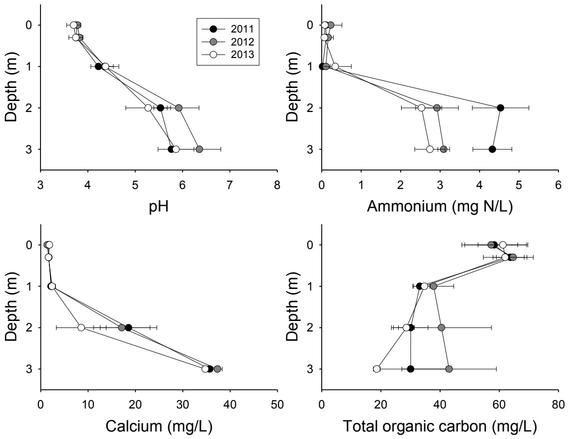


Fig. 2.9 – Vertical profiles of pH, and ammonium (NH_4-N), calcium, and total organic C concentrations in the south end of S1 bog in 2011, 2012, and 2013 (plotted are mean values per year with error as ± SD)

Porewater peatland comparison – To determine whether the vertical chemistry profiles are representative of northern peatlands, we installed three sets of depth-specific piezometers in the nearby S2 bog (precipitation-fed bog peatland like the S1 bog) and Bog Lake Fen (groundwater-fed poor-fen peatland). Results indicate that pH increased with depth, and profiles were fairly similar among the peatlands. TOC depth profiles were similar in Bog Lake Fen and S1 bog, but concentrations were lower in Bog Lake Fen. TOC concentrations in S2 bog did not change considerably with depth. Such data will help extrapolate SPRUCE results to wetlands in general.

DPH porewater observations – Peat porewater chemistry was sampled every two weeks during the *DPH* experiment. We hypothesized that warmer temperatures at depth would increase peat decomposition and thus increase the concentration of TOC in porewater with the potential for cascading effects to coupled biogeochemical cycles (i.e., increased porewater ammonium concentrations from mineralization). At the end of the sampling season, TOC concentrations were highest in the +9 °C and +6.75 °C treatments (Fig. 2.10), suggesting that the higher TOC concentrations may have come from decomposing peat. However, longer-term measurements are needed to determine whether this increase in TOC concentration persists. No substantial changes in other chemical constituents (pH, specific conductivity) have been observed thus far.

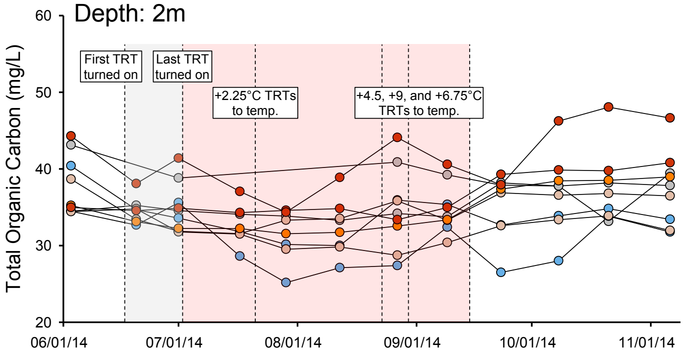


Fig. 2.10 – Total organic C concentration in porewater at 2 m in the 10 experimental plots before and during the deep-peat heat experiment in 2014. Note that the 2 m piezometer in one +6.75 °C chamber was likely cracked, and the TOC data from that piezometer are not displayed. TRT = treatment.

2.1.10 SPRUCE Collaborations

The SPRUCE project has generated significant interest in the scientific community and we have strived to actively attract and engage a range of collaborators to address disciplines and science questions not covered by ORNL and USDA Forest Service researchers. We are hosting the 14 projects summarized in **Listing of External Collaborations** (see page 151) representing 13 Universities, the Lawrence Livermore National Laboratory, the USDA Forest Service (Minnesota and Oregon), the US Environmental Protection Agency (EPA; Duluth, Minnesota) and the JGI. Over 40 persons are on our distribution listing for these funded projects and routinely participate in monthly teleconferences on SPRUCE science and project operational details. We continue to encourage collaborators to propose supplemental work in areas that are not fully represented by established working groups when they are complementary to ongoing work and do not compromise the decadal experimental plans.

2.2 Walker Branch (Task 2)

Walker Branch Watershed (WBW) is a forested watershed on the Oak Ridge Reservation and has been the site of long-term environmental research since the 1960s. DOE-BER funded WBW research was phased out over the past 3 years. Synthesis work focuses on completing several watershed ecology and biogeochemistry studies. Griffiths and Hill (2014) detailed the role of consumer excretion in stream N cycling. Excretion by a dominant snail supplied over half of the stream water ammonium concentrations and supported 26% of stream N demand, thus demonstrating an important role of consumers in stream nutrient cycling. Another study examined the role of temperature variation (diel, daily, and seasonal time scales) on leaf litter decomposition in streams (Griffiths and Tiegs, in revision). Limited work in 2012-2015 involved completing field experiments on stream N and phosphorus uptake dynamics. One study focused on seasonal changes in nutrient uptake kinetics. The data were used to develop a method to analyze uncertainty in nutrient uptake metrics. The second study focused on the effect of dual N and P releases on nutrient uptake metrics, and fieldwork and initial analysis was completed.

2.3 Mechanistic C-Cycle modeling (Task 3)

This task incorporates model development and MODEX activities at point scales (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. We report key progress in the areas of site-scale model-data integration (Task 3a), regional and global land ecosystem modeling (Task 3b), coupled ESM (Task 3c), and model functional testing (Task 3d).

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, Community Earth System Model (CESM) code repositories (Oleson *et al.* 2013), and also plays an important role in the Next Generation Ecosystem Experiment (NGEE-Arctic) and the newly initiated Accelerated Climate Model for Energy (ACME) project. PTCLM serves as a test bed for CLM development, providing the ability to quickly test the model against site observations. Recent work has focused on improving the efficiency of PTCLM simulations through improvements to spin up procedures and software infrastructure. PTCLM remains computationally expensive, especially in the context of uncertainty quantification (UQ) where large ensembles are required. This is being addressed by increasing the modularity of the code and focusing UQ and development efforts on specific subroutines and modules through the functional testing framework (Task 3d).

CLM_SPRUCE modeling – We completed model modifications needed to represent the isolated hydrologic cycle of the SPRUCE bog environment (Shi et al., 2015), as well as the microtopography in raised hummocks and sunken hollows (Fig. 2.12). Current efforts focus on representing bog biogeochemistry, and we are in the process of incorporating a new microbial functional-group based methane module developed for the NGEE Arctic project into a point version of CLM4.5. The new CH_4 module considers DOC dynamics, 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*). The new module is merged with the CLM-SPRUCE hydrology model to estimate CH_4 flux while capturing the seasonality of methane emissions (Fig. 2.13) and annual total CH_4 emissions. Recent work confirms the importance of modeling vertical and horizontal transport of DOM, acetic acid, CO_2 and CH_4 belowground at SPRUCE. The model is being used for projecting the effects of warming and elevated CO_2 on C cycling in the peatland, particularly CO_2 and CH_4 processes and surface C fluxes.

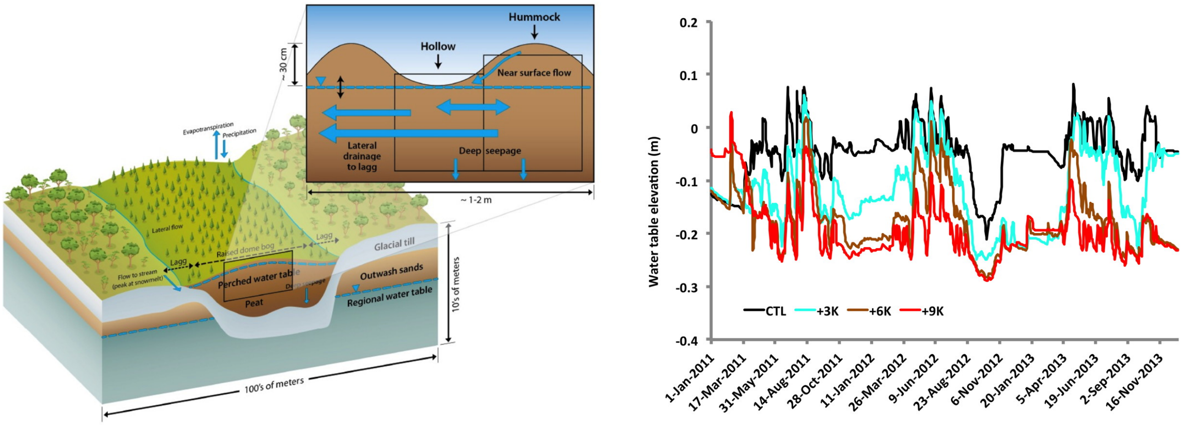


Fig. 2.11 – CLM-SPRUCE representation of S1-Bog hydrology (left panel). CLM-SPRUCE prediction of S1-Bog water table heights (relative to the hollow surface) with different levels of warming (right panel).

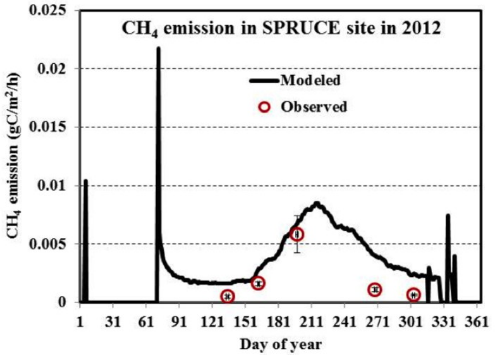


Fig. 2.12 – Comparison between observed and simulated surface CH_4 flux in 2012. Simulations use new CLM CH_4 module, which is currently being merged with the CLM-SPRUCE hydrology model.

<u>*Other site-level CLM MODEX activities*</u> –We completed a CLM-CN modeling study at the Partitioning in Trees and Soil (PiTS) phase 1 (Task 4) site (Mao *et al.* 2015a submitted), and have initiated modeling of PiTS phase 2 and 3. In cooperation with the C-Climate feedbacks project, Xiaojuan Yang developed CLM-CNP, which introduces phosphorous dynamics into CLM. The TES SFA has supported site-level evaluation and parameterization of CLM-CNP (Yang *et al.* 2014). We are currently simulating the EBIS in CLM. We have also introduced a non-structural carbohydrate pool CLM-CN 4.5 and evaluated it 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 MOFLUX (Gu *et al.* 2015c) and 15 other sites in North America evaluated in the North American Carbon Program (NACP) interim synthesis (Raczka *et al.* 2013). A detailed parameter sensitivity analysis of CLM-CN expanding on 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.

Task 3b – Improve ecosystem process models with regional observations

We performed evaluations of CLM against global estimate of GPP (Mao *et al.* 2012b) and evapotranspiration (Shi *et al.* 2013). The TES SFA also supported global CLM, GTEC and TEM model simulations for the Multiscale Terrestrial Intercomparison (MsTMIP), which have been evaluated in several studies (e.g. Zscheischler *et al.* 2014; Wei *et al.* 2014). Using both MsTMIP and CLM-CN simulations, we are evaluating how model structure affects the attribution of changes in ET to different forcing factors including climate, land use change, CO_2 fertilization and N deposition (Mao *et al.* 2015b). 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 performed 200 global 2x2 degree 50-year simulations of CLM-SP (satellite phenology) in which we are varying 24 biogeophysical parameters. We are using this model ensemble to determine the optimal parameters for best simulating FLUXNET synthesized GPP and ET. A smaller ensemble is being run with C-N cycles (CLM-CN mode) is being evaluated against biomass, soil C, 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. 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 leaf area index (LAI).

Task 3c – Earth System model process integration and evaluation

The recently initiated ACME project focuses on ESM development, reducing the need for this task. We anticipate selected TES SFA model developments will become part of the standard ACME release, and we also expect to regularly integrate ACME changes into the TES SFA. Future TES SFA efforts will focus on single point, regional and global offline model development rather than fully coupled simulations that will be led by ACME. We will continue to exercise the fully coupled model or otherwise perform atmospheric transport of CLM fluxes to evaluate SFA developments against atmospheric CO_2 benchmarks.(e.g. Bauerle *et al.* 2012), which continues the need for accurate fossil fuel emissions estimates within the SFA (Task 7). The TES SFA also supports CLM simulations in regional or global offline mode in preparation for evaluations in fully coupled mode under ACME. A major effort is continuing to integrate dynamics of the P cycle into existing structures of CLM (Fig. 2.13).

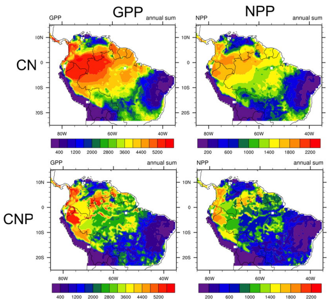


Fig. 2.13 – Comparison of both average annual gross primary productivity (GPP) and net primary productivity (NPP) between CLM-CN and CLM-CNP between 2000 and 2009. Both fluxes are highly limited by P in much of the Amazon region. All values are g C m^{-2} y^{-1}.

Task 3d - Functional testing for CLM

Working with National Center for Computational Science (http://www.nccs.gov), we developed a systematic approach to analyze the CLM software system, a web-based, interactive CLM Software Structure Analysis and Visualization System (www.ornl.gov/~7xw/Overview.html) (Wang D et al., 2014a, Wang D et al., 2014b). Our software platform (Wang D et al., 2014c, Wang D et al., 2013) supports comprehensive CLM Ecosystem Function Testing using site-based measurements and observational datasets (supported in part by the newly-initiated DOE-BER ACME project). A photosynthesis testing module has been implemented and verified using leaf web datasets (leafweb.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., 2014ab). We are also working to extend parameter optimization and UQ techniques to the functional testing framework to allow for CLM functional units to be parameterized by data across a range of scales. Note that task 3d as proposed in 2012 (integrating land-surface model constraints with inverse modeling) was redirected in FY2013 to support development of this functional testing framework. In section 3, Tasks 3b and3c are now combined into a single Task 3b, and functional testing becomes the new Task 3c.

2.4 Partitioning in Trees and Soil (PiTS; Task 4a)

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 in CLM4 or 4.5. A key feature of this task is the tight MODEX interaction between modeling and empirical scientists in experimental planning, data collection, and the analysis of results (Warren *et al.* 2012). Regular and ongoing MODEX meetings are assessing CLM simulation results from the PiTS studies, 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 replication, and data from conditions that are not normally encountered in the field: data with extreme endpoints such as photosynthetic light response curves that include radiation values that are much greater than saturated conditions.

Now the focus has shifted to the similarly structured and improved PiTS-3 (dogwood $^{13}CO_2$ labeling and shading) study. Key results from the initial PiTS-1 modeling effort indicate that CLM4 performed well simulating standing biomass and C; however, internal C dynamics were missing. Without an explicit C storage component, the ^{13}C pulse that was introduced during the labeling event was instantly sent to sinks, revealing the lack of adequate representation of C flow and storage. Modeled soil respiration was reasonable, but there was little difference between shade treatments, suggesting a need to separate soil autotrophic from heterotrophic C efflux. In addition, there were poor model estimates of soil water extraction and sap flux indicating that more experimental data were needed, specifically on the energy balance of the shade cloth (and thus canopy T), greater separation of treatments, and more replication. Also, modeled change in stem diameter was static, and was not linked to soil water availability as evidenced by the data. Results were used to help design the improved experimental system of PiTS-3.

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, and new samples of root carbohydrate concentrations showed substantial drawdown of girdled tree root starch reserves and much lower soil water extraction. In FY15, PiTS-2 field data will be synthesized by Sarah O'Brien, Argonne National Laboratory (ANL), in collaboration with ORNL and Doug Lynch (now at LiCOR).

At PiTS-3, the experimentalists collected additional field data to fulfill the needs of the modelers – especially increased seasonal replication of foliar gas exchange. A large amount of automated data has been collected including sap flow, tree basal area, soil moisture, soil $^{13}CO_2$ and $^{12}CO_2$ efflux, with and without roots or mycorrhizae. Initial results show strong seasonal dependence of C partitioning to new leaves and fruits (Fig. 2.14 left), as well as a substantial and rapid transfer of new C belowground to arbuscular mycorrhizal fungi (Fig. 2.14 right). Model simulations will begin later in 2015.

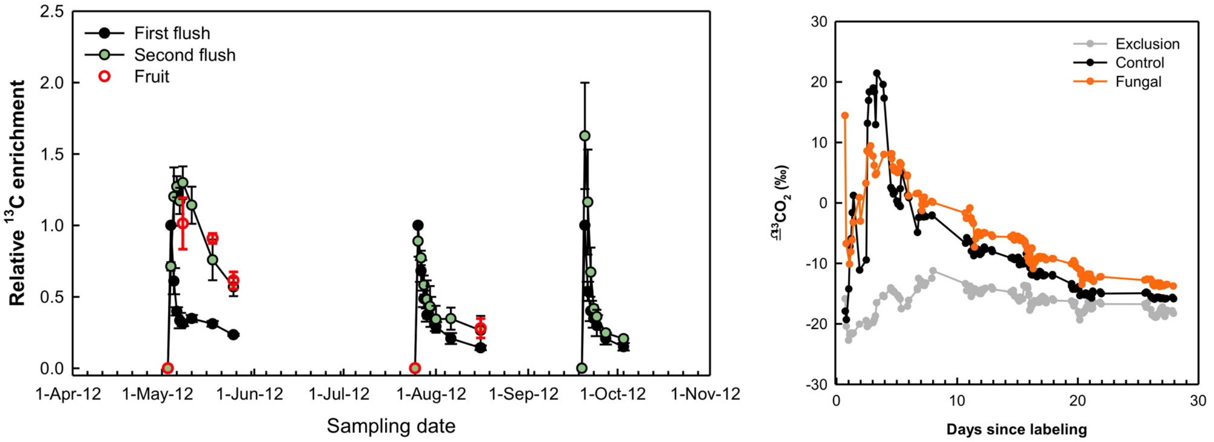


Fig. 2.14 – (Left) Timing of C flow through various tissues based on seasonal $^{13}CO_2$ pulse labeling in dogwood trees (Right) Timing and relative magnitude of $^{13}CO_2$ efflux from bulk soil (control), from soil where roots and mycorrhizal fungi have been excluded (Exclusion) or from soil where roots have been excluded, but not mycorrhizal fungi (Fungal).

2.5 Integrating Root Functional Dynamics into Models (Task 4b)

Root functional dynamics remain noticeably absent from terrestrial biosphere models (TBMs) such as CLM. Plant water and nutrient uptake and C release to the soils is thus independent of most root traits – often based solely on demand, or site characteristics such as soil texture. This task was designed to assess and improve representation of root function within TBMs through an iterative program that assesses current knowledge, tests model sensitivity, identifies specific areas for improved root process representation, and modifies or develops novel modules to improve target model processes. Model development work will be used to design and direct a paired empirical research program to provide targeted data for parameterization and validation of the new root elements within CLM4.5.

The multi-discipline Root Function Team (plant, soil and hydrological modelers, scientists and data managers) developed a comprehensive review manuscript that assesses current and future incorporation of root structure and function into models (Warren *et al.* 2015a). Key findings illustrate the lack of mechanistic detail in representation of root function across TBMs (Fig. 2.15 left), with few models considering 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 from the rhizosphere to the landscape was another central tenet of the review, and describes a path forward to scale mechanistic root functions, through plant traits, for application in TBMs (Fig. 2.15 right).

A variety of different modeling recommendations emerged from the study including the need to develop functional modules that represent specific root processes, pairing detailed root trait data (e.g., minirhizotron-sourced root dimensions and distribution) with soil water and nutrient 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. Since water efflux has been shown to be sensitive to rooting depth in CLM (Hou *et al.* 2012), in FY15 we plan to implement simple structural changes into the current CLM to test if we implement more realistic root function in the model, if the sensitivity increases. Future sensitivity analyses are also planned (described in new tasks below).

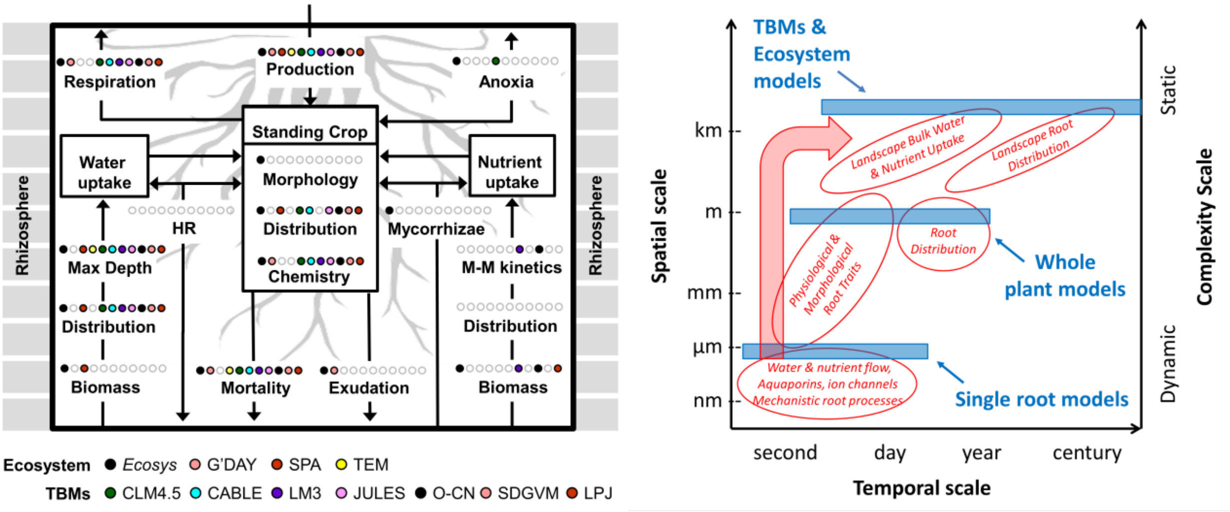


Fig. 2.15 – (Left) Presence or absence of root related functions in ecosystem and terrestrial biosphere models, and (Right) potential to scale mechanistic root process knowledge through root traits to those models.

The ORNL Root Function Team led a number of international workshops focused on roots and belowground process representation in models, made possible by generous supplemental funding from DOE in FY14 to PI Iversen, including a successful workshop at ORNL in June, 2014, on the ‘Improved Representation of Roots in Models’ and an Organized Oral Session at the 2014 Ecological Society of America meeting, “A Path Forward for Improved Representation of Fine Roots in Large-Scale Models: Linking Models, Data, and Experiments.” The supplemental funding also allowed Iversen to initiate the creation of a much-needed root trait database to provide novel synthesis of root data and to aid model development, one of the key workshop recommendations, and to continue the development of a ‘root module’ in CLM, which will allow root scientists to access and experience model treatment of root processes.

2.6 Modeling of Microbial Processing of Soil C (Task 5)

We targeted critical uncertainties in modeling coupled climate and terrestrial ecosystem processes, namely, microbially-mediated decomposition of soil organic carbon (SOC), sorption and desorption of depolymerized DOC, and measurable soil pools. Our goal is to advance understanding and representation of terrestrial ecosystem feedbacks by providing a fully functional, validated, enzyme-based C and N mechanistic cycling model – the Microbial-ENzyme-mediated Decomposition (MEND) model (Wang G *et al.* 2013) – as an alternative formulation of SOM dynamics currently in the Community Land Model (CLM-CN). The MEND model is included in future development of the CLM model under the aegis of the ACME funded through BER’s Earth System Modeling Program. Development is ongoing.

Testing MEND Against Lab-scale Incubation Data – Lab-scale incubation experiments and the accompanying data product involved 4 substrates and 5 soils, using both bulk soils and separate fractions consisting of particulate carbon (sand-sized) and mineral-associated carbon (silt- and clay-sized)(Wang *et al.* 2014ab; Jagadamma *et al.* 2014ab). For simple substrates (glucose, starch), a 3-pool first-order decomposition model was used, while for native SOC and more complex substrates (cinnamic acid, stearic acid, a 2-pool first-order model was sufficient (Jagadamma *et al.* 2013). Complex substrates induced priming of native SOC and enhanced fungi over bacteria (Jagadamma *et al.* 2013).

MEND (Wang G *et al.* 2013) was parameterized with the incubation data (Wang G *et al.* 2014b), where calibration targets were native CO_2 fluxes, $^{14}CO_2$ fluxes from substrate additions, DOC, and microbial biomass carbon (MBC). Over longer times, CO_2 fluxes decreased, and the model was unable to match observations of MBC (Fig. 2.17) (Wang G *et al.* 2014b). We concluded that large proportions of the microbial community became dormant, and we developed a new physiological model to account for dormancy (Wang G *et al.* 2014ab). Subsequently, the physiology model and the SOC decomposition model (Wang G *et al.* 2013) were united and tested against incubation data (Wang G *et al.* 2014b) (Fig. 2.17). Another research group also tested our original MEND model against other models (Li *et al.* 2014).

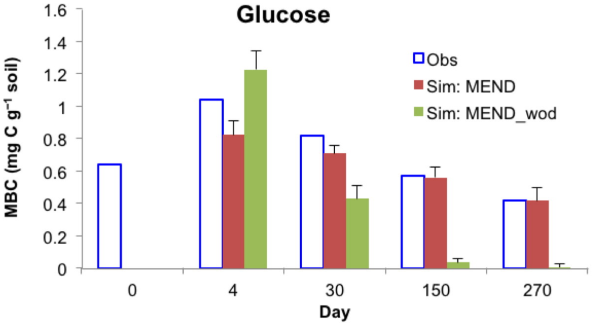


Fig. 2.16 – Microbial biomass carbon (MBC) in the Mollisol incubation experiment, as observed and simulated with MEND and MEND without dormancy (MEND_wod).

Carbon Use Efficiency (CUE) – CUE or "true growth yield (Y_G)" controls the allocation of C to maintenance and reproduction versus waste (CO_2) (Wang *et al.* 2013). True growth yield (Y_G) is dependent on changes in temperature (ΔT), where ΔT is the difference between incubation temperature (20 ºC) and the mean annual temperature (MAT). We found that Y_G had a mean value of 0.56 with 95% confidence interval of 0.48–0.64 (Wang *et al.* 2014a). Y_G decreased with increasing ΔT from 0.7 to 22.9 ºC. The temperature response coefficient for Y_G (i.e., the regression slope) was approximately -0.01 $^{\circ}C^{-1}$ with 95% CI of (-0.016, -0.005) $^{\circ}C^{-1}$. Substantial differences are observed with a temperature-dependent Y_G compared to simulations using a constant Y_G. Most ESMs use constant Y_G (Wieder *et al.* 2013).

Proxies for Microbial Biomass Carbon – Accurate MBC estimates are difficult to obtain in soils, but their importance is increasing with the incorporation of more microbial parameters in ecosystem models (Wang G *et al.* 2014ab). 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 QPCR could be a proxy for MBC while providing a better estimate of the relative size of the major soil MBC components (bacteria, fungi, archaea). Although others have compared methods for estimating soil MBC, the studies occurred prior to the development of QPCR (Bailey *et al.* 2002), or were focused on a single soil (Leckie *et al.* 2004; Buckeridge *et al.* 2013) or organism type (Baldrian *et al.* 2013; Landeweert *et al.* 2003). DNA extraction and QPCR for 16S bacteria, 18S fungi, and 16S archaea was used to determine gene copy numbers, direct counting methods were used for fungi and bacteria, and phospholipid fatty acid (PLFA) was compared to chloroform fumigation extraction MBC. Understanding the quantitative relationships between these four measures of microbial abundance in a variety of soil types and numbers (~40 soils) provided an expanding data set for modeling. Data collection is complete and the paper is being prepared (J. Dabbs et al., personal communication).

Short- and long-term decomposition experiments for model validation – During model calibration (Wang G *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 account for growth yield and maintenance rates. 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 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 began a new set of experiments using ^{13}C cellulose and ^{13}C glucose, with much greater resolution over both short and long timeframes, using paired forest and grassland soils from Thomas S. Baskett Wildlife Research and Education Center near the MOFLUX site, Freel's Bend in TN, Athens OH, and Chichaqua Bottoms Greenbelt in IA. Thus, a new deliverable is planned for August 2015 involving the short-term experiments and initial six months of the long-term experiments.

2.7 Terrestrial impacts & feedbacks of climate variability, extreme events & disturbances (Task 6)

From Jan 2012 to Feb 2015, Task 6 has produced 34 peer-reviewed papers in leading national and international journals including PNAS. Three additional manuscripts are in review. These papers covered scales from leaf to canopy to globe and ranged from theoretical to empirical to data-model integrative studies. The topics included and transcended the boundaries of ecological, physiological, and atmospheric sciences. Advances made by Task 6 have contributed directly to improving ESMs.

Task 6 supported the operation of the MOFLUX site and the SFA's interactions with the broader AmeriFlux, Fluxnet and global change research communities. The measurements at MOFLUX have been crucial to the reformulation of the fundamental EC equation (Gu *et al.* 2012), the development of novel EC theories (Gu *et al.* 2013), regional and global syntheses (e.g. Xiao *et al.* 2014), and validation of innovative remote sensing products (e.g. Joiner *et al.* 2014). Because of its strategic location, MOFLUX has attracted researchers from other institutions: Dr. Andrew Richardson has a Phenocam Webcam on the MOFLUX tower; MOFLUX is part of the soil moisture network for the project of Cosmic-ray Soil Moisture Observing System (COSMOS, http://cosmos.hwr.arizona.edu); volatile organic carbon (VOC) measurements by Dr. Alex Guenther and Dr. Mark Potosnak have led to the discovery that MOFLUX forest is the world's strongest isoprene source that has ever been measured (Potosnak *et al.* 2014, Carlton and Baker 2011). Task 6 also supported LeafWeb (http://leafweb.ornl.gov) that has been used by plant physiologists in different countries of the world.

2.7.1 Progress in MOFLUX site operations with strengthened belowground observations

The MOFLUX data acquisition systems includes EC instrumentation, meteorological and radiation sensors, vertical profiles of CO_2, H_2O, temperature and humidity, soil respiration systems, and vertical profiles of soil temperature and water content. Measurements are processed and quality-checked daily with the MOFLUX Automated Daily Data Processing and Reporting System (MADDPRS) and regularly submitted to AmeriFlux data management. We also perform scheduled measurements of leaf biochemistry and physiology, predawn leaf water potential, litter collection/weighing, coarse woody debris collection/weighing, and tree mortality survey.

MOFLUX has strengthened its investment in understanding belowground C fluxes. During the late fall of 2012 ten minirhizotron tubes were installed in the footprint of the tower. Each tube was positioned near an automated soil respiration chamber (LiCOR 8100A) to enable studies that relate root dynamics to soil efflux of CO_2. The tubes have since been sampled biweekly during subsequent growing seasons (March-November). Photos are electronically uploaded to the ORNL file upload system and are then analyzed by Joanne Childs. Analyses include, but are not limited to: root count, diameter, and length. These ongoing efforts and the coupling in observations of root dynamics and soil efflux provide a foundation for the proposed plans beyond FY2015 (Section 3.7).

2.7.2 Progress in Task 6 Science

Here we presented a few examples of scientific progress that Task 6 research has supported.

Impact of mesophyll diffusion on estimated global land CO_2 fertilization (Sun et al. 2014; L. Gu, corresponding author) – We found that an explicit consideration of mesophyll diffusion increases the modeled cumulative CO_2 fertilization effect (CFE) for global GPP from 915 Pg C to 1057 Pg C for the period of 1901 to 2010. This increase represents a 16% correction, large enough to explain the persistent overestimation of growth rates of historical atmospheric CO_2 by ESMs. Without this correction, the CFE for global GPP is underestimated by 0.05 Pg C yr^{-1}ppm^{-1}. This finding implies that the contemporary terrestrial biosphere is more CO_2-limited than previously thought.

Predictors and mechanisms of the drought-influenced mortality of tree species along the isohydric to anisohydic continuum (Gu *et al.* 2015a) – Using decade-long continuous observations of tree mortality and plant water status at MOFLUX, we studied the impacts of precipitation regimes on mortality of tree species along a wide isohydric to anisohydric continuum. We developed several effective mortality predictors, including Predawn Leaf Water Potential Integral, Mean Effective Precipitation Interval, and Precipitation Variability Index. We found that species occupying extreme positions in the isohydric axis (i.e. strongly isohydric or strongly anisohydric) suffered higher mortality than those occupying intermediate positions. Our findings point to a new direction in predicting drought-induced tree mortality.

Observed and modeled interannual variations in C uptake and water use at the Missouri Ozark AmeriFlux site (Gu *et al.* 2015c) – Water availability controls inter-annual variations in MOFLUX C uptake (Fig. 2.17). Although annual precipitation exceeded annual evaporation and transpiration demand, the precipitation did not come at the right time in most years and therefore drought stress was common. A threshold precipitation has been identified to predict the ecosystem C-water relations. Seasonal variation in C uptake was more closely related to variation in leaf biochemistry than to environmental forcing variables such as PAR. The CLM predicted interannual variations in evapotranspiration relatively well but failed to capture those of C uptake, suggesting that at interannual time scales, model predictions of C and water processes can be decoupled. Causes for such decoupling are identified, which will be useful for future model improvement.

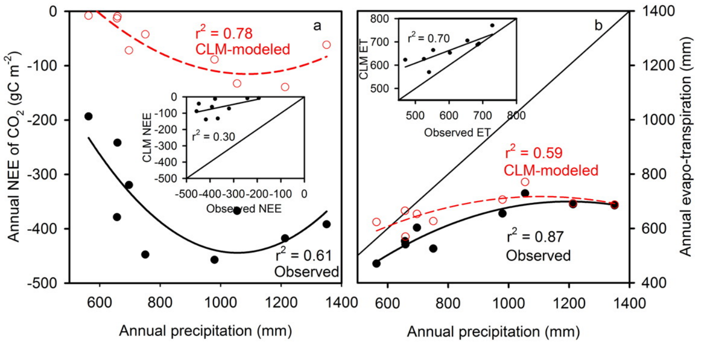


Fig. 2.17 – Measured and modeled annual net ecosystem exchange (NEE) of CO_2 and water vapor as a function of annual precipitation at the Missouri Ozark AmeriFlux site.

Artifactual responses of mesophyll conductance to CO_2 and irradiance estimated with the variable J and online isotope discrimination methods (Gu and Sun 2014) – An unresolved issue in the study of mesophyll diffusion is whether previously reported rapid responses of mesophyll conductance to CO_2 and irradiance have physiological/biochemical origins. Such responses have been reported with both the chlorophyll fluorescence-based (i.e., variable J) and C isotope-based (i.e., online C isotope discrimination) methods. Our study identified deficiencies in both methods, providing plausible explanations for the reported patterns. In addition, we refined the photosynthesis C isotope discrimination equation developed by Prof. Graham Farquhar.

Asymmetrical effects of mesophyll conductance on fundamental photosynthetic parameters and their relationships estimated from leaf gas exchange measurements (Sun *et al.* 2014; L. Gu corresponding author) – Worldwide A/C_i measurements from nearly 130 C_3 species covering all major plant functional types and collected by LeafWeb were analyzed to determine the effects of mesophyll conductance (g_m) on fundamental photosynthetic parameters and their relationships. We found that without explicitly considering mesophyll effects, the true biochemical capacities of chloroplasts are markedly underestimated and the relationships among key biochemical parameters are significantly distorted. These findings suggest the importance of quantifying g_m for understanding in-situ photosynthetic machinery functioning and show that the virtual laboratory LeafWeb is a cost effective tool for promoting international collaboration, collecting spatially distributed datasets of global importance, and conducting syntheses that would otherwise be difficult to carry out.

An eddy covariance (EC) theory of using O_2 to CO_2 exchange ratio to constrain measurements of net ecosystem exchange of any gas species – A new EC theory was developed (Gu 2013) that constrains measurements of NEE of any atmospheric gas species with the ecosystem O_2 to CO_2 exchange ratio (g), also known as oxidative ratio. The fundamental equation of the new theory was derived. A convenient method for measuring g with existing O_2 technologies was also described. The new approach uses less restrictive assumptions, avoids indirect calculations, and is expected to be more reliable than the currently used EC approach. Specific technological innovations were recommended to support the full application of the new approach. The adoption of the new approach will greatly enhance the scientific and societal values of flux sites and networks by eliminating measurement biases and by providing value-added datasets to enable understanding the oxidation state of the biosphere.

2.7.3 Progress in LeafWeb and ESM support

LeafWeb is an automated online tool that has two primary objectives: (1) provide plant physiologists and photosynthesis researchers a reliable, convenient tool for analyzing leaf gas exchange measurements for key biochemical and physiological photosynthetic parameters, and (2) to develop a global database of plant biochemical and physiological parameters needed by ESMs. LeafWeb (Gu *et al.* 2010) recognized the critical importance of the model of Farquhar, von Caemmerer, Berry (1980) as a changing-point model for estimating photosynthetic parameters. Users of LeafWeb are from Asia, Europe, South America and North America. Tens of thousands of A/Ci curves have been accumulated. The first synthesis paper based on data gathered through LeafWeb is now published (Sun *et al.* 2014), and was featured on the journal's cover. Data collected by LeafWeb was vital to the development of the first global mesophyll conductance model and its implementation in CLM4.5 to study the impact of mesophyll diffusion on global land CO_2 fertilization effect. Collaboration with the TRY plant trait database is now under discussion. Dr. Jens Kattge.

2.8 Fossil Emissions (Task 7)

Task 7 centers on estimating CO_2 emissions from fossil fuel consumption and their uncertainty. Over the last three years, TES SFA funding has contributed to creating global emission inventories at monthly temporal resolution and national spatial resolution for use in Task 3 analyses; examining the global and spatial distribution of emissions; and calculating the evolution of global uncertainty of those emissions with time.

The calculation of monthly emission inventories has been completed for emission years 2009 and 2010; emission year 2011 is in progress as critical input data were greatly delayed and just received from the United Nations Statistical Office at the time of this writing. Data have been and will continue to be maintained by the Carbon Dioxide Information Analysis Center (CDIAC) and are made freely available to the public (as well as SFA Task 3 analysis). Global, spatial distributions of emissions have been created for both annual and monthly data sets. Data have been and will continue to be maintained by CDIAC and are made freely available to the public. Andres *et al.* (2014) examines the evolution of uncertainty in global fossil CO_2 emission estimates through three different analyses and considers the unique attributes of this data set including dependent and independent data, temporal and spatial relationships, missing and filled values, and expert judgment. This was the first published, comprehensive examination of this subject in 30 years. Fig. 2.18 compares the uncertainty associated with fossil fuel estimates to other major components in the global C-Cycle.

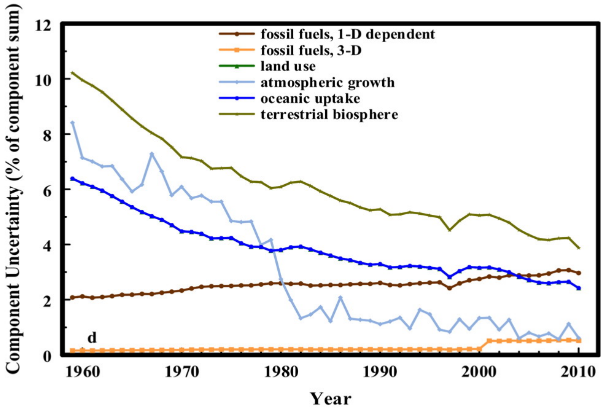


Fig. 2.18– Fossil fuel CO_2 compared to other global C-Cycle components. One σ uncertainty is expressed in percent of total C-Cycle flux and reservoir stock changes. 1-D dependent and 3-D are respectively the maximum and minimum uncertainty analysis results. The land use curve lies directly under the oceanic uptake curve

This task contributed to other related activities. Since the last triennial report, these activities include 18 peer-reviewed publications, 2 edited works, 53-meeting abstracts, 14 technical reports, and 4 invited presentations at universities and institutes. These include Andres as a contributing author to "Chapter 5 Drivers, Trends and Mitigation" of the *IPCC Fifth Assessment Report (Mitigation of Climate Change)*. That IPCC-related work continues as Andres is contributing to the ongoing Coupled Model Intercomparison Project (CMIP) 6 activities. Andres also continues to play a prominent role in Global Carbon Project activities, including the recently updated Global Carbon Atlas (originally released at the UNFCCC COP19 in Warsaw, Poland November 2013, and had more than 24,000 unique visits from 164 countries in the first week after release). Finally, the uncertainty emphasis is expanding to examine the uncertainty with spatially distributing emissions on a one-degree grid; this work is nearing publication and will have application to mapped emissions produced by other researchers.

2.9 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 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. A listing of data archives generated for the TES SFA is compiled in Appendix B.

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. Publically available data products include value-added environmental monitoring data, completed S1-Bog characterization studies including vegetation surveys, vegetation allometric and biomass sampling results, and investigations of peat depth with ground penetrating radar (GPR). Publically and project-only available data, the Data Policy, and Data Management Plans are available: http://mnspruce.ornl.gov/content/spruce-data-policies, and the TES SFA: http://tes-sfa.ornl.gov/sites/default/files/TES_SFA_Data_Policy_20130510_Ver_1_approved.pdf

Task 5 data are available for lab-scale experiments conducted to investigate the dynamics of organic C decomposition from several soils and to test the newly developed MEND model on the ORNL TES SFA web site: http://tes-sfa.ornl.gov/node/80.

Additional SFA task data products have been archived at program-specific archives, Fossil Emissions at CDIAC, MOFLUX at AmeriFlux, and NACP data synthesis products at the ORNL Distributed Active Archive Center (ORNL DAAC).

2.10 TES SFA Personnel Effort Not Defined in a Specific Task

Staff effort is primarily expended to accomplish defined TES SFA tasks described above, however, TES SFA funding is also allocated to allow staff to take advantage of new scientific opportunities and to exercise their involvement in science development workshops (e.g., *Data Model Needs for Belowground Ecology; Root Workshops*), and to contribute to science responsibilities for both organized (Journal Editorships) and ad hoc review processes (paper and proposal reviews). The FACE Model-Data Synthesis activity focusing on the Oak Ridge and Duke FACE studies, is a notable activity reaching fruition in 2014 to which the following TES SFA staff made significant contributions with TES SFA support: P. Hanson, A. Walker, R. Norby, C. Iversen, J. Warren, P. Thornton and D. Ricciuto. Additional results from the latter years of the ORNL FACE study have also been recently analyzed and published with TES SFA support (e.g., Kim *et al.* 2015, Lynch *et al.* 2013, Warren *et al.* 2015b). TES SFA also supported staff participation in the preparation of the IPCC AR5 (Blanco *et al.* 2014) and US Assessment (e.g., Ryan *et al.* 2013, 2014) reports in either authorship or reviewer role.

3. RESEARCH PLANS FOR FY2016, FY2017 AND FY2018

3.1 SPRUCE Future Plans and Deliverables (Task 1 – Future Plans)

The motivation for SPRUCE (outlined in our original SFA plans provided online; http://tes-sfa.ornl.gov/node/17) was to develop quantitative information on ecosystem responses associated with climate change as a prerequisite for the development of ecological forecasting tools for policy makers to evaluate safe levels of greenhouse gases in the atmosphere. The SPRUCE experiment (Section 2.1) provides a platform for testing mechanisms controlling vulnerability of organisms and ecosystems to important climate change variables. SPRUCE addresses key science questions for understudied high-C ecosystems essential for informing models of vegetation change under projected future climates:

1. Will belowground warming reverse 10,000 years of C accumulation in peatlands that store 1/3 of the earth's terrestrial C?
    a. If the peatland turns into a C source, how much C release will occur?
    b. Will the released C be in the form of CO_2 or CH_4 with about 28 to 34 times the global warming potential of CO_2 at the end of this century (Myhre *et al.* 2013)?
2. Are peatland ecosystems and their organisms vulnerable to atmospheric and climatic change?
    a. What changes are likely? To what degree will changes in plant and microbial physiology under elevated CO_2 impact a species' sensitivity to climate or competitive capacity within the community?
3. Do critical air and soil temperature thresholds exist for ecosystem processes and organisms?
    a. What level of warming changes the annual C and water balance?
4. Will ecosystem services (e.g., regional water balance) be compromised or enhanced by atmospheric and climatic change?

As described in Section 2.1, the belowground warming component of the SPRUCE project has been initiated and we are beginning to address these questions for deep undisturbed peats. We expect to initiate whole-ecosystem warming including the addition of air warming and elevated CO_2 exposures in June 2015. SPRUCE treatments will be deployed and responses measured and interpreted over a full decade. Such a time period should allow time for interannual variation effects on treatments to be observed and for long-term nutrient cycle alterations to develop in response to the warming and CO_2 treatments. The following text briefly describes the measurement tasks for SPRUCE in the next three years of whole-ecosystem warming in the context of the hypotheses or key questions most relevant to the instantaneous and early responses. Proposed measurement methods have typically been described in prior review documents (http://tes-sfa.ornl.gov/node/17).

Net C Exchange – Early responses in C exchange at the ecosystem level to the imposed warming treatments are hypothesized to be driven by instantaneous changes in subsurface aerobic and anaerobic microbial activity. Large collar flux measurements including subsurface, *Sphagnum* and short stature vegetation (Hanson *et al.* in review) will be a focus of our measurement activity during the next three years. Measurements using this approach will provide an early index of the cumulative response of the column of biological activity from shrubs to the complex microbial community. Light and dark collar flux measurements allow one to distinguish the C uptake capacity of the photosynthetic vegetation against the dominant heterotrophic microbial activity in this high-C peatland. The surface CO_2 and CH_4 flux observations have been and will continue to be complemented by periodic measures of their isotopic composition (^{14}C-CO_2, $^{14}CH_4$, $^{13}CO_2$, $^{14}CH_4$, ^{2}H-CH_4). Such data will allow us to understand not only levels and direction of change in C flux, but the source of C pools from which such change may have been derived (e.g., new photosynthate vs. very old deep C).

To complement the large-collar approach described above an exploratory system for EC "like" observations will be deployed within a SPRUCE enclosure to pursue an innovative method for measuring net ecosystem C and water vapor fluxes in an open-top enclosure with defined forced air circulation and turbulence. The SPRUCE enclosures have a dimension of tens of meters in the vertical and horizontal directions. Air is withdrawn from the enclosures at a height of about 7m, warmed and returned to the enclosure at a height of about 1m. There are 8 of the ground-level blowers symmetrically positioned around the wall of the enclosure. Estimating ground references fluxes of naturally produced gas species such as CO_2, water vapor and CH_4 in such a structure has never been attempted. The enclosure is too big to cap for traditional chamber approaches. A Lagrangian trajectory inversion approach could be pursued, but this method has low accuracies that may not resolve differences between treatments. Preliminary data suggested that natural fluxes within the enclosure may be measured by placing instruments along the central axis of the enclosure at a height that is either slightly lower than the center height of the blower or at the height of the inlet where the air is recycled to the blower. At these heights, mass flow caused by the blowers is minimized, allowing gas fluxes from the natural ecosystem to be measured. Fluxes of CO_2, methane and water vapor measured in the Oak Ridge prototype showed reasonable diurnal patterns and had expected magnitudes for a well-sealed enclosure. This approach will be deployed at the SPRUCE site in the summer of FY2016. If successful, we will pursue options to acquire or reallocate funding to fully instrument the SPRUCE study with such observations.

Sphagnum – *Sphagnum* sp. are hypothesized to be the plant species most dramatically affected by the warming treatments and will be given focused attention in the first three years of SPRUCE whole-ecosystem manipulations. In the context of the SPRUCE treatments we hypothesize that warming and repeated drying will drastically influence within and among species distributions, net photosynthesis and production. Furthermore, we hypothesize that warming will indirectly influence nutrient cycling and alter moss and vascular plant competition. Our measurements will target the assessment of moss physiological responses to warming including gas exchange, tissue water content and holding capacity, and changes in N, P and carbohydrate metabolism. A key addition to these measurements will be the inclusion of the *Sphagnum* associated microbiome through a recent Joint Genome Institute CSP award (PI Joel Kostka). This will allow us to link our moss physiological results to the greater SPRUCE microbiology and biogeochemistry tasks.

Plant Physiology – With final plot instrument installation completed by mid FY15, we will begin long-term measurements of automated sap flow in trees and soil water content within the hummock-hollow complex. Plant water relations measurements will continue throughout the growing seasons during FY16-18. We hypothesize that the warming treatments will produce a shift in *Picea* leaf area by accelerating loss of older foliar cohorts in favor of the new tissue developed under treatment conditions. Thus the first several years of treatments are expected to cause a substantial change in plant water use, and simultaneous net C uptake. Sap flow sensors will be maintained for up to two years based on performance, then will be replaced every two years. Predawn and midday stem and leaf xylem water potential will also be assessed during seasonal dry periods for all woody species in each plot to determine relative water potential stress in leaves and stems across treatments. Measurements will be conducted on transpiring and non-transpiring foliar twigs (i.e., foliage and stem tissue in equilibrium) seasonally, which will indicate relative water stress of bulk leaf or woody xylem, respectively. Assessment of stomatal conductance will also be conducted as part of the gas exchange campaigns.

We hypothesize the warming and CO_2 treatments will lead to substantial shifts in foliar display, chemistry and photosynthetic capacity. In FY15, we will conduct two intensive physiology campaigns during mid-late summer, one in July as the new *Picea* shoots are developing, and one in late August after shoots are fully elongated. Our focus during these two campaigns will be to assess initial foliar sensitivities for *Larix* and the three most recent *Picea* needle cohorts. We will measure light saturated photosynthesis (A_{max}) and stomatal conductance (g_s) at ambient and elevated CO_2 concentrations, as well as dark respiration (R_d), all at a common T across plots. Foliage from these trees as well as the two dominant shrubs will be analyzed for leaf mass per area and N to track morphological responses to treatments. Future FY 16-18 physiological measurement strategies will be adjusted based on initial and cumulative responses beginning in FY 15 campaigns.

In FY 17, we plan to add assessment of temperature response of A-Ci, light response curves and respiration of excised woody and foliar tissue of the 4 primary woody species*: Picea, Larix, Ledum* and *Chamaedaphne*. Since this is destructive, measurements will be limited based on available material. In conjunction with the A-Ci and light response curves we will quantify leaf level chlorophyll fluorescence and PSII quantum yield of the primary species. These data will be used to develop a scalable fluorescence model (see also Task 6). Targeted physiology and water relations campaigns will depend on vegetation responses during the prior treatment year, data needs from the CLM-SPRUCE modeling group, and collaborations with external researchers.

Tree Growth, Shrub Layer NPP, and Vegetation Phenology – We hypothesize that tree, shrub and forb growth responses to the warming treatments to develop gradually over time in conjunction with enhanced mineralization of stored elements with the peat within which the trees are rooted. The response of these organisms to elevated CO_2 may develop faster, but are likely to be only expressed in the second and third years of treatment (and beyond) since annual current-year stem and leaf growth is controlled in a part by tissue primordial laid down in the overwintering buds from the prior growing season. Fall senescence and spring foliar development for *Picea, Larix, Ledum, Chamaedaphne* and *Smilacina* will be tracked closely in the spring and fall and supplemented by the phenology images collected by Andrew Richardson.

Rapid community changes for bog species exposed to warmer mesocosms environments have recently been reported by Dieleman *et al.* (2015). Significant pretreatment efforts has been expended in the assessment of community composition within the SPRUCE enclosures (three 1× 2 m plots per enclosure) and the potential rapid expansion of graminoid species with warming and elevated CO_2 will be tracked closely over the initial years of treatment and beyond.

Root and rhizosphere dynamics – We have found that average summer water table depth exerts an important control over rooting depth distribution and root production in the S1 bog. We expect that a major outcome of warming will be a decline in water table levels, and potential increases in nutrient mineralization, which could lead to increased rooting depth distribution and a decline in root production, though we expect these responses to be mediated by elevated [CO_2]. We will track these potential outcomes using the tools and techniques we have developed prior to the experimental manipulation. Furthermore, we will continue to ask cutting-edge questions regarding interactions between fine roots and fungal hyphae in the rhizosphere using novel AMR technology

Microbial Community Activity and Change – Our work on microbial communities in the treatments will focus on understanding how the overall microbial community (bacteria, fungi and archaea) responds to the balance of direct (heating) and indirect (drying, plant communities, C-input, etc.) effects of the treatments. Our specific focus will be on changes that occur with fluctuation in the water table and temperature due to seasonal or experimental treatments as we anticipate this will have critical impacts on the balance of methanogenic and methanotrophic activity in the system as the boundary between aerobic and anaerobic conditions moves deeper in the peat profile. While there are number of collaborative partners in these efforts, our group in particular will focus on understanding these changes using measurements based on QPCR and DNA sequencing techniques across the entire breadth of treatments and with depth in the peat profile. Currently we combining QPCR and rRNA gene amplicons on all samples, and are collaborating with JGI to conduct metagenomic analyses on select samples/experiments. This will be accomplished using a combination of extensive sampling schemes conducted repeatedly over the decadal time frame of the experiment, as well as intensive short term campaigns to investigate other patterns associated seasonal variation, rooting depth dynamics, and other specific phenomena.

We share our results across the project and work to coordinate measurements and avoid redundancy among the collaborating projects from Kostka (Georgia Tech), Bridgham (Oregon), Hofmockel (Iowa State) that are focused on peat decomposition, controls on methanogenesis, and mycorrhizal responses respectively.

Organic Matter Decomposition – We hypothesize that warming will accelerate organic matter decomposition in the first 3 years due to increased microbial activity. A lower water table in warmer treatments is also predicted to affect decomposition rates in hollows relative to hummocks. In ambient plots (+0 °C), decomposition is expected to be slower in hollows than hummocks due to moisture differences. With warming, decomposition may be less variable between hummock and hollow locations as a lower water table and thus deeper oxic zone of peat will accelerate decomposition in hollows. Work on the main decomposition experiment will focus on constructing and deploying litterbags in the 10 experimental plots in 2015, and collecting and analyzing litterbags over time (with pick updates over the next 3 years currently planned in 2015 and 2016). The short-term (3 year) moss decomposition experiment that was initiated in 2014 to examine the effect of location (hummock, hollow, lawn) and moss species on decomposition rates will be completed in summer 2017.

We propose to carry out additional decomposition experiments to 1) examine inter-annual and depth-specific variation in cellulose decomposition and responses to warming and elevated CO_2, 2) examine the decomposition of litter grown in the elevated vs. ambient CO_2 plots, and 3) examine the interaction between the decomposition of litter mixtures (*Sphagnum* and aboveground litter together) and temperature.

Hydrology and Porewater Chemistry – During the first few years of the experiment, we predict that TOC and nutrient concentrations in porewater will increase with warming due to increased mineralization. However, the increase in TOC and nutrient concentrations may not lead to increased solute fluxes as a lower water table is predicted to decrease water runoff from the warmer plots. Sampling of piezometers (0 to 3 m deep) in each of the 10 experimental chambers will occur every 2 weeks. Biweekly sampling is necessary to capture the temporal dynamics of porewater chemistry that were observed during pre-treatment period and to examine whether these temporal dynamics are altered with warming. In 2015, the basin that collects runoff from each plot will be outfitted with an automated water sampler that will measure water outflow and collect a flow-weighed water sample. The flow-weighted water sample will be retrieved weekly and analyzed for chemistry in order to calculate water, C, and solute fluxes. These repeated samplings over space and time using both the piezometers and outflow collectors will be used to determine how solute yields, particularly TOC, respond to warming and elevated CO_2. Measurements of water yields and TOC concentrations in outflowing waters will directly contribute to the calculation of TOC yields from the whole-ecosystem experiment. Other solute data will contribute to assessments of nutrient cycling, decomposition, and organismal responses and will be critical to our interpretation of the sources, cycling, and transport of organic matter from the peatland.

We also plan to characterize some aspects of bog hydrology that are important parameters in the CLM_SPRUCE model, but have not yet been measured in the S1 peatland including 1) the snow depth and the depth of the frozen peat layer, 2) throughfall volume and chemistry for estimating canopy interception, and 3) the hydrological connection between the water table and the *Sphagnum* surface via field measurements (weighing lysimeters) or laboratory experiment (peat column and water table manipulation) to determine the conditions under which *Sphagnum* and surface peats lose their hydrological connection to the water table.

Modeling SPRUCE Response Mechanisms – SPRUCE project staff provide measurements, parameters and mechanistic algorithms for model development, evaluation and forecasting in the CLM-SPRUCE model (section 3.3.1). The modeling framework is also expected to reveal key process uncertainties and to forecast key transitions (e.g. ice thaw or bud break) to inform the nature or timing of new observations. Model improvements in CLM-SPRUCE will advance wetland model concepts for application in regional and global models.

Table 3.1 outlines the major SPRUCE activities anticipated for the remainder of FY2015 and the proposed work over the next 3-year funding cycle.

Table 3.1 – Future deliverables for SPRUCE

Date	Deliverable	Status
Remaining FY2015 Deliverables		
March 2015	Submission of manuscript describing vertical pore water profiles in the S1 bog.	In progress.
March 2015	Submission of baseline SPRUCE water relations manuscripts	In progress
June 2015	Full deployment of remaining SPRUCE sensors in all treatment plots	Planned
Sep 2015	Manuscript on peat age and historical C accumulation from ^{14}C data.	McFarlane *et al.*
Sep 2015	Initial whole-ecosystem response measurements for all tasks	Planned
Sep 2015	Submit High-profile paper(s) describing results from DPH	Planned
Sep 2015	A manuscript on a 2-year preliminary investigation of fine-root dynamics in the S1 bog is currently being prepared	In progress
FY 2016 Deliverables		
Oct 2015	Recruit strong plant physiologist / ecophysiologist post docs	Planned
Jan 2016	Whole-Ecosystem Warming Technique Paper	Planned

Jan 2016	Draft manuscript detailing spatial variation in porewater profiles in S1	In progress
Oct 2016	Full season of task measurements under whole-ecosystem warming	Planned
Oct 2016	Manuscript on root-fungal interactions using AMR technology	Planned
FY 2017 Deliverables		
January 2017	Draft manuscript comparing porewater chemistry across peatlands (S1 bog, S2 bog, Bog Lake Fen).	Planned
Oct 2017	Full season of task measurements under whole-ecosystem warming	Ongoing work
Oct 2017	Temperature response of A-Ci, light response curves and respiration of excised woody and foliar tissue of 4 primary species	Planned
Dec 2017	Manuscript of initial physiological plant responses	Planned
Dec 2017	Manuscript on initial rhizosphere responses to warming and elevated [CO_2]	Planned
FY2018 Deliverables		
Jan 2018	Based on prior results, plan physiological campaigns for 2018	Planned
Oct 2018	Full season of task measurements under whole-ecosystem warming	Ongoing work
Summer 2018	Complete draft manuscript on the moss decomposition study.	Planned

3.2 Walker Branch Summary Activities (Task 2 – Limited Summary Effort)

Work on Walker Branch research will focus on completing analyses of stream nutrient cycling and whole-stream metabolism (GPP and ecosystem respiration) and quantifying the uncertainty in stream nutrient uptake. A10-year-long dataset of daily stream metabolism measurements will be used to develop a stream metabolism model to examine the effects of climate change (changes in forest phenology, stream flow, temperature) on stream C cycling. This work is being done in collaboration with an ecosystem modeler (Kyle Whittinghill at St. Olaf College) and ecosystem ecologist (Brian Roberts at Louisiana Universities Marine Consortium) and model development has begun.

Table 3.2 – Walker Branch Deliverables.

Date	Deliverable	Status
Summer 2015	Submit paper on uncertainty in nutrient uptake kinetics.	Planned
Fall 2015	Draft paper on dual N and P uptake in streams.	Planned
Fall 2016	Complete development of stream metabolism model and analyze various climate change scenarios.	Metabolism model in development.
Fall 2017	Manuscript on effects of climate change on stream C cycling.	Planned

3.3 Mechanistic C-Cycle Modeling (Task 3 – Future Plans)

This proposed task integrates observations from past and current DOE-funded flagship experiments, observation networks, and related activities into models across spatial and temporal scales to identify and reduce terrestrial process and parameter uncertainties in the global climate-C system. Our key goal is to convey new process knowledge from plot-level and focused model-data studies to improve climate prediction in an ESM, and to use modeling to inform new measurements. A consistent modeling framework across scales is therefore essential. The TES SFA adopts the CESM, which has an extensive user base and development community, and forms the foundation for the recently initiated ACME. The CLM within the CESM framework provides the opportunity to integrate knowledge from across projects and institutions with the goal of improving climate predictions. Subtask 3.1 outlines future plans for model development and testing at the site scale, while Subtask 3.2 outlines plans for scaling these results to regional and global scales, and testing them with regional datasets. Task 3.3 involves the development and application of a functional testing framework for CLM, which will be utilized in other subtasks as appropriate.

3.3.1 Task 3.1 – Improve ecosystem process models with site-level observations and experimental data

Site-level observations from numerous sources, including SPRUCE, PiTS, NGEE-Arctic, FACE and AmeriFlux are already being used to inform CLM-CN for the purpose of model evaluation and development. Many of these analyses indicate that current CLM representations of key C-Cycle processes are too simplistic, contributing to biases in biomass (DeKauwe *et al.* 2014), hydrology (DeKauwe *et al.* 2014, nutrient limitation (Walker *et al.* 2014) and soil C stocks (Luo *et al.* 2012). Given the model biases and the expertise and investments within the TES SFA, we propose to focus model development efforts on the following processes: 1) wetland biogeochemistry, 2) allocation, 3) rhizosphere interactions 4) photosynthesis, 5) root function, and 6) soil C decomposition. The first four are described below; the last two are expanded into independent MODEX activities within Tasks 4 and 5. Model improvements made in these tasks will be integrated into a common code base within the SFA and under the guidance of ACME land-team lead Peter Thornton, model improvements will also be merged into the ACME code base for testing in a fully coupled ESM.

Model development in this task will first focus on point CLM (PTCLM) at 3 "supersites" where a) multiple long-term co-located datasets are available to constrain model processes, and b) ORNL TES investigators have access for MODEX-style activities with a relatively short turnaround time. The supersites are 1) The S1-Bog near Marcell, Minnesota containing the SPRUCE experiment, 2) Oak Ridge Reservation studies in eastern Tennessee including the WBW, FACE, and PiTS study sites, and 3) the MOFLUX eddy covariance tower footprint near Columbia, Missouri. In addition to point-scale modeling, we will design high-resolution 3-D simulations of associated watersheds using CLM combined with a subsurface reactive transport model to test assumptions about model scaling. We will also develop an ecological forecasting system for these supersites to assimilate observations and predict ecosystem behavior over synoptic to interannual timescales. This forecasting system will track model skill, reveal key process uncertainties, and inform measurement campaigns by assessing the importance of specific observations at specific times. Beyond the supersites, an extended network of long-record core AmeriFlux, FLUXNET, FACE and NSF Long Term Ecological Research (LTER) sites will be used for benchmarking and spatial scaling of new model versions. We will also use synthesis datasets developed within DOE BER benchmarking activity, and the NGEE experiments for additional model evaluation. Model structural improvements will be evaluated at regional to global scales (Task 3.2).

Model development activities

Wetlands – Modeling efforts will focus on *Sphagnum* physiology and more realistic bog biogeochemistry at the SPRUCE bog. *Sphagnum* peat mosses are keystone species in peatland ecosystem and therefore exert a substantial impact on ecosystem function and net C balance across the landscape (Clymo and Hayward 1982, Gorham 1991, Wieder 2006, Weston et el. 2014). We will introduce a new moss plant functional type in CLM_SPRUCE [Shi *et al.* 2015] using site observations to parameterize the influence of water content on *Sphagnum* photosynthesis, and to better understand the influence of moss on hydrological and biogeochemical conditions in peatland bogs. Specifically, we will use site measurements to develop and parameterize model representations of *Sphagnum* internal water dynamics including capitulum uptake from the peat, rehydration from surface water, and evaporative losses. *Sphagnum* photosynthesis and its relationship to water content, temperature and other environmental variables will also be tested and improved as a part of the photosynthesis modeling subtask and the functional unit testing framework (see below).

We will also continue to develop a new methane module has been developed to predict methane production and consumption from laboratory incubation experiments in conjunction with NGEE Arctic (Xu *et al.* 2015). In collaboration with Xiaofeng Xu (University of Texas El Paso), improvement is underway in terms of detailed biogeochemical processes along the soil column. The data-model integration effort will primarily include model parameterization, up-scaling from plot to watershed scale, model sensitivity analysis, and model synthesis. We will use observational biogeochemical data along the soil profile from Scott Bridgham at Oregon State University and Jeff Chanton at Florida State University for model evaluation and parameterization at SPRUCE. We will merge this model with the updated *Sphagnum* model to explore the potential impacts of warming and elevated CO_2 on belowground biogeochemical processes and land surface methane and CO_2 fluxes.

Finally, we also plan to conduct a small model intercomparison workshop with participants representing existing land-surface models including wetland processes to conduct simulations of pretreatment and 10-year manipulations at the SPRUCE site in FY2016, and provide information to the SPRUCE study group about process uncertainty and measurement needs.

Allocation –Data from FACE and other experiments indicate substantial shifts in allocation patterns resulting from increases in CO_2 concentrations (DeKauwe *et al.* 2014) and changing nutrient status. Allocation changes are not captured in models like CLM with constant annual allocation ratios. We will improve CLM by incorporating realistic non-structural carbohydrate reserves and incorporating seasonal patterns for leaf, stem, seed and root allocation. More in-depth study on fine root allocation will be conducted in the root function task. The new model will be tested and parameterized using the PiTS dogwood experiment (phase 3), FACE data and AmeriFlux observations.

Photosynthesis – Huge uncertainty in model simulation of GPP remains a feature of current TBMs, including, somewhat surprisingly, the response of GPP to elevated CO_2. Multi-scale photosynthesis measurements will be used in a formal mathematical UQ of model assumptions and parameters. In collaboration with Ming Ye at Florida State University, the latest pioneering hierarchical Bayesian methods will be used to assess the likelihood of various model representations of processes relevant to the simulation of GPP. The UQ will link with experiments and observations in Task 1, specifically, lab and field data from the SPRUCE S1-Bog will be used to rapidly assess models of *Sphagnum* photosynthesis, and data from the MOFLUX tower will be used to assess models of temperate forest photosynthesis, particularly in relation to water stress. Activities addressing forest photosynthesis will also focus on the scaling from leaf photosynthesis to canopy photosynthesis, including scaling of the CO_2 response. We will incorporate mesophyll conductance into site-level CLM (Gu *et al.* 2014) and investigate its effects on CO_2 fertilization and water use. Formulations of leaf and canopy acclimation to both water stress and high temperature stress will be investigated based on the literature (e.g. Smith and Dukes 2013), and new measurements (e.g., SPRUCE physiology).

Effects of rhizosphere processes on nutrient cycling – In order to accurately predict plant uptake of **immobile** nutrients, it is important to take rhizosphere processes into account (Hinsinger *et al.* 2011). Therefore, in addition to the proposed work on improving root uptake of **mobile** nutrients (Task 4c), we propose to initiate the development of the representation of rhizosphere effects on nutrient cycling. We focus on two aspects of rhizosphere processes: root exudate and mycorrhizae. We plan to incorporate an existing three-dimensional P uptake model that includes the effect of exudation on root system P uptake (Schnepf *et al.* 2011, 2012). We plan to perform sensitivity experiments using the existing P uptake model to explore the importance of root exudate to soil P availability and overall plant P uptake. We also plan to add a simper representation of root exudate effects on soil P availability in CLM-CNP. The complex three-dimensional model can be directly parameterized by intensive observations and can be used to help parameterize the P-enabled large-scale land surface models.

Mycorrhizae play a pivotal role in nutrient cycling and nutrient transfer, particular for phosphorus (P) uptake in P-impoverished ecosystems (Smith and Read 1997). Mycorrhizae fungi can 1) increase the soil volume that plant can exploit for phosphorus 2) lead to the increase in the surface area for the absorption of P due to smaller size of hyphae, and (3) acquire P from soil solution at lower concentrations than root (Smith 2011). It is imperative to explicitly represent mycorrhizae P uptake in P-limitation enabled models. The Fixation and Uptake of Nitrogen (FUN) model (Brzostek *et al.* 2014) provides a mechanistic framework to assess the impacts of both arbuscular mycorrhizal and ectomycorrhizal uptake strategies on coupled C-N cycles. We plan to collaborate with Joshua Fisher at Jet Propulsion Laboratory (JPL) to develop a representation of mycorrhizae P uptake in CLM.

This task will improve the representation of rhizosphere processes and rhizosphere-nutrient interactions in CLM-CNP and is closely linked to efforts in Task 4b and Task 4c. The global root ecology database in Task 4b will be used to scale up modeled processes to the global scale. The proposed experiments and future Rhizosphere Ecology Laboratory in Task 4c will be providing valuable data to further improve process representation and parameterization of rhizosphere-nutrient cycling interactions. The rhizosphere-enabled CLM-CNP model can be applied at the supersites like SPRUCE and help improve representation of nutrient controls on C uptake in peatland ecosystems. Vegetation productivity in peatland ecosystems is often P limited or N-P co-limited (Bridgham *et al.*1996). Early survey at SPRUCE sites also suggests P limitation for woody species like *Ledum*. Changes in temperature, [CO_2]

and N deposition will change the dynamics of nutrient cycling (both N and P) and nutrient limitation, therefore affecting C cycling in peatlands.

Ecological forecasting – Past drivers, future scenarios, model processes and parameters, and real or proposed observations will be used to predict future states in a probabilistic ensemble using uncertainty quantification (Luo *et al.* 2011; Niu *et al.* 2014). In collaboration with Yiqi Luo (University of Oklahoma), we will use this approach to make hindcasts and predictions, identify model shortcomings, and provide feedback to field scientists to prioritize observations that will maximize uncertainty reduction. We will first determine the most sensitive parameters in CLM using sensitivity analysis (Sargsyan *et al.* 2014). This will reduce the dimensionality of the data assimilation (DA) problem for CLM, which contains over 100 parameters. One of the most popular sequential DA methods is the ensemble Kalman filter (EnKF), which uses a Monte Carlo technique to generate an ensemble of models (varying both states and parameters) for sequential DA (Evensen 2007; Gao *et al.* 2011). The covariance among parameters can be computed directly from the ensemble.

Ecological system dynamics are so influenced by weather and climate that rarely are ecological models used to make a forecast alone. More often, what-if analyses are conducted using assumed future climate conditions as boundary or forcing conditions. Past meteorological driver data will be sampled to construct scenarios for typical, slightly anomalous or extreme conditions at the sites. The forecasting system will be fully automated, run on a regular basis and placed on a web server freely available. We will also track model skill over time, which will quantify improvements from model process development and parameterization.

Spatially resolved simulations for supersites – Coupled CLM-PFLOTRAN model was developed first under NGEE-Arctic and is being continued under ACME. CLM-PFLOTRAN couples CLM with massively parallel multi-physics surface-subsurface flow and reactive transport model PFLOTRAN allowing high resolution 3-D simulations of hydrology and biogeochemical flow and transport processes. CLM-PFLOTRAN biogeochemistry modules provides a flexible platform to incorporate and test detailed processes learned from the observations and to study their role, impacts and sensitivity at high spatial resolution. We would employ CLM-PFLOTRAN at selected “supersites” at high resolution to model detailed land surface hydro-bio-geo-chemical processes extensively parameterized and forced by observations in an iterative manner. These high resolution simulations would allow detailed process studies, evaluation and improvement of current parameterization schemes and inform new and improved parameterizations in a multi-scale modeling framework. At the S1 bog containing SPRUCE and nearby S2-Bog, extensive hydrologic observations are available from our USDA Forest Service collaborators to parameterize and validate these simulations. CLM-PFLOTRAN simulations at the Missouri flux site will take advantage of extensive observations, and more detail is provided in Task 6.

Table 3.3 – Future Task 3.1 Deliverables

Date	Deliverable	Status
2016	Document CLM_SPRUCE with improved microbial model and simulations from multi-model SPRUCE ensemble; Prototype ecological forecasting system at SPRUCE	Planned
2017	Completion of CLM_SPRUCE model with improved *Sphagnum* and photosynthesis, evaluated with initial treatment data; Complete 3D PFLOTRAN simulations for supersites	Planned
2018	Document ecological forecasting system at supersites Deliver improved model to outside investigators (e.g. ACME).	Planned

3.3.2 Task 3.2 – Regional and Global Land Ecosystem Modeling

Carbon flux reanalysis and UQ – Large uncertainties remain in characterizing spatial and temporal patterns of carbon stocks and land-atmosphere carbon, water and energy fluxes (Arora *et al*. 2013, Friedlingstein *et al.* 2006). This is mainly because of the relative scarcity of *in situ* and regional observations, and the internal and external uncertainties associated with terrestrial ecosystem models (Luo *et al*. 2012, Zaehle *et al*. 2014). The estimation of GPP, the major input to the terrestrial carbon cycle, remains highly uncertain (Beer *et al.* 2010; Sun *et al.* 2014). By fusing the recently compiled quality-controlled large-scale data, such as Normalized Difference Vegetation Index (NDVI) (Zhu *et al.* 2013), Sun-Induced chlorophyll Fluorescence (SIF) (Frankenberg *et al.* 2011), and evapotranspiration (ET) (Mao *et al.* 2015b) with the satellite phenology version of the Community Land Model (CLM-SP) (Oleson *et al.* 2013), we propose a consistent framework for simulating and analyzing the spatial-temporal GPP dynamics. The remote-sensing SIF and NDVI have recently been shown as an excellent proxy for GPP and a direct link with the actual terrestrial photosynthesis at various scales (Guanter *et al.* 2014, Lee *et al.* 2013). We will first roughly derive the SIF based GPP estimations using a linear assumption between the satellite SIF and GPP (Guanter *et al.* 2014) while moving towards more sophisticated methods (van der Tol *et al.* 2009; Zhang *et al.* 2014; proposed in Task 6) model modifications. We will apply sensitivity analysis methods (Li *et al.* 2013) using credible prior distributions to perform parameter screening and reduce the number of CLM parameters needed to do the full uncertainty quantification analysis. We will then perform a parameter optimization using an ensemble of model simulations. The model structure for predicting GPP will also be informed by UQ studies at the functional level.

Once the canopy-level processes for GPP are constrained, we will use a similar sensitivity analysis and optimization framework in CLM-CN with prognostic LAI fused to biomass compartment datasets (Thurner *et al.* 2014), litterfall (Holland *et al.* 2005), soil respiration (Bond-Lamberty and Thomson, 2010), and soil carbon (Todd-Brown *et al.* 2013) to constrain carbon allocation and belowground processes that control GPP through feedbacks with LAI. When the initial carbon pool constraints are included, the model uncertainties for carbon flux simulations can be significantly reduced (Ricciuto *et al.* 2011). This version of CLM-CN will integrate new model structure and parameterization informed by the site-level modeling effort (Task 3.1), root function research (Task 4c), and microbial modeling task (Task 5). We will use the results from this model-data fusion to produce a new GPP product in the satellite era with uncertainty estimates. These uncertainty estimates will include driver uncertainties as well, including meteorological forcing and land-use change.

<u>*Detection and attribution*</u> – Using the above optimized modeling system will increase the fidelity of the simulations and our confidence in attributing observed changes to natural and anthropogenic factors, which contribute to changes in carbon cycle variables (Ciais *et al.* 2013). Model simulations that apply forcing factors in a factorial design have been useful for determining the influence of these factors on specific model outputs (Mao *et al.* 2013, Shi *et al.* 2013), but assessing the statistical significance of these signals is more difficult. Specifically, we will work with collaborator Mingzhou Jin (University of Tennessee) to apply the statistical methods of Detection and Attribution (D&A) (Allen and Tett 1999, Allen and Scott 2003, Ribes *et al.* 2013), which have been widely used in studies of climate change, onto the quantification of causes underlying the multi-year changes of terrestrial GPP. Detection is the process of demonstrating that change has occurred in a defined statistical sense, while attribution is the process of establishing the most likely cause for the detected change with some defined level of statistical confidence (Hegerl *et al.* 2007). Various traditional methods can be used, but improving those methods and establishing new methods is a priority. Most of the methods used for D&A utilize the internal climate variability from fully coupled simulations, but there is a push to develop methodology for offline land model simulations since they are much less time-consuming computationally. Therefore, another goal would be to establish methods for off-line simulations (Appendix E). In addition to GPP, we will conduct D&A studies on related variables with long-term broad-scale observational records, such as NDVI and river flow, using the same optimized modeling system.

<u>*Model reduction using representativeness*</u> – Quantifying the uncertainty of ecosystem models like CLM consisting of very large number of coupled processes and associate model parameters is an algorithmic as well as computational challenge. PTCLM has been successfully used for exploring the model sensitivities and UQ at site scales where rich data sets are available. Multi-variant cluster analysis based landscape characterization provides a statistical strategy to stratify the globe among desired number of regions which can be individually studied using rigorous UQ analysis. We will employ the methods developed by Maddalena *et al.* 2014 to identify a selected number of locations for the UQ analysis. Representativeness analysis (Maddalena et al. 2014) provides a method to extrapolate the optimized parameter and models derived at selected sites to the global scale by quantifying the similarity of any spatial location to studied sites.

<u>*Participation in model intercomparisons*</u> – TES SFA team members have recently been closely involved in participating in, as well as organizing, the NACP MultiScale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP). The goal of MsTMIP is to provide feedback to the TBM community

in order to improve the diagnosis and attribution of C fluxes at regional and global scales. This project builds upon current and past synthesis activities by developing an integrative framework to isolate, interpret, and evaluate differences in how TBMs parameterize key physical and biological processes. As part of the MsTMIP activity, we have performed model simulations at the regional and global scale. We are leading the data and simulation protocol development for including an analysis of the impacts of disturbance and land use change on C cycling at the global and continental scales. We are also participating in the CSIRO model intercomparison project (MIP), which is a multi-model UQ analysis of land-surface processes, and the PalEON MIP.

Table 3.4 – Future Task 3.2 Deliverables

Date	Deliverable	Status
2016	Collection and compilation of the SIF, NDVI, ET, biomass, SR and river flow data; the online and offline D&A methodology testing and development	Planned
2017	The CLM-SIF module validation; experimental design and ensemble model simulations; D&A study of the NDVI and river flow	Planned
2018	Finish the global optimization framework, and produce the global GPP time series; D&A study of the global GPP	Planned

3.3.3 Task 3.3 – Functional testing

We will implement a more interactive approach to establish user-defined models using existing functional modules within CLM, we will also design general graphical user interface (GUI) templates to visualize user-defined variables. We will work with experimentalists (Tasks 1, 4abc, Task 5, Task 6) to develop software tools to allow experimentalists to design computational experiments based on their research efforts and also translate those computational experiments settings into appropriate data formats (using machine learning technologies). Along with increasing interests on functional testing for other components (such as hydrology) within CLM, we will start to develop testing platform for hydrological components to facilitate model couple with external hydrological modeling systems. We will also identify traits and functions that are or may be important to model outcome, and direct or reinforce focused experiments to assess root function.

The functional unit testing framework allows for use of UQ methods that are not practical with CLM. The functional unit testing framework also allows for structured multi-scale analyses of parameter uncertainty (using, for example, leaf-scale functional units in conjunction with whole-canopy functional units). In addition the modularity of the functional unit testing framework allows for structural uncertainty analysis where alternative functional representations of specific processes (e.g., alternative equations or algorithms describing the same process) are “swapped in and out” to quantify the influence of those alternatives on uncertainty in the higher level, integrated model results. The alternative functional units might describe alternative hypotheses for how an individual process operates or alternative functional representations encoded within different models by different modeling teams and thus useful in diagnosing inter-model differences in multi-model MIPs. Finally, we will extend the single cell focus functional testing to a regional CLM modeling effort, with emphasis on the model-data validation on multiple grid cells using regional level observational dataset. The initial case should come from the collaborations with effort in Task 3.1.

Table 3.5 – Future Task 3.3 Deliverables

Date	Deliverable	Status
FY2016	Functional testing for "root" modules and integration with UQ methods	Planned
FY2017	Functional testing for ecosystem dynamics and hydrological components and module structure UQ development	Planned
FY2018	Regional CLM functional testing and multiscale UQ with observational datasets	Planned

TES SFA Mechanistic Processes Studies

Sections 3.4, 3.5 and 3.6 describe TES SFA process-level studies designed to emphasize plant and ecosystem characteristics that are inadequately captured by ecosystem models. Our goals are to provide data and an improved theoretical basis for the inclusion and use of these processes within ecosystem models. This research is targeted and designed to be conducted, evaluated, and incorporated into models and the funding recycled to other pressing questions or areas of uncertainty.

3.4 Plant C Allocation (Task 4a – Future Direction)

The PiTS projects have been very successful in developing new relationships within the SFA group, and addressing a key limitation of carbon storage and timing of carbon flow in CLM and other terrestrial biosphere models. There is strong continued interest in C partitioning (especially belowground) among the ORNL PiTS group, which has been bolstered by the new hire of Anthony Walker, a modeler who has worked extensively on the model-data synthesis of the Duke and ORNL –FACE sites, as well as the by the arrival of joint University of Tennessee-ORNL National Institute for Mathematical and Biological Synthesis (NIMBios) postdoctoral fellow Caroline Farrior who is interested in application of game theory to plant allocation dynamics. As such we plan to continue our carbon partitioning focus into the next 3-year funding cycle, and begin application of the MODEX framework to our developing belowground and root function tasks. PiTS data analysis and modeling efforts will continue in FY16 based on existing data from the three PiTS studies. Once the modeling runs are complete, we will reassess the utility of this MODEX, and in context of the primary goal (improved C partitioning model routines) if additional modeling or experimental studies are warranted in FY 17-18. Future efforts will use knowledge gained from the three PiTS field studies and simulation insights of model successes and failures to determine new avenues to pursue. Currently, the team plans to leverage the success of the PiTS collaboration to address a more comprehensive and integrative model-experiment program that focuses on measurement and modeling of the broader belowground plant-rhizosphere-soil system (described below in new task "Linking Root Traits to Function"). This effort will be coordinated with other proposed and ongoing SFA tasks (e.g., "Modeling of Microbial Processing of Soil C") to assess the belowground environment more broadly, and is anticipated to culminate in establishment of a "Rhizosphere Ecology Laboratory" (REL). The REL will be a focused, multi-scaled laboratory and small-scale field capacity to facilitate assessment of specific co-occurring mechanisms related to carbon partitioning, biogeochemical cycling, rhizosphere ecology and root function, and will be designed to provide pertinent data to the modeling group.

Table 3.6 – Task 4a Future Deliverables

Date	Deliverable	Status
Oct 2016	Finish existing PiTS data and model analysis and finalize publications and archived datasets	Planned
Oct 2016	Levering PiTS results, assess if additional partitioning-specific MODEX activities should be established	Planned
Future	Initiate PiTS Phase II activities, as warranted	Future Goal

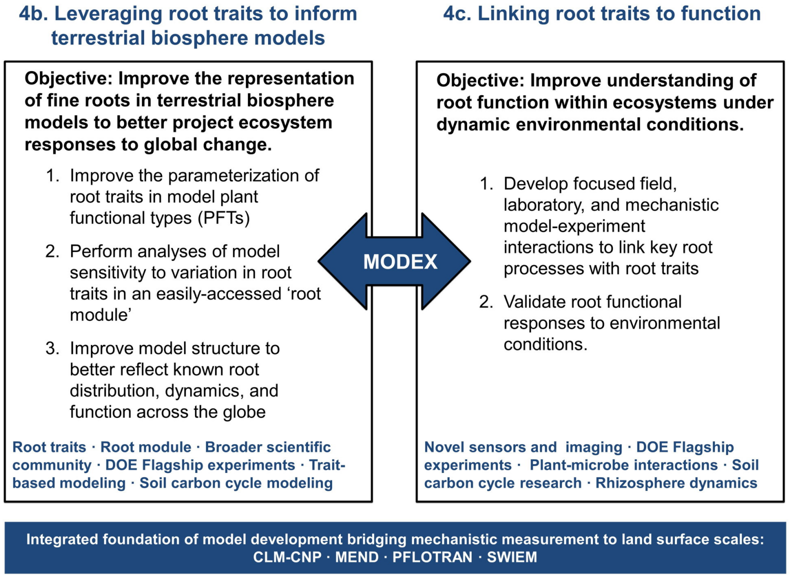
3.5 Root Traits and Functions – (Task 4b & 4c New Directions)

Global terrestrial biosphere models (TBMs) are used to represent ecosystem processes and functions, and their feedbacks to the atmosphere, across the diverse biomes of Earth. ORNL, through the TES SFA and other DOE-funded activities, continues to have a strong focus on improving the representation of belowground processes in models. Roots from all ecosystems are poorly represented in global models (Warren *et al*. 2015a), leading to a disconnection between data streams collected by ecologists and model representation of belowground processes. Reasons for the overly-simplistic representation of roots include poor empirical understanding (and therefore representation) of important processes at scales at which TBMs operate, limited communication among empiricists and modelers, and lack of data from ecosystems spanning the globe.

Furthermore, plant functional types (PFTs) used by TBMs to simplify and encompass the diversity of plant species across the globe are currently represented by static parameters, where plant traits, including root traits, do not vary within a PFT, and do not respond to environmental conditions (reviewed in Wullschleger *et al.* 2014). The incorporation and representation of the variation of plant traits in modeling approaches in current and future TBMs will be necessary to allow acclimation and plasticity of modeled plants to a changing environment. For example, models that have included dynamic root function have yielded results that more accurately represented observed patterns in ecosystem water fluxes (Lee *et al.* 2005; Schymanski *et al.* 2008).

It has long been recognized that plant traits and strategies strongly predict plant function, including growth, survival, and capture of limiting resources (Grime 1974). In turn, suites of plant characteristics are filtered and shaped by current and future environmental conditions, resulting in competitive exclusion and changing plant community composition and structure over time. Until recently, leaf or aboveground traits have been the primary focus of research on plant strategies, their effects on ecosystem functioning, and their treatment in global models (van Bodegom *et al.* 2014). However, evidence suggests that the spectrum of plant strategies integrates across leaves, wood, and roots (Reich 2014), and a rising tide of data is exposing important linkages between species-specific root traits (e.g., anatomy, morphology, architecture, chemistry, and mycorrhizal colonization) and important root functions (e.g., water and nutrient absorption potential, and root lifespan; reviewed in Iversen 2014).

Our overarching objective thus far has been to improve the representation of fine roots in TBMs in order to better project responses of terrestrial ecosystems to global change. With additional funding we propose to expand our focus, continuing a MODEX approach, by pursuing two new tasks (Fig. 3.1). *Task 4b—Leveraging root traits to inform terrestrial biosphere models*—aims to improve the parameterization of root traits in model PFTs, perform analyses of model sensitivity to variation in root traits in an easily-accessed "root module", and improve model structure to better reflect known root distribution, dynamics, and function across the globe. *Task 4c—Linking Root Traits to Function*—aims to leverage and develop focused field, laboratory, and mechanistic model-experiment interactions to link key root processes with root traits, and to validate root functional responses to environmental conditions. These tasks embrace the recommendations of a recent DOE workshop to pursue both short- and long-term opportunities to meet data-model needs in belowground ecology (Bailey *et al.* 2014). While these tasks will leverage ORNL's significant and ongoing investment in CLM development, results, including development of a root ecology database, will be directly applicable to root and rhizosphere processes across the global suite of TBMs.



4b. Leveraging root traits to inform terrestrial biosphere models

Objective: Improve the representation of fine roots in terrestrial biosphere models to better project ecosystem responses to global change.

1. Improve the parameterization of root traits in model plant functional types (PFTs)
2. Perform analyses of model sensitivity to variation in root traits in an easily-accessed 'root module'
3. Improve model structure to better reflect known root distribution, dynamics, and function across the globe

Root traits · Root module · Broader scientific community · DOE Flagship experiments · Trait-based modeling · Soil carbon cycle modeling

4c. Linking root traits to function

Objective: Improve understanding of root function within ecosystems under dynamic environmental conditions.

1. Develop focused field, laboratory, and mechanistic model-experiment interactions to link key root processes with root traits
2. Validate root functional responses to environmental conditions.

Novel sensors and imaging · DOE Flagship experiments · Plant-microbe interactions · Soil carbon cycle research · Rhizosphere dynamics

Integrated foundation of model development bridging mechanistic measurement to land surface scales:
CLM-CNP · MEND · PFLOTRAN · SWIEM

Fig. 3.1 – Proposed framework for future root-related tasks that distinguish two complementary efforts focused on (1) global data compilation and model development and (2) targeted experimental systems. The efforts will be linked through a MODEX framework that requires close coordination with one another, as well as with other ORNL efforts such as flagship DOE-funded experiments SPRUCE and NGEE (arctic and tropics), the MOFLUX and other AmeriFlux sites, historical experiments PiTS and FACE, as well as modeling efforts through the SFA, ACME, and MEND

3.5.1 Leveraging Root Traits to Inform Biosphere Models (Task 4b)

With supplemental funding from DOE BER, we have worked to develop a consensus in the broader community of root and rhizosphere ecologists on the path forward for improving the representation of fine roots in TBMs. A series of workshops and continued community engagement in formal and informal conversations have served to distill a strategy and prioritization. Taking a MODEX approach, our strategy is three-pronged: (1) to develop a global root ecology database to improve the parameterization of root traits in existing PFTs and to inform developing trait-enabled modeling approaches, (2) to facilitate the development of a 'root module' in CLM to perform analyses of model sensitivity to variation in root traits and to engage the broader community of root and rhizosphere ecologists, and (3) to improve CLM-CNP model structure to better reflect empirical knowledge gained from sensitivity analyses and the knowledge base of the broader community of root and rhizosphere ecologists. In contrast to the mechanistic observations and experiments proposed in Task 4c, this task is broadly focused at understanding the variation in root traits and function across the globe, which is the scale at which land surface models like CLM operate.

A global root ecology database – Developing modeling approaches that embrace the inherent variation and tradeoffs in plant traits in response to current and future environmental conditions requires a wealth of trait data for species spanning the globe (Kattge *et al.* 2014). Unfortunately, root traits are extremely underrepresented in widely-used databases like TRY (Kattge *et al.* 2011), and most root trait data have yet to be accumulated in any central, and model-accessible, database. A root trait database will allow quantification of root trait variation among PFTs (as defined, for example, by CLM), and to develop probability density functions within each PFT that will allow sensitivity analyses of the effects of root trait variation on ecosystem processes, including soil C storage, soil CO_2 efflux, and water and nutrient cycling (e.g., Sargsyan *et al.* 2014).

We are currently compiling the Fine-Root Ecology Database (FRED) from published literature and unpublished data. Currently, FRED houses ~7000 observations from across the globe of structural and functional root traits and their associated edaphic and environmental conditions (Fig. 3.2). While FRED is inclusive, our priority thus far has been the collection of data on root traits that have been found to be related to root function, including root growth, phenology, and lifespan (ecosystem C fluxes), rooting depth distribution, mycorrhizal colonization, and root-specific uptake rates (nutrient and water acquisition), and root litter quality (decomposition); these traits and processes are often underrepresented by TBMs (Warren *et al.* 2015). In particular, we have prioritized studies that characterize these traits according to root order; the broader community of root and rhizosphere ecologists has been steadily moving away from a diameter-based definition of fine roots (i.e., less than 2 mm) to a more functional classification based on the position of roots in a complex branching architecture (McCormack *et al. in press*). The work we propose here continues the development of FRED, and will focus on the deployment of a web interface that will allow FRED to be freely available to the broader community of root and rhizosphere ecologists and modelers. FRED will be archived in the TES SFA data archive, with associated metadata acquisition and data management and usage policies that allow for and encourage the submission of the numerous unpublished data sets that have been offered by the broader ecological community. We plan to continue to engage the empirical and modeling communities to contribute to and utilize FRED for ongoing scientific efforts. For example, we are planning to collaborate with a recent DOE-funded activity to better utilize the global variability of plant traits in TBMs (Peter Reich, PI).

Fig. 3.2 – Map of ~4000 locations spanning the globe where root trait data have been collected and input into FRED. FRED includes structural root traits such as biomass, depth distribution, morphology, anatomy, chemistry, mycorrhizal association, and functional root traits such as growth, death, lifespan, respiration, nutrient and water uptake, and respiration, along with their associated edaphic and environmental conditions (climate, soil, and vegetation characteristics).

The spatial coverage of root functional trait observations in FRED is relatively poor; most measurements have been concentrated in the Northern Hemisphere, and in temperate ecosystems. FRED provides an opportunity to focus future measurement campaigns on PFTs and biomes that are currently underrepresented, including leveraging ongoing and planned work at SPRUCE and NGEE. Given the strong linkages between plant characteristics and their function, root traits can be a useful mechanism to extrapolate small-scale, mechanistic measurements of root function to the larger spatial and temporal scales at which TBMs operate (Iversen 2014, Warren *et al*. 2015). Unfortunately, the compilation of global data in FRED highlights the gaps in our mechanistic understanding of woody root function (e.g., respiration, and water and nutrient acquisition). Targeted experiments are needed to quantify the linkages between root traits and their associated function, and in turn, how traits and function are shaped by changing environmental conditions (new Task 4c).

Given the poor data coverage of root traits, quantifying the relationships or tradeoffs between above- and belowground traits (e.g., Liu *et al.* 2010) may allow the prediction of belowground traits in model framework where no data exist for a given species or functional type (e.g., McCormack *et al.* 2012, Kong *et al.* 2014). The published root trait data housed within FRED will be submitted to the TRY database (Kattge *et al.* 2011), to facilitate collective research development of relationships between above- and belowground traits across the globe.

The Community Root Module – Using the Functional Unit Testing platform developed in collaboration with D. Wang (Task 3.3), we are working to develop a Community Root Module (CRM). The CRM encompasses the Canopy Fluxes and Ecosystem Dynamics components of CLM, and essentially acts as a "virtual plant", isolating processes in the CLM that are related with root structure and function, which necessarily include linkages with aboveground processes such as photosynthesis (Wang D *et al.* submitted). We propose to use this platform to perform uncertainty quantification and sensitivity analyses based on the root trait variables associated with different PFTs that are derived from FRED. Prior sensitivity analyses using the full CLM model have found that rooting depth distribution affects the sensitivity of parameters associated with surface water fluxes (Hou *et al.* 2012). However, few other root traits have been investigated, and no sensitivity analyses have been performed across the range of PFTs that CLM uses to characterize and simplify the diversity of plant species across the globe.

The current version of CLM (Oleson *et al.* 2013) includes a number of root parameters that will benefit from being informed with empirical data. In turn, we will use these sensitivity analyses to inform which observations and experiments are necessary to improve our understanding of roots and root processes. The initial focuses of our analyses will be: 1) root phenology, which exerts important controls over soil CO_2 efflux, and in CLM is currently parameterized as a one-to-one relationship with leaf phenology but varies among species and biomes (Abramoff *et al.* 2015, McCormack *et al.* 2015a), 2) rooting depth distribution, which exerts important controls over plant water extraction and where all species are represented by only one of five fixed depth distributions (Oleson *et al.* 2013), and 3) root lifespan, where lifespan variation affects total ecosystem C storage but is a fixed parameter in most TBMs (McCormack *et al.* 2015b). We will also investigate the effects of differing root litter quality (C/N ratio) within and among PFTs on the decomposition rates of different soil pools. This allows us to inform and leverage the mechanistic experiments proposed in Task 5 (Section 3.6) to determine the effects of root litter of differing quality on the sensitivity of decomposition rates to further inform the MEND Model.

We also propose to leverage data streams from SPRUCE and NGEE, as well as historical experiments FACE (Free-Air CO_2 Enrichment) and PiTS (Partitioning in Trees and Soils) for point-level sensitivity analyses focused on belowground processes and feedbacks. These point analyses can serve as a jumping-off point to validate and support mechanistic understanding and modeling at a global scale (e.g., Walker *et al.* 2014, Warren *et al.* 2012). To this end, we propose to host a break-out session at an annual DOE investigator meeting that will bring together consensus and data from these experiments, as well as other DOE-funded efforts, such as AmeriFlux. Further, we will leverage our interactions with the Carbon Cycle Interagency Working Group to develop synergies with belowground databases being developed by other federal agencies in order to inform and place bounds on model processes.

Perhaps most importantly, the CRM will be made available on-line through a graphical user interface to allow the community of empirical scientists a glimpse of the inner workings of the model, and to better understand the relative importance of different root trait parameters for ecosystem C and nutrient cycling. This will serve to both guide future field research and to inspire empiricists to contribute collected data directly to databases for modeling applications by providing a means through which empiricists can directly observe how their data are used and contribute to overall scientific and modeling goals.

Informing the next generation of terrestrial biosphere models – The general consensus gained from a workshop hosted at ORNL during June 2014 that brought together root and rhizosphere ecologists, database managers, and modelers, was that the next generation of TBMs should focus on capturing inherent variation in the structure and function of the fine-root pool. The state of science in the root and rhizosphere community is a focus on differences in root form and function across root orders from the most distal fine-root tips, which are known to be active in water and nutrient uptake and are colonized by mycorrhizae, to higher-order fine roots that are mainly responsible for solute transport (Iversen 2014, McCormack *et al. in press*). Building upon the FRED database, and using the CRM, we will develop an additional fine-root pool in CLM-CNP. The "absorptive" fine-root pool will be parameterized for nutrient uptake kinetics, and will have a short lifespan (years), and the potential for mycorrhizal associates to affect key root processes, including lifespan, nutrient acquisition, and C cost. The mechanistic understanding and model representation of root fungal associates, including mycorrhizae, is in its infancy (Brzostek *et al.* 2014), but model representation of a separate pool of fine roots that associate with the rhizosphere will facilitate the overlay of these processes once mechanistic relationships have been developed. The 'transport' fine-root pool will be parameterized for solute transport rates, and have a longer lifespan (decades), and different respiration and decomposition rates compared with the absorptive fine-root pool. Once an additional pool has been added to the model, we will repeat the sensitivity analyses described above to determine the effect of an altered model structure, and parameterizations of the two new fine-root pools, on projected ecosystem C, nutrient, and water fluxes.

Table 3.7 – Task 4b Root Trait Deliverables

Date	Deliverable	Status
Jan 2016	Fine-root ecology database (FRED) – Accessible to the broader community of root and rhizosphere ecologists and modelers through TES SFA and TRY.	Planned
Sep 2016	Synthesize and highlight global patterns and trends in root traits, and root trait variation within and among model-defined plant functional types.	Planned
April 2017	Break-out session hosted at annual DOE PI meeting to continue engagement of broader community and leverage above- and belowground trait linkages and data collected in other DOE-funded efforts (SPRUCE, NGEEs, PiTS, FACE, AmeriFlux)	Planned
Sep 2017	Sensitivity analyses linking PFT root parameterizations with ecosystem function using FRED and CRM.	Planned
Sep 2018	New model structure that includes an additional fine-root pool. Fine roots will be divided into absorptive and transport fine roots, and trait-function relationships will be overlaid on new pools using synergy of Tasks 4b and 4c. A new round of sensitivity analyses using FRED and CRM will be conducted based on new model structure.	Planned

3.5.2 Linking Root Traits to Function (Task 4c: Expanded task)

Based on our recent review manuscript (*Incorporation of Root Structure and Function into Models*; Warren *et al.* 2015) we developed a framework to improve fine-root representation in large-scale models through new data compilation and collection efforts, scaling and modeling. A primary component of these efforts will be quantifying root function for key root traits based on existing data and new experiments. Fine-root biomass and depth distribution are the most common datasets available, and are crudely used by some TBMs to limit water or nutrient uptake, often without a process-based mechanism. Combining our knowledge of root traits for a given PFT with specific root functions (i.e., water and nutrient uptake kinetics, and C release through respiration, exudation and turnover), will allow us to link traits with function that can be scaled to the landscape level. The scope of this task will depend on results from FY15 and FY16 modeling and uncertainly analyses (i.e., if CLM or other relevant models are sensitive to root function, and if relevant data exist). Based on these analyses and initial results from *Task 4b: Leveraging Root Traits to Inform Biosphere Models*, we will develop the appropriate experimental research plan in late FY16 to be deployed in FY 17-18. We anticipate the primary focus for this task will be on functional root nutrient and water uptake dynamics; however, appropriate linkages to root C sinks or C release will also be considered. Objectives for this task are: 1) Initially assess state of knowledge of trait-specific nutrient and water uptake kinetics, 2) Where justified by our modeling and data analyses, initiate new experimental systems to quantify trait-specific root and water uptake kinetics, and 3) Leverage new and existing data related to nutrient or water extraction patterns for use in modeling exercises.

Assess Root Trait-Specific Uptake Kinetics – The global root trait database under development at ORNL (FRED; see above), as well as the TRY database (Kattge *et al.* 2011) will provide a wealth of root data that will be the cornerstone of incorporation of root traits into models. However, much of those data have not been specifically linked to quantitative root functions such as nutrient or water uptake kinetics. Thus database development and assessment is a critical first step to direct future coupled trait-function experiments to achieve more complete addition of mechanistic root knowledge into the TBMs. This initial task will be to consolidate results from specific experiments (i.e., from FRED and the general literature) to assess the current depth and breadth of knowledge quantifying root nutrient and water uptake kinetics, and if uptake rates are associated with specific root traits. A review manuscript will be developed if warranted. Results will be used to direct the focused experimental effort.

Quantify Root Trait-Specific Uptake Kinetics – In this task, through experiments, we will begin to examine specific root traits and their functional responses to changing edaphic and environmental conditions. We will coordinate specific experiments based on existing root data (e.g., root distribution, size, age class) and environmental datasets (e.g., soil water or nutrient content) to provide mechanistic parameters of root function that might be scaled through traits into models. Our focus will be on mechanistic understanding of root behavior under different laboratory or field conditions using existing and new data. Initial experiments will focus on the simplest classification of fine root traits – those that are highly absorptive, and those that are not (i.e., 'absorptive' fine roots and 'transport' fine roots). We will first focus on water and nutrient uptake kinetics and root hydraulic conductivity under varying temperature and water stress conditions. Resolving drought and temperature impacts on uptake kinetics will allow root uptake capacity to be temporally dynamic. Resulting data can be applied to known root distributions to determine a spatial water or nutrient uptake capacity. We will initially work with woody species for which we have associated root distribution data, including *Liquidambar styraciflua*, *Picea mariana* and *Cornus florida*, from the ORNL-FACE, SPRUCE and PiTS experiments, respectively. Root function of arctic or tropical species will also be considered in context of the significant field efforts associated with NGEE programs. Experiments will be conducted on excised and *in situ* root systems using a variety of existing (e.g., root potometer, pressure chamber, depletion), or advanced (e.g., isotopes, soil uptake monitoring, neutron imaging) techniques (Kramer 1946, Scholander *et al*. 1965, Escamilla and Comerford 1998, Ogle *et al*. 2004, Lucash *et al*. 2007, Warren *et al.* 2013). An important component of this task will be to initiate discussion of a future Rhizosphere Ecology Laboratory at ORNL that will facilitate small-scale comprehensive lab, growth chamber and field experiments that focus on plant-soil-microbial interactions in context of biogeochemical cycling. Such a Laboratory would facilitate additional interactions among the SFA-Tasks at smaller spatial and time scales than achievable in remote field facilities such as SPRUCE or NGEE. Integrated process-level work will allow consideration of expanded MODEX frameworks that link measured root functional kinetics with soil C and nutrient cycling.

Apply Data to Integrated Efforts across the SFA – Results from these experiments, and from the FRED database will be tested with existing and new root uptake models and linked to ongoing efforts focused on inclusion of root traits within Task 4b, as well as other SFA modeling efforts – such as X. Yang's initiative to resolve P availability-mycorrhizae linkages within the FUN (*Fixation and Uptake of Nitrogen*) root module (Brzostek *et al.* 2014). One avenue will be to leverage existing knowledge of rooting depth distribution and water extraction patterns (e.g., from FACE, MOFLUX, SPRUCE, etc.) to test or validate specific models. Rooting depth has been shown to be a key driver of latent heat exchange in CLM (Hou *et al.* 2012) and models of depth distribution in response to water (SWIEM, Schenk, 2008) and nutrient availability (*MaxNup*, McMurtrie *et al.* 2012) have been developed. These models provide dynamic rooting distributions that respond to environmental variation. We propose the development of the SWIEM model and MaxNup model in CLM and the testing of this model across sites and the globe. The FRED will provide essential data to parameterize the relationship between root biomass distributions and root function and to validate the results of the model in ecosystems across Earth. In another, multi-scale approach, knowledge and data for root functions from existing and new experiments will be used to develop mechanistic process model for root processes in massively-parallel high-resolution flow and reactive transport model PFLOTRAN. We will develop detailed representation of root morphology and distribution, dynamic growth and mortality and water and nutrient uptake to mechanistically simulate the field and experimental conditions. Tested and evaluated using experimental data sets, these models would provide an ideal platform to understand dynamic root process and sensitivity under a range of conditions. Modeling experiments conducted using PFLOTRAN under a range of conditions will be used to develop statistical parameterizations applicable at the scale of TBMs. This multi-scale approach from experiments to mechanistic models to parameterized global-scale TBMs would allow quantification of errors in upscaling fine scale processes and help calibrations. Through MODEX multi-scale framework, experiments will be focused to provide data and parameterization for mechanistic scaling of root functional knowledge into global scale TBMs.

Table 3.8 – Task 4c Deliverables

Date	Deliverable	Status
Dec 2015	Leverage existing data sets (e.g., FACE water content, water use, root distribution) and apply root uptake models for uncertainty and sensitivity analyses	Planned
March 2016	Based on data/modeling results, define scale of interest/scope of task	Planned
July 2016	Recruit strong root physiology/hydraulics post doc	Planned
Oct 2016	Begin directed laboratory and field-based experiments to quantify water and nutrient uptake kinetics by root functional classes in response to environmental conditions as justified by model uncertainty and sensitivity analyses	Planned
Oct 2017	Begin deployment of Rhizosphere Ecology Laboratory for integrative assessment of belowground dynamics	Based on Funding
Oct 2018	Manuscript publication of water and nutrient uptake kinetics by root functional classes	Planned

3.6 Microbial Processing of Soil C (Task 5 Future Plans)

Understanding the response of soil microbial populations to climate change is essential to predicting future land surface CO_2 fluxes and storage of SOC (Wieder *et al.* 2013), and requires the integration of models and experiments. Microbial models include the parameter C-use efficiency (CUE) or microbial growth efficiency (MGE) to determine the proportion of C allocated to maintenance and growth versus C respired and lost as CO_2 (Sinsabaugh *et al*. 2013, Wieder *et al*. 2013, Tang and Riley 2014). CUE is typically fixed in global ESMs such as CLM. When we allowed CUE to fluctuate with temperature in the MEND model, we observed greater soil C stabilization with warming than predicted by use of a static CUE (Wang G *et al*. 2013). In contrast, when CUE was allowed to fluctuate with temperature in the Century model, reduced soil C stocks were predicted with warming (Frey *et al*. 2013). The difference between models is due to MEND’s incorporation of explicit pools of microbial biomass and enzymes, which allowed for critical feedbacks due to reduced enzyme production and microbial biomass (Wang G *et al*. 2013). Over time, the microbial population became less efficient and was not able to allocate as many resources to enzyme production, microbial maintenance, microbial growth and reproduction, ultimately resulting in greater stabilization of soil C. This is a type of microbial acclimation to different climatic conditions. There is considerable experimental support for scenarios similar to the MEND predictions, as many lab- and field-scale warming experiments have not yielded dramatic losses in SOC stocks (Bradford *et al*. 2008, 2010, Zhou *et al*. 2011). In addition to variation in CUE, microbial physiological acclimation to external factors may also include changing dormancy levels over time and under substrate limiting conditions (e.g. Manzoni *et al.* 2011, 2012). Including dormancy in MEND (Fig. 3.3) has led to more realistic predictions of microbial biomass (Wang G *et al.* 2014ab). Clearly, acclimation has important implications for the climate-C feedbacks, and it forms a key rationale for explicitly including microbes in ESMs.

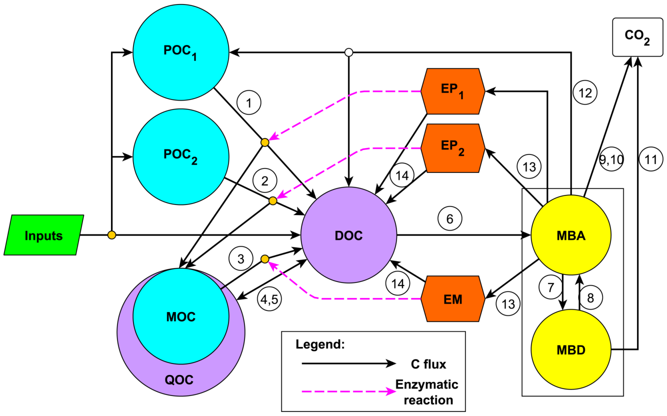


Fig. 3.3 – The MEND model. Pools are as follows: Particulate organic C (POC), mineral-associated organic C (MOC), adsorbed organic C (QOC), dissolved organic C (DOC), enzymes (EP for particulate C and EM for mineral-associated C), active microbial biomass (MBA), and dormant microbial biomass (MBD). Two classes of POC and enzymes are considered: cellulose/cellulase and lignin/ligninase (Wang G *et al.* 2014b).

Understanding microbial physiological under changing environmental conditions is critical for modeling soil CO_2 fluxes. Microbial physiological adjustments to environmental conditions may be captured in part by a variable CUE parameter that reflects acclimation of the microbial community. Such an acclimation scenario, however, does not represent a shift in microbial community composition, where one group of microbes is outcompeted by a second group that is more resilient to new environmental conditions. There is some evidence to support concepts of shifting communities (Bradford *et al.* 2008, Castro *et al.* 2010, Zhou *et al.* 2011, Melillo *et al.* 2011, Manzoni *et al.* 2012), and our laboratory incubations also showed an increase in the fungal over bacterial community (Jagadamma *et al.* 2014b). However, there is generally a lack of application of coupled metagenomics and process level techniques within soil manipulation experiments to attribute response to climate change to either physiological adjustments like CUE and dormancy, or microbial community shifts.

Microbial dynamics are strongly affected by substrate quality and quantity. Atmospheric and climatic change often effect plant chemistry, plant community composition, and subsequent plant litter (Sturm *et al.* 2005; Epstein *et al.* 2004). Differential leaf and root traits (Section 3.5) affect the quality and quantity of litter and exudate inputs into the soil, and root inputs account for a substantial portion of C and N input to belowground ecosystems (Iversen *et al.* 2008, Kramer *et al.* 2010, Fröberg *et al.* 2009). Changing substrate quality may induce microbial acclimation and/or community shifts.

To our knowledge, the importance of acclimation of microbial physiology or communities has not been fully accounted for in models that have explicit microbial representation. While MEND currently allows for variable CUE and microbial dormancy, it does not have the capability to represent community shifts or to respond to changes in substrate quality. Therefore, we plan to use existing datasets and new experimental results to develop the model structure and parameters to account for both physiological acclimation and community shifts under climate change scenarios. Because temperature-sensitive CUE can be accounted for in current model parameterization (Sinsabaugh *et al.* 2013), we will focus on other forcing factors on microbial physiology and community, e.g., drought and input chemistry (Frey *et al.* 2013, Manzoni *et al.* 2011, 2012).

Objectives and Hypotheses – The **Objective** of our research is to understand the extent of microbial physiological versus community shifts in response to various stimuli, and to develop model structures to predict the effect of different acclimatization strategies. We will focus on processes with particular relevance to plant communities – C:N ratio of inputs and soil moisture – that are likely to impose physiological and community changes. We **hypothesize** that physiological acclimation will be important in all systems, but that the extent of community shifts will be governed by edaphic properties such as substrate quality and supply. Specifically, high quality substrate and high supply will inhibit community shifts while low quality substrate and low supply levels will encourage community shifts.

Approach – Our approach will involve lab- and meso-scale investigations designed to enhance understanding of coupled biogeochemical processing of SOC and root inputs in the face of climate change conditions such as changing moisture content and shifting plant communities. Our goal will be to determine and model the extent of physiological acclimation of microbes versus community shifts. We will use the experimental data to improve the representation of a number of processes in MEND, including (1) the effect of moisture on SOC decomposition, (2) the role of substrate C:N ratio on decomposition rates and the composition of downstream model pools, (3) the role of physiological acclimation on SOC decomposition and microbial dormancy, and (4) the role of community shifts between bacteria and fungi. Our experimental design will determine the importance of physiological versus community shifts, which will resolve a major uncertainty regarding microbial decomposition models. Model development will proceed in parallel and will focus on developing the capabilities to represent community shifts in response to environmental forcing factors not currently represented. These efforts support the development of microbial models in the Carbon Cycle Modeling Task 3 (Section 3.3.1) and build future concepts for incorporation into DOE's ACME model. We plan to integrate our experiments with those designed to link root traits to function (Section 3.5.2), and thereby develop a framework to assess the coupled root rhizosphere and bulk soil processes (likely in FY18 and beyond).

Subtask 1. Moisture Sensitivity of Decomposition – The purpose of this subtask will be to develop controls for moisture sensitivity in the MEND model. We aim to develop parameters and models that are widely applicable by using a variety of sites, and using sites for which longer-term and larger-scale data are available. In the past we have also focused on global soils, but the detailed nature of experiments planned in this proposal will preclude the consideration of large numbers of soils.

We will conduct lab-scale incubations in which we apply three different steady-state treatments of moisture per soil. Our current experiments use paired forest and grassland soils from MOFLUX, Freel's Bend in TN, Athens, OH, and the Chichaqua Bottoms Greenbelt in IA. We will conduct a combination of both short-term (<14 days) and long-term experiments (up to 90 days), both of which are needed to calibrate microbial physiological behavior, e.g., maintenance versus growth respiration (Wang *et al.* 2014a,b). Soils will be monitored to maintain moisture content within 10% of target. We will use newly acquired Micro-Oxymax respirometer (Columbus Instruments, Columbus, OH), which is capable of simultaneously measuring CO_2, CH_4, H_2S, H_2, and O_2 in the headspace in 20 chambers at once, and is designed to maintain constant moisture content during the experiments. Select experiments will also occur outside of the respirometer and will allow for transient reduction of moisture as a function of time, followed by re-wetting. Soils will be destructively sampled at intervals to obtain sufficient measurements of MBC, gene copy numbers of bacteria, fungal, and archaea by QPCR, and 16S ribosomal ribonucleic acid (rRNA) using standard methods. QPCR and 16S information will be used to determine the extent of community shifts over time, both between bacteria and fungi (QPCR) and specific phylogenetic and functional groups within communities of bacteria and fungi (16S). MBC measurements are used, along with CO_2 flux measurements, as a calibration target for the model (Wang *et al.* 2014b). Our recent work (J. Dabbs et al., personal communication) identified correlations between MBC and gene copy numbers for bacteria in particular and fungi to a lesser extent. Thus, QPCR measurements will replace MBC measurements for model calibration targets.

Modeling: We will develop the mechanisms to account for the sensitivity of decomposition rates and microbial dormancy/resuscitation rates as functions of soil moisture in the MEND model. We hypothesize soil moisture conditions will exhibit different influences on activities of various enzymes (Wang *et al.* 2012). We will test and calibrate the sigmoidal-type switching functions modifying microbial dormancy and resuscitation rates (Manzoni and Porporato, 2009). We will further develop the structure to account for two microbial biomass pools, bacteria and fungi that have different C:N ratio, turnover rate, CUE and enzymatic capabilities (Waring *et al.* 2013). In addition, we expect to distinguish fungi from bacteria by their differences in composition and physiology. We will use QPCR and 16S data to calibrate observed community shifts between bacteria and fungi. The combination of short- and long-term experiments will be used to calibrate the extent of growth versus maintenance respiration, and thereby provide an indication of the extent of physiological acclimation through dormancy. We will use a temperature-dependent CUE (Sinsabaugh *et al.* 2013, Wang *et al.* 2013). The 16S rRNA data will also be used to understand the extent of microbial dormancy as a function of time and moisture content in the experiments, but it will not provide a direct model input.

<u>Subtask 2. Substrate Quality Controls on Decomposition</u> – We will conduct experiments using the framework described above to determine the sensitivity of decomposition rates to different initial substrates as measured by CO_2 fluxes. Substrates will include different ^{13}C-labeled plant root litters having different C:N ratios to test the sensitivity of decomposition rates to substrate quality. As discussed above, root litter constitutes a major input to below ground communities, but it is seldom used in decomposition experiments. Measurements will be taken of soil and microbial biomass C:N ratios, initially and at various time points during the decomposition experiments. This set of experiments will enable including variable C:N ratios through the decomposition pathway in MEND. The experiments will be matrixed with the moisture content experiments to determine coupled effects. As above, community composition analyses (QPCR and 16S) will be periodically conducted to understand potential community shifts in response to treatments.

Modeling: We will develop a fully coupled C and N cycle in the MEND model, with the ability to track the C:N ratio through inputs and into microbial biomass and SOM pools. This will allow full integration of MEND in CLM, which will benefit the modeling task within the TES SFA and the ACME ESM. Variable C:N ratios in SOM pools will be allowed. Dynamic C:N ratios in SOM pools will be regulated by inputs from litter decomposition and microbial turnover. Pertaining to microbial C:N ratios, we will test two hypotheses: fixed C:N ratio and flexible C:N ratio. The latter hypothesis allows the microbial C:N ratio to fluctuate within a range, e.g., between 5 and 13 (Cleveland and Liptzin 2007, Wang G *et al.* 2013, Xu *et al.* 2013). In addition, the model behavior under mineral N limitation will be investigated, in which the N inhibition hypothesis, the C overflow hypothesis (Manzoni and Porporato 2009) or the integration of these two approaches will be tested. Data from this experiment will be used to validate our new C-N coupled MEND model and test different hypotheses accounting for microbial stoichiometry and microbial responses to mineral N limitation.

Subtask 3. Upscaling from the laboratory to mesocosm scale – We will conduct upscaled mesocosm-scale experiments to identify how the microbial community and C fluxes are influenced by different moisture conditions and plant communities. This work will be coupled with Subtask 4b (Section 3.5.2) which is designed to determine root function under various moisture conditions. Each mesocosm will be split so that processes with and without direct plant root and mycorrhizal interactions can be separately interrogated. Mesh will be used to exclude roots and mycorrhizae, only roots, or to exclude nothing, thereby facilitating calibration of the model with and without root rhizosphere effects. At least two plant species will be used, with different ^{13}C- and ^{15}N-labeled C:N ratios of litter and to be representative of the substrate quality experiments in our Subtask 2 lab-scale incubations. Moisture contents will also be representative of some of the treatments replicated in the more detailed lab incubations described above. CO_2 fluxes will be measured over time in each partition. Occasional destructive harvests will be used to understand the microbial community in each partition as described above.

Modeling: The objective of this task is to investigate the applicability of lab-derived parameter values to larger-scale mesocosms, and to test will the capability of MEND to represent coupled root and microbial processes. After development of the model capabilities in moisture response, fungi and bacterial biomass pools, and tracking of C:N ratios through inputs into biomass, C and N fluxes, and SOC/N pools as described above, we will test the performance of the improved MEND model against the larger-scale mesocosm experiments. This test will constitute the capstone of our task by incorporating several new and existing processes simultaneously and testing at a larger experimental scale.

Table 3.9 – Task 5 Deliverables

Date	Deliverable	Status
Aug 2016	Complete the proposed soil moisture experiments	Planned
Feb 2017	Complete the proposed C:N ratio experiments	Planned
May 2017	Incorporate soil moisture effects and flexible C:N ratios into MEND and test against experimental data	Planned
Dec 2017	Incorporate community shifts into MEND and test against experiments	Planned
Apr 2018	Complete experimental measurements of coupled soil moisture and plant input chemistry at the meso-scale	Planned
Sep 2018	Test meso-scale experimental data against upscaled MEND model	Planned

3.7 Terrestrial impacts and feedbacks of climate variability and extreme events (Task 6 – Future Plans)

Task 6 serves as a bridge between ORNL TES SFA components in manipulative experiments and fundamental process studies and those in modeling. Its overall goal for FY2016, 2017 and 2018 will be to develop a mechanistic understanding of ecosystem structural and functional responses to climate variability at different spatial and temporal scales and to transform such understanding to ecological, societal and modeling applications concerning impacts of various atmospheric stresses (e.g., droughts, heatwaves, unseasonable temperature changes). This overall goal will be achieved by:

- Providing coordinated, continuous, process-rich measurements from belowground to top of canopy and from leaf scale to landscape scale for process understanding and model testing
- Developing improved and new process representations suitable for implementation in large-scale ESMs
- Developing and testing ecologically and physiologically-based indicators and predictors of impacts of climate variability and extreme events that can contribute to the National Climate Change Indicator System (Kenney *et al.* 2014)

- Conducting cross-scale/site syntheses of new advances, datasets and models to answer crucial science questions related to ecosystem structural and functional responses to climate variability and extreme events.

Measurements of NEE of mass and energy with the EC technique have been and will continue to be key in the Task 6 research.

In the past, the Missouri Ozark AmeriFlux (MOFLUX) site has been the main focus of field observations. But coordinated research activities between MOFLUX and SPRUCE have always been a part of the overall ORNL TES SFA Plan. The infrastructure development of the SPRUCE has advanced to a stage that flux measurements with the EC technique in proper SPRUCE experimental footprints can now begin. Thus the new science plan of Task 6 will include continuous NEE measurements of CO_2, methane, water vapor and sensible heat fluxes with the EC technique at the SPRUCE site to support SPRUCE science objectives.

The renewed Task 6 will emphasize resolving process controls on and contributions to the net mass and energy exchanges measured by the EC technique. This emphasis will be pursued along three lines: root dynamics and its relation to soil efflux and canopy functions, spatial/temporal heterogeneity of soil moisture and its ecological impact, and leaf to canopy solar induced chlorophyll fluorescence measurements and modeling. While these three lines are distinct, they intercept at the bottleneck of our understanding of biological processes controlling ecosystem fluxes under atmospheric stresses. Below we outline our renewed plan with these elements highlighted.

3.7.1 MOFLUX (Task 6a – Future plans)

The MOFLUX site is strategically located within the geographically and ecologically distinct prairie-forest biome / precipitation transition in the central United States. From its initiation in 2004, MOFLUX has played a key role in nearly all major Fluxnet and AmeriFlux network syntheses. MOFLUX is an adjunct core site in the new AmeriFlux network management system. As MOFLUX enters a decade of operation, the time series of coordinated measurements allow investigations of biotic and abiotic controls of inter-annual variability of C uptake and water use in this ecologically vital region of the US. Continued operation of MOFLUX represents an optimum use of resources for a fully developed eddy covariance site. The AmeriFlux network considers MOFLUX to be a solid anchor site in the central US for understanding and predicting C sources and sinks, and they endorse its continued operation (Appendix D).

MOFLUX now operates a suite of meteorological, flux, ecological, physiological, and biometrical measurement systems that are either above or within the canopy, or on the forest floor, or in the soil; these existing measurement systems described in previous plans will continue in the renewed plan. New research at MOFLUX will focus on the following three areas in order to meet the reshaped project goal:

Root dynamics and its relation to soil CO_2 efflux and canopy functions – Patterns of soil CO_2 efflux at MOFLUX cannot be explained adequately by variation in environmental forcing factors such as soil temperature and moisture (Huang, Gu & Niu, 2014, Gu *et al.* 2008). Root respiration of recent photosynthate has been shown previously to contribute up to 65% of total soil CO_2 efflux (Eckblad and Högberg 2001), and the magnitude and timing of root respiration is driven more by the availability of photosynthate, and seasonal patterns of belowground C allocation, than by soil temperature (Högberg *et al.* 2001). In order to quantify how root dynamics may be driving patterns of soil efflux of CO_2 observed at MOFLUX, we installed ten acrylic minirhizotron tubes in 2012 in the footprint of the MOFLUX tower, and coupled each with an automated soil CO_2 efflux chamber (LiCor 8100A). We hypothesize that at the MOFLUX site, new photosynthates and the spatial and temporal patterns of fine-root growth are a dominant contribution to soil CO_2 efflux and this contribution is tightly linked with phenological changes in canopy functions, particularly the dynamics of GPP.

To test this hypothesis, we will continue to collect and analyze weekly images of root birth, growth, and death from the ten minirhizotron tubes; rates of growth and death should have stabilized after ~ 2 years of colonization. Patterns of C and nutrient allocation will be extrapolated from non-destructive, and frequent, minirhizotron measurements of root length and diameter, we will develop species-specific relationships between root diameter, length, mass, and nutrient content as in Iversen *et al.* (2008), focusing on the six dominant tree species at the MOFLUX site (*Quercus alba, Quercus velutina, Acer* *saccharum, Juniperus virginiana, Carya ovata, Fraxinus americana*). Root dynamics and C allocation will be correlated to soil CO_2 efflux observations and GPP inferred from EC NEE and canopy fluorescence measurements.

Spatial/temporal heterogeneity of soil moisture and its ecological impact – Root water uptake, root dynamics and soil efflux are micro-scale processes affected by local availability of soil water. Because canopy functions (e.g. gross primary production, transpiration) depend on water uptake by roots and are sensitive to spatial heterogeneity of soil moisture, such issues are of particular interest to MOFLUX as water is a dominate driver of ecosystem functions at this site (Gu *et al.* 2006, 2015abc). Soil water content has already been measured at multiple locations and depths, but the existing measurements are not sufficiently dense for the purpose of determining spatial heterogeneity and specific vegetation response. New effort will allow an in-depth analysis of ecological functions of soil water variation in space (see the Integrated Research subtask).

Plant canopies act not only as a hydrological sink (Kim and Jackson 2012) but also as a precipitation interceptor and collector, inducing flow path convergence via stemflow and drip points. These locally enhanced fluxes can be several times larger than the aerially averaged rainfall and introduce considerable spatial heterogeneity in infiltration and soil ecosystem processes (Liang *et al.* 2007, Pressland 1976). This effect of plant canopies can be offset by differential root uptake of water for transpiration, which over time tends to homogenize soil moisture patterns (Guswa 2012). The persistence and balance between these two opposing processes depend on a variety of abiotic and biotic factors including vegetation type, species assemblages, tree and root morphology, rainfall regimes and wind characteristics (Keim *et al.* 2005, Wullaert *et al.* 2009, Zehe *et al.* 2010, Crockford and Richardson 2000, Levia and Frost 2003). Given these considerations, we have designed the following soil moisture monitoring strategy.

A soil moisture sensor network will be installed to monitor spatial / temporal variations of soil volumetric water content (VWC) (Campbell Scientific, or Decagon Devices) (Hupet *et al.* 2003, Breña-Naranjo *et al.* 2011). Sensors will be positioned around randomly selected canopy trees in radial arrangements and installed at 10 and 25cm depth to characterize vertical variations and monitor wetting fronts (Western *et al.* 1998, Brocca *et al.* 2007). There will be about 60 sampling locations (i.e. 120+ VWC sensors) as per Zimmermann *et al.* (2010). Surface soil infiltration capacity will be quantified as per Hubbart *et al.* (2011), and complemented with in-field soil saturated hydraulic conductivity tests above and below the root zone. Soil water and shallow groundwater will be monitored using stilling wells (surface runoff), lysimeters (Western *et al.* 1998), and shallow piezometers as per Chinnasamy and Hubbart (2014a, b) located in the two drainages and the confluence of those drainages (n = 3 sites) associated with the tower.

Leaf to canopy solar induced chlorophyll fluorescence measurements and modeling – The EC technique measures NEE of CO_2. This is an advantage but simultaneously also a disadvantage because it allows determination of C sources and sinks but does not provide component estimates of NEE which is a net result of two large opposing processes (GPP and ecosystem respiration, ER) controlled by fundamentally different environmental factors and biological mechanisms. This disadvantage means that EC flux measurements have not been able to provide modeling constraints as strongly as desired because models can freely adjust these two opposing processes to match NEE observed even though the mechanisms may be represented inadequately. New advances in ultra-high resolution spectroradiometry have enabled reliable measurements of Sun-Induced chlorophyll Fluorescence (SIF), which offers a real possibility to monitor GPP more directly than having been possible so far (e.g., Meroni *et al.* 2009; Guanter *et al.* 2013, 2014). If SIF measurements are coupled with EC flux measurements, both GPP and ER can be potentially estimated, which will substantially increase the constraining power of EC flux sites and networks for ESMs. Additionally, these coupled SIF and EC flux measurements will be crucial to validate remote sensing products of SIF from satellites such as OCO-2 (Frankenberg *et al.* 2014), GOSAT (Joiner *et al.* 2011, 2012), GOME-2 (Joiner *et al.* 2013, 2014), and SCIAMACHY (Joiner *et al.* 2012), which may soon be joined by FLEX, a potential ESA satellite to be specifically designed for a fluorescence mission. Adding SIF measurements at the MOFLUX or other AmeriFlux sites may lead to synergistic datasets and significantly enhance the scientific value of the sites.

The relationship between photosynthesis and chlorophyll fluorescence is complicated and unlikely to be linear, particularly under environmental stresses and high-light conditions (Papageorgiou and

Govindjee 2004, Baker 2008, Porcar-Castell 2014). Studies of how the photosynthesis – fluorescence relationship changes with environmental conditions from leaf to canopy scales are urgently needed to evaluate the potential and effectiveness of this approach. Thus we propose to conduct leaf to canopy solar induced chlorophyll fluorescence measurements and modeling. We have considerable experiences in leaf-scale fluorescence (Gu *et al.* 2010; Gu and Sun 2014) and in canopy-scale radiative transfer modeling (Gu *et al.* 1999, 2007). These experiences will be valuable to this proposed fluorescence subtask. We have access to LiCor 6400 leaf chamber fluorometers both at ORNL and at University of Missouri. We will use these fluorometers to determine leaf fluorescence parameters needed to parameterize the leaf fluorescence model of van der Tol *et al.* (2014). This model appears to diverge from measurements made under high light conditions. We will determine whether it is possible to improve over this model by parameterizing the fraction q of the PSII reaction centers that are open and available for photochemistry as a function of photosynthetic capacities, temperature, light levels, CO_2 concentrations. The q will be determined with PAM fluorometry and saturating actinic pulses on both dark-adapted and illuminated leaves (Kramer *et al.* 2004, Klughammer and Schreiber 2008). This strategy will allow us to bypass the much more difficult modeling of regulated non-photochemical quenching under environmental stresses (Muller *et al.* 2001, Zaks *et al.* 2013). If so, we will then be able to relate fluorescence F directly to the electron transport rate J through $F = (K_F/K_{P,intri}) \times J/(q\times\beta)$. Here K_F is the quantum yield of fluorescence and $K_{P,intri}$ the intrinsic quantum yield of the PSII photochemistry. The ratio of K_F to $K_{P,intri}$ can be determined as per Kramer *et al.* (2004) and Klughammer and Schreiber (2008). The fraction of the absorbed light allocated to PSII (β) is often assumed to be 0.5. We will estimate it using an optimization approach with simultaneous measurements of fluorescence and light response curves, which has been implemented in the updated but yet-to-be- released code of LeafWeb (Gu *et al.* unpublished results).

We will couple the relationship discussed above and the model of van der Tol *et al.* (2014) to the Farquhar-von Caemmerer-Berry (FvCB) model of photosynthesis extended with mesophyll conductance (g_m) (Gu *et al.* 2010, Sun *et al.* 2014a, Gu and Sun 2014, Sun *et al.* 2014b) to simulate leaf fluorescence and photosynthesis. This fluorescence-g_m-FvCB leaf model will first be implemented into the Fluxes And Pools Integrated Simulators (FAPIS, Gu *et al.* 1999 and 2007). FAPIS has a flexible multilayer canopy structure and a sophisticated radiative transfer scheme that is suitable as a base framework for fluorescence emission/transfer modeling. This will allow us to determine a proper level of canopy representation needed to capture the canopy-scale fluorescence – photosynthesis relationship and whether any compensating parameterization is needed to accommodate a simpler canopy structure representation. Once these insights are obtained with FAPIS, we will transfer the resulting algorithms to CLM4.5 to be used for large-scale applications.

To validate canopy-scale fluorescence modeling, we will measure hyperspectral solar reflectance and fluorescence with portable QEPRO spectrometers (OceanOptics, USA) with the grating positioned within the fluorescence emission wavelength region. The measurements will be made from the top of the MOFLUX tower. Solar reflectance contamination on canopy fluorescence will be removed using the Fraunhofer Line Depth (FLD) approach (Meroni *et al.* 2009; Damm *et al.* 2014). To provide an independent estimate of GPP to be compared against GPP modeled from FAPIS and canopy fluorescence, we will calculate GPP from EC measurements of NEE with the method of light-temperature-vapor pressure deficit response functions as in Gu *et al.* (2002). With measured and modeled leaf/canopy fluorescence, measured and modeled leaf photosynthesis, and modeled and NEE-based, calculated canopy photosynthesis, we will be able to answer the following questions:

- How does the relationship between fluorescence and photosynthesis change from leaf to canopy scales and with environmental conditions, particularly water stress?
- What is the implication of the answer to the above question for remote sensing of GPP with satellite SIF?

3.7.2 SPRUCE eddy covariance fluxes and fluorescence measurements (Task 6b – Future Plans)

Eddy covariance measurements at the SPRUCE site in northern Minnesota will include fluxes of CO_2, methane, water vapor and sensible heat while fluorescence measurements using protocols similar to MOFLUX will provide multi-scale GPP estimates at SPRUCE. The primary objective is to collect ambient landscape-level flux observations for these variables for comparison to plot-level SPRUCE manipulations. Such measurements will produce temporally resolved measures for testing ecosystem models with a specific focus on the development of an efficacious CLM-Wetland model. An associated empirical objective is to quantify raised-bog peatland CH_4 and CO_2 fluxes and the relationships between them as the ecosystem responds to climate variability at hourly to inter-annual time scales.

Two EC systems will be deployed at the S1-Bog site by FY2018. The two ambient systems will include a bog surface system and a canopy top system. The bog surface EC system will be installed in the summer of 2015. It will operate at a height of about 1.5 m from the bog hollow surface on a tripod anchored by helical piles drilled to the bottom of the bog. Because of its height, this system has a minimal contribution from surrounding trees, allowing a focus on the community of ericaceous shrubs, forbs, graminaceous species, and *Sphagnum sp.*, which play an important function in the bog ecosystem.

The canopy-top system is an ecosystem-scale observation platform. The canopy top EC system provides integrated measurements of functioning of the northern raised-bog peatland that are difficult to obtain through other means, but are needed for validating ecosystem-scale model predictions and for extrapolating SPRUCE process-based research. The canopy-top system will require erecting an aluminum scaffolding flux tower 15-m tall in the northern end of the S1-Bog. This location is located away from the influence of the planned manipulative experimental units. As the maximal tree heights in that area of the bog are about 7 to 8m, a 15m tall tower should satisfy the eddy flux measurement requirements. The exact height of the EC instrumentation for this canopy top system will be determined with footprint analyses so that the influence from the manipulative experimental units and the upland forests surrounding the S1 Bog on flux measurements will be minimal under the prevailing wind direction from the west.

Each EC systems will have identical instrumentation with the main instruments including a CSAT3 sonic anemometer, a Li7500A CO_2/H_2O open path analyzer and a Li7700 CH_4 open path analyzer plus data logging and communication devices. A profile system that measures the vertical variations in the concentrations of CO_2, CH_4 and H_2O will be developed with a Los Gatos Research $CO_2/CH_4/H_2O$ gas analyzer. SPRUCE has a suite of routine meteorological, radiation, bog temperature and water measurements which will be used in the analyses of flux data. In addition to EC flux measurements, fluorescence measurements similar to those described at the MOFLUX site will also be measured at the SPRUCE site. GPP from SIF and from partitioning NEE measurements will be compared with each other and also with estimates based on the sap flow approach (see the Plant Physiology section in Task 1). SIF will initially be measured with the EC systems. As SPRUCE treatment experiments begin, we will also measure SIF inside the SPRUCE enclosures to determine treatment effects on the photosynthesis of *Sphagnum* and spruce. Measured fluxes of CO_2, water vapor, sensible heat, methane and SIF will be used to test ecosystem models at the SPRUCE site to identify potential deficiencies in these models so that they can provide better guidance for future SPRUCE experiments and be generalized for regional to global applications.

Until final operating costs for SPRUCE are verified during the summer of 2015, we are not certain that we will have sufficient funding to establish the canopy-top tower and EC systems in FY2018 (a provisional budget has been prepared). If funds are sufficient, we will plan for installations in FY2017 and proceed with tower and support system installations in the winter of FY2018. The tower will be located along an existing boardwalk access route. Electrical service will need to be extended to the tower site along the boardwalk. Instrumentation of the flux tower will follow once the tower is erected. The flux tower would be expected to be fully operational by June 2018.

EC flux data analyses will focus on the diurnal to seasonal variations in the fluxes of CO_2, water vapor, sensible heat, methane, and gross photosynthesis (via SIF) and how such variations are related to variations in temperature, radiation, atmospheric vapor pressure deficit, wind speed and water table depth. We will also investigate the interannual variability of these fluxes and their implication for ecosystem C storage or release at landscape scales. By the end of FY2018, we expect we will be able to answer the following questions:

- What are the budgets of CO_2, water and methane at daily, weekly, monthly time scales for the S1-Bog peatland?
- How are the methane budgets related to those of CO_2 and water at different time scales?
- What are the controlling processes for the net ecosystem exchanges of CO_2, gross photosynthesis, water and methane?

3.7.3 Integrated research (Task 6c – Future Plans)

To move beyond an investigation of individual ecosystem components, Task 6 measurements and process understanding will be integrated into broad system modeling frameworks in close collaboration with the TES SFA modeling efforts (Task 3 and 4b). Specifically, MOFLUX root observations will contribute to the development and validation of CLM root module (Task 3 and 4b). The partitioning of NEE into GPP and ER with joint SIF and EC measurements will be used to validate and improve CLM photosynthesis and ecosystem respiration modeling (Task 3). Measurements of vadose zone water content, ground water, and drainages will be made available to the ORNL's ACME and PFLOTRAN teams for validating and improving subsurface flow and reactive transport model (Mills *et al.* 2007, http://www.pflotran.org/). These efforts will lead to a better integrative understanding of how dynamic environmental forcings such as precipitation regimes affect ecosystem C uptake, water use, surface energy balance, spatial/temporal heterogeneity of soil moisture, and other above- and below-ground biogeochemical processes.

It is a challenging task to scale up point measurements such as those represented by soil chambers and mini-rhizotron tubes to ecosystem/landscape scales represented by flux towers because processes such as root dynamics and soil efflux are extremely heterogeneous. The proposed spatially dense, parallel measurements of root dynamics, soil efflux and soil moisture will offer an opportunity to discover potentially general scaling relationships that enable aggregating limited point measurements to ecosystem scales. We will determine how the spatial heterogeneities of these variables are related to each other, to temporal variations in precipitation regimes (precipitation event spacing and intensity distribution), temperature and vapor pressure deficit. They will also be related to fluxes measured by the EC system and GPP by SIF. Such analyses will lead to insights on the importance of small-scale variations for ecosystem functions and whether next generation of ecosystem / land surface models should represent such variations and if so, how.

We have recently developed a number of physiologically based climate indices, including the mean effective precipitation interval (MEPI), precipitation variability index (PVI), positive temperature anomaly interval (PTAI), and vapor pressure deficit interval (VPDI) and showed that these indices are closely related to vegetation water stress (Gu *et al.* 2015a), tree mortality (Gu *et al.* 2015b) and ecosystem C and water fluxes (Gu *et al.* 2015c). We will continue to evaluate the potential of these indices as predictors of other ecosystem functions, for example, GPP, root dynamics, soil efflux, LAI and ecosystem energy exchanges at the MOFLUX site and other AmeriFlux sites as well. If these indices are proven to be general, they have the potential to be part of the National Climate Change Indicator System (Kenney *et al.* 2014).

By the end of FY2018, integrated Task 6 research will address the following primary questions:

- How does horizontal and vertical variability in soil moisture affect the spatial heterogeneity in root dynamics and soil respiration?
- How does horizontal and vertical variability in soil moisture affect the magnitude and responses to VPD of net ecosystem exchanges of CO_2, water vapor and sensible heat fluxes and their partitioning among ecosystem components?
- What meteorological, biological, physical and canopy geometrical factors control horizontal and vertical variability in soil moisture?
- What are the most effective indicators of ecosystem functioning in a changing climate?

Table 3.10 – Task 6 Deliverables

Date	Deliverable	Status
Mar 2016	Submit 2015 MOFLUX data to AmeriFlux	Annual Delivery
Jun-Jul 2016	Install new instruments for expanded process work.	Planned
Summer 2016	Measure vadose Zone Soil Water, Shallow Groundwater Flow	Planned
March 2017	Submit 2016 MOFLUX data to AmeriFlux	Annual Delivery
Summer 2017	Quantify relationship between SIF- and EC-based GPP estimates at two contrast ecosystems	Publication

Dec 2017	Report on species-specific relationships between root morphometrics and nutrient content	Publication
March 2018	Submit 2017 MOFLUX data to AmeriFlux	Annual delivery
2018	Funding-dependent installation of EC instrument systems at the S1-Bog	Planned
Summer 2018	Report on the potential EC application in large open-top enclosures	Publication
Sep 2018	Report on spatial heterogeneity of soil moisture, root growth and soil efflux	Publication

3.8 Fossil Emissions (Task 7 – Future Plans)

Task 7 will continue to address a number of items consistent with the original SFA deliverables list. Specifically, Task 7 will

1. Create monthly emission inventories at the scale of states and months at a global scale – Due annually.
2. Create annual and monthly distributions of emissions – Due annually.
3. Explore and publish uncertainty estimates associated with annual emissions – 2015.
4. Explore opportunities and implement closer ties between fossil fuel and other TES SFA tasks – ongoing effort.

Data from items 1 and 2 will be made freely available to the public by CDIAC. Item 4 is new to this list and is explicitly included because the DOE program managers and the ORNL SFA leadership recognize that these ties need to be strengthened. Tony King joined Task 7 in FY15 to facilitate these ties. Tony has extensive experience in terrestrial ecosystem modeling, a long and growing interest in fossil fuel emissions, and has recently led several national efforts synthesizing C-Cycle understanding. It is expected Task 7 activities will continue to lead to peer-reviewed publications on these four items (20 major publications resulting from Task 7 activities occurred during the last three years of SFA funding). For example, to be submitted in late 2015 will be a manuscript describing the CDIAC fossil fuel emission data product being used in the CMIP 6 activities.

Uncertainty analysis of these emissions continues to be a growing area of emphasis globally. We expect to continue our participation and leadership roles in uncertainty analysis of these emissions: our new work describes the first effort to report uncertainty values by grid cell. These gridded uncertainty values will exactly overlay the corresponding CDIAC gridded fossil fuel emission values. This should lead to a better understanding of the global C-Cycle and its individual components (e.g., terrestrial biosphere, fossil fuels, land use, atmospheric growth, and oceanic uptake).

Table 3.11 – Future Task 7 Deliverables

Date	Deliverable	Status
FY 2016-18	Create monthly emission inventories at the scale of states and months at a global scale	Annual
FY 2016-18	Create annual and monthly distributions of emissions	Annual
FY 2016	Explore and publish uncertainty estimates associated with annual emissions	2015
FY 2016-18	Create closer fossil fuel-terrestrial biosphere ties	Ongoing

3.9 LeafWeb (Task 8 – Newly Emphasized Task)

LeafWeb represents an innovative, effective and efficient way to provide a community service and gather globally distributed plant ecophysiological/biochemical data needed for synthesis studies and parameterizing global models. The correct analysis of leaf gas exchange measurements to estimate fundamental photosynthetic parameters (e.g., Vcmax, Jmax and TPU in the FvCB model) and mesophyll conductance requires not only deep understanding of leaf physiology and biochemistry but also highly sophisticated mathematical skills (Gu *et al.* 2010). Previously LeafWeb applied skills and expertise developed in Task 6 and was a subsidiary effort of this larger task. However, LeafWeb has grown out of Task 6's main scientific objectives. To fulfill LeafWeb's potential and better serve multiple scientific communities, professional IT support is needed. Thus we decided to separate LeafWeb from Task 6 and list it as a new TES SFA task. The availability of LeafWeb service removes a heavy mathematical burden from researchers so that they can focus on what is most important to them: the biological processes revealed by their data. LeafWeb enables preservation of data it receives from researchers and ecosystems located in any part of the world.

We propose to enhance and expand LeafWeb to better serve the rapidly developing scientific needs of users and to increase the number of users. LeafWeb's user interface will be improved for optimum performance of multiple users (as opposed to its current one-user-at-a-time processing). The capabilities of LeafWeb will be expanded beyond A/Ci curve analysis to the evaluation of light response curves and leaf fluorescence with the Pulse Amplitude Modulation (PAM) fluorometry and saturation actinic beam method. Such data are important for understanding and modeling plant photosynthesis at different spatial and temporal scales. In particular, leaf fluorescence data are a critical need for developing leaf fluorescence models (van der Tol *et al.* 2014) to support land surface fluorescence modeling and remote sensing for estimating GPP (Frankenberg *et al.* 2014; Joiner *et al.* 2011, 2012, 2013, 2014). We also hope to include C4 species in LeafWeb. CAM species are currently not represented in ESMs. But if there is such a need in the future, LeafWeb should also consider adding functionality for analyzing CAM photosynthesis.

Table 3.12 – Task 8 LeafWeb Deliverables

Date	Deliverable	Status
FY 2016	Parallelize LeafWeb background processing algorithms so that multiple users can be served and multiple datasets can be analyzed simultaneously	Planned
FY 2016	Transfer the LeafWeb system from CDK to ORNL's supercomputing clusters	Planned
FY 2017	Enable joint A/Ci, A/light and leaf fluorescence analyses	Planned
FY 2017	Enable analyses for C4 species	Planned
FY 2018	Redesign the LeafWeb user interface to accommodate the added functionalities	Planned

4. MANAGEMENT AND TEAM INTEGRATION

4.1 Organizational Structure and Key Personnel

The TES SFA includes a science and management teams to guide and direct research activities. The organization chart for the TES SFA is presented in Fig. 4.1.

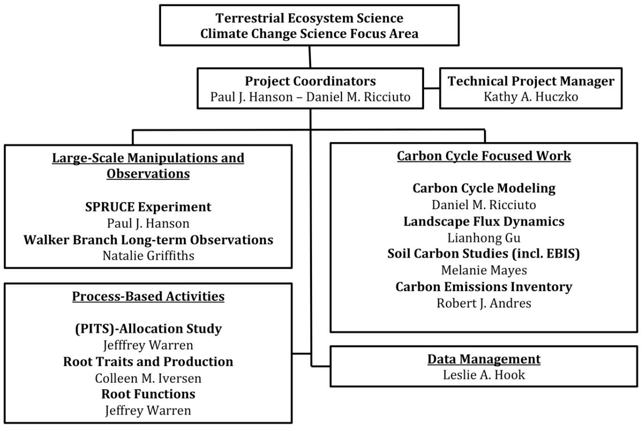


Fig. 4.1 – Organizational chart for the TES SFA.

Dr. Paul J. Hanson is the Principal Investigator (PI) for the TES SFA, and Dr. Daniel M. Ricciuto is the PI for the C-Cycle modeling tasks which are integrated across the TES SFA. Task Leads described in Fig. 4.1 and Section 5 are given independent science and financial responsibility to achieve the goals of their respective tasks. Drs. Hanson and Ricciuto are supported by Kathy A. Huczko in the area of ORNL procedures, purchasing, contracts and engineering. Responsibility for the TES SFA resides within the Energy and Environmental Sciences Directorate and is aligned with associated and related activities of the Climate Change Science Institute (CCSI). Project coordinators and task leaders work with the leadership of CCSI (Dr. Jack Fellows) to integrate TES SFA activities within a broader program of climate change research at Oak Ridge National Laboratory. The TES SFA benefits from external advice of the CCSI Science Advisory Panel with periodically rotating membership. The CCSI panel currently hosts Drs. Peter Curtis, Sasha Reed and Anna Michalak in research areas related to the TES SFA efforts.

4.2 Project Planning and Execution

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

Budget planning for the TES SFA is a cooperative activity between the PIs and Task Leads and ORNL accounting staff. When annual funds are received they are distributed among the TES SFA Task leads and SPRUCE Sub-Task Leads according to the funding schedule laid out in Table B3. Task Leads are expected to manage their funds throughout the fiscal year without exceeding planned funding levels. If task or subtask overages do occur near the end of the fiscal year the PI (Dr. Hanson) will seek to cover such cost over runs from limited carry-over funding from the prior fiscal year. If such funds are insufficient the PI may consult with Task Leads having excess funds to balance the overall TES SFA budget.

4.3 Data Systems And Informatics

Data systems and informatics are not a separate task, but an integral part of the overall TES SFA concept. Open sharing of all data and results from TES SFA research and modeling tasks are critical to advancing the mission of DOE's Program of Terrestrial Ecosystem Science. TES SFA researchers identify and deploy data management systems needed for the collection, storage, processing, archiving, access, discovery, delivery, and assimilation of available measurements, synthetic analysis results, model forcing and boundary condition data sets, and model outputs. Such capabilities facilitate model-data integration and provide accessibility to model output and benchmark data for analysis, visualization, and synthesis activities. Task specific web sites and web-based tools provide for such interactions. Established data management plans are posted for SPRUCE (http://mnspruce.ornl.gov/content/spruce-data-policies) and the TES SFA in general (http://tes-sfa.ornl.gov/node/80). The CDIAC at ORNL will be the final long-term destination for these archive products (http://cdiac.ornl.gov). CDIAC provides long-term system stability, archive longevity, and reliable public data access.

4.4 Collaborative Research Activities

A variety of collaborations, both within the TES SFA and externally, are being fostered to provide necessary expertise or effort in areas critical to the completion of research tasks (see page 151). ORNL subcontract collaborations are detailed in the description of budget details. We continue to encourage key external groups to develop complementary research tasks for the benefit of TES SFA research tasks.

5. PERSONNEL

ORNL is uniquely positioned to deliver the science required to support the vision of the TES SFA. The original team (established in 2009) has undergone several staff changes, but has been supplemented by developing staff in both the modeling and experimental areas and by acquisition of key technical support personnel. The TES SFA is supported by more than 40 dedicated scientific and technical staff with a record of research, publication and leadership in climate change research. 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 Coordinating Investigator and provides integrated leadership across tasks, and coordinates financial management. Dr. Hanson has 28 years of experience as a plant physiologist and environmental ecologist. He operated and managed the long-term (14-year) Throughfall Displacement Experiment on the Oak Ridge Reservation, and coordinated the multi-lab Enriched Background Isotope Study. He currently manages an 11-member Ecosystem Studies Group within the Environmental Sciences Division at ORNL, is a Subject Editor for *Global Change Biology*, and is coordinating the SPRUCE study.
- Dr. Daniel M. Ricciuto is the coordinating investigator for terrestrial C-Cycle modeling taking over for Dr. Peter E. Thornton who continues in an advisory role. Dr. Ricciuto is a staff scientist in the

Terrestrial Systems Modeling Group in the CCSI. His research expertise covers the application of data assimilation techniques that confront terrestrial C-Cycle models with observations, and in the quantification of prediction uncertainty and parameter sensitivity in land surface models. Dan's efforts are focused on improving model parameterization and predictive skill at spatial scales ranging from individual research and observation sites to the entire globe.

- Kathy A. Huczko serves as a Technical Project Manager. She brings expertise and technical skills in ORNL procedures, purchasing, contracts, project management and engineering.
- Dr. Les A. Hook serves as the Data Management Coordinator. He brings expertise and technical skills for data policy, management, and archive planning and implementation. Along with web site developer, Ranjeet Devarakonda, he has developed and maintained task-specific web sites with project information, resources, and public data access.

Individual Task leads take responsibility for their respective continuing or future initiatives as follows (person-specific annual effort is summarized in Table 5.1).

Task 1 SPRUCE Personnel

Experimental design, maintenance and environmental documentation – Paul Hanson leads the development of the SPRUCE experimental infrastructure together with a team of ORNL structural and electrical engineers. W. Robert Nettles (an ORNL employee located full-time in Minnesota) is in charge of the day-to-day onsite activities at the SPRUCE site. He is supported Jeff Riggs (Lead Instrument Technician) to keep the treatments running and data streams flowing. Misha Krassovski, system engineer, designed and implemented automated data acquisition system for SPRUCE.

Plant growth phenology and NPP – Paul Hanson, Colleen Iversen and Richard Norby are splitting efforts in this area. Paul Hanson is leading tree and shrub growth and vegetation phenology with the participation of W. Robert Nettles and Jana Phillips. Richard Norby leads characterization of growth and community dynamics of the diverse *Sphagnum* communities occupying the bog surface beneath the higher plants. Belowground measurements are led by Colleen Iversen, with technical assistance from Joanne Childs and Deanne Brice.

Community composition – Community compositional changes are being led by Brian Palik of the USFS. Chris Schadt leads efforts on microbial community changes, and coordinates related efforts among the SPRUCE collaborators.

Plant Physiology – Characterization of pre- and post- treatment plant physiological responses are led by Jeff Warren with the support of Stan Wullschleger and past and planned postdoctoral staff. We are actively encouraging external participation in the observations of physiological processes including gas exchange, carbohydrate dynamics, C partitioning, hydraulic conductivity and woody respiration assessments.

Biogeochemical cycling responses – Work on hydrologic cycling is led by Steve Sebestyen and Natalie Griffiths. Colleen Iversen leads the subtask focused on plant nutrient availability in the shallow rhizosphere, with technical support from Deanne Brice and Joanne Childs. C-Cycle observations focused on peat changes and C emissions are coordinated by Paul Hanson, with technical support from Jana Phillips and Deanne Brice.

Modeling of terrestrial ecosystem responses to temperature and CO_2 –Daniel Ricciuto coordinates efforts to utilize and incorporate experimental results into improved modeling frameworks for understanding the peatland C-Cycle and its feedbacks to climate together with Xiaoying Shi, and Jiafu Mao.

A coordinating panel made up of the Response SFA research manager (Hanson), the local USFS contact (Kolka), the Technical Task leaders listed above, and members from the scientific community make up the experimental advisory panel. This complete serves as the decision-making body for major operational considerations and the decision making body for vetting requests for new research initiatives to be conducted within the experimental system.

Task 2 – Natalie Griffiths is responsible for synthesizing the watershed biogeochemistry research in Walker Branch Watershed.

Task 3 – C-Cycle modeling activities are led by Daniel Ricciuto with input from Peter Thornton. Subtask contributions are made as follows: Wetlands (Shi, Xu), Allocation (Mao, Ricciuto), Photosynthesis (King, Walker), rhizosphere (Yang), ecological forecasting (Ricciuto, Luo), supersites (Kumar), C flux reanalysis (Mao), detection and attribution (Jin, Mao), model reduction using representativeness (Kumar), and model intercomparisons (Ricciuto, Mao, Shi, King).

Task 4a – Jeff Warren leads efforts to translate results from experimental C allocation manipulations into mechanistic representations for ecosystem model applications in collaboration with Jiafu Mao, Dan Ricciuto, Peter Thornton and Anthony King. Additional modeling personnel have been engaged, including Caroline Farrior (NimBios) and Anthony Walker.

Task 4b – Colleen Iversen leads this new initiative that develops a path forward for improving the representation of fine roots in models by developing a global root ecology database, facilitating the development of a "root module" in CLM, and improving model structure to better reflect empirical knowledge.

Task 4c –Jeff Warren leads this new initiative to experimentally link root function to specific root traits in collaboration with Colleen Iversen and modelers Jitu Kumar, Anthony Walker and Dali Wang who are considering how to apply root function to models.

Task 5 – Melanie Mayes provides expertise in soil C cycling, Chris Schadt in microbial ecology and Gangsheng Wang in modeling to develop an improved process model (MEND) for soil C cycling. The TES's MEND model is currently being incorporated into CLM through the ACME project, and our future TES activities are expected to contribute to the future development of ACME.

Task 6 – Lianhong Gu leads activities in landscape flux of greenhouse gases associated with climate extremes utilizing eddy covariance data and associated experiments. Jason Hubbart has taken MOFLUX on-site activities following Steve Pallardy's retirement. Other contributing staff include Colleen Iversen, Anthony Walker, and Joanne Childs.

Task 7 – Robert Andres is responsible for the Emissions task focusing on uncertainty analyses to enhance our understanding of fossil fuel emissions for model and synthesis activities from an integrative perspective. Anthony King is assisting on this task.

Task 8 – Drs. Lianhong Gu, Anthony Walker and Dali Wang support LeafWeb.

Recent Personnel Actions – W. Robert Nettles was hired to live in Minnesota to provide on-site technical support for the SPRUCE project. Dr. Daniel Ricciuto has taken on the oversight responsibility for the terrestrial C-Cycle modeling group (Task 3 activities), and Dr. Peter Thornton remains engaged as a senior advisor to that group and the TES SFA in general. Drs. Natalie Griffiths, Xiaojuan Yang, Anthony Walker and Gangsheng Wang were all hired as ORNL research staff persons from their prior postdoctoral positions. At the time of this review, our postdoctoral research associate contributions to the TES SFA have cycled to a low level. An objective over the next year is to repopulate that component of the TES SFA personnel profile.

Table 5.1 – Approximate annual person hours by TES SFA in future fiscal years (160 hours = 1 person month). Hours shown as a range indicate variation across fiscal years.

Personnel Contributing to Tasks	Task 1 &2	Task 3	Task 4abc	Task 5	Task 6	Task 7	Task 8
Scientific Staff							
Andres R	---	---	---	---	---	416	---
Devarakonda R	20	20	10	20	10	---	---
Griffiths N	936	---	---	---	---	---	---
Gu L	500-1000	---	---	---	1000-500	---	183
Hanson P	1520-1426	---	0-94	---	---	---	---
Hook L	120	40	40	40	40	---	---
Iversen C	586-602	---	159-200	---	150	---	---
King A	---	640	---	---	---	416	---
Krassovski M	240	---	---	---	---	---	---
Kumar	---	320	160	---	---	---	---
Mao J	---	920	---	---	---	---	---
Mayes M	---	---	---	550-500	---	---	---
Norby R	600-506	---	94	---	---	---	---
Ricciuto D	---	850	---	---	---	---	---
Schadt C	364	---	---	150-100	---	---	---
Shi X	---	650	---	---	---	---	---
Thornton P	---	90	---	---	---	---	---
Walker A		370	80-375				80-187
Wang D	---	740	---	---	---	---	187
Wang G	---	---	---	320-400	---	---	---
Warren J	1310	---	468-375	---	---	---	---
Weston D	460	---	---	---	---	---	---
Wullschleger S	375-400	---	0-94	---	---	---	
Yang X	---	280-550	---	---	---	---	---
USFS In Kind – Science*	880	---	---	---	----	---	---
Postdoctoral Staff							
SPRUCE PDs 1,2,3	3745-4494	---	---	---	---	---	---
CC PD	---	1498	---	---	---	---	---
Soil C PD	---	---	---	749-1498	---	---	---
Root Trait PD	---	---	1198-1498	---	---	---	---
Root Function PD	---	---	0-749	---	---	---	---
Technical and Support staff							
Brice D (ORNL)	1500	---	---	---	---	---	--
Childs J (ORNL)	750	---	---	---	150	---	--
Huczko K (ORNL)	300-0	--	--	--	--	--	--
Nettles WR (ORNL-MN)	1872	---	---	---	---	---	--
Phillips (ORNL)	1020	---	---	500	---	---	--
Riggs (ORNL-Inst.)	1500-900	---	---	---	---	---	
USFS In-Kind Technical*	1320	---	---	---	----	---	---
Annual Person Hours By Task	18830-21208	6418-6688	2250-3782	2229-3158	850-1350	832	450-557

*Unfunded in-kind effort estimated by Randal K. Kolka USDA Forest Service, Northern Research Station.

<u>Succession Planning</u> – We use various methods to prepare for and replace TES SFA staff to ensure project continuity and productivity through time. New TES SFA staff are often 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. Where an identified disciplinary need is established (and for which adequate funding is available) the TES SFA may hire established staff persons directly into a task leadership role. When such a need is identified, but TES SFA funding is not sufficient to initiate a hire, ORNL internal funds may be requested through a strategic hire program.

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. However, individual Task leads are given the responsibility to track scientific progress and for managing their fiscal resources within an annual cycle. Training to allow new staff to understand ORNL procedures, accounting systems, and managerial activities is provided. Such training, in addition to side-by-side transitional mentoring with established staff, provides developing staff with the information and skill sets required to transition into leadership roles. ORNL also has formal programs for mentoring high-potential early career staff, and we use informal mentoring to enable career development.

6. FACILITIES AND RESOURCES

ORNL has made substantial investments 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. Recent acquisitions include a Columbus Instruments Micro-Oxymax Respirometer for lab-scale incubations, and it is capable of detecting CO_2, CH_4, H_2S, H_2, and O_2. In addition ORNL acquired a Picarro G2508 can detect CO_2, CH_4, N_2O, NH_3, and H_2O, and it is coupled with 12 autochambers from Forerunner. The Climate Change Science Institute brought together all ORNL Climate Change staff including members of the TES SFA into a single building (4500N) and has been fostering better day-to-day interactions among modelers, experimentalists and data management specialists.

The TES SFA is supported by world-class capabilities at ORNL. The National Leadership Computing Facility provides an open, unclassified resource that we will use to enable breakthrough discoveries in climate prediction. It houses the largest unclassified computing capability available to climate change researchers in the world. CDIAC provides infrastructure support for data and model integration that we will use and build upon. The Atmospheric Radiation Measurement Program data system (ARM Archive) and the NASA Distributed Active Archive Center for Biogeochemical Dynamics (NASA-DAAC) provide additional expertise in this emerging research discipline. ORNL is also home to the High Flux Isotope Reactor and the Spallation Neutron Source, which we can use to understand physical, chemical, and biological complexity in plant and soil processes.

Other facilities to be used include 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.

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Listing of External Collaborations

TES SFA FUNDED EXTERNAL COLLABORATION

The following individuals or groups are being subcontracted to facilitate the execution of TES SFA task science. Subcontract budget details are provided in the budget section.

Task 1: SPRUCE – Funding will be provided for 1) onsite SPRUCE maintenance, 2) sustained support for operation of the AMR systems, and 3) FY2016 support for ^{14}C analysis of peat, plant material, dissolved C forms and gases and their interpretation with Karis McFarlane and Tom Guilderson at Lawrence Livermore National Laboratory. Other funding will be allocated to fund manual minirhizotron data collection (John Latimer), on-site hydrology and peat biogeochemistry sampling and analysis (Keith Oleheiser), and occasional student support.

Task 3: Terrestrial Ecosystem and Carbon Cycle Modeling – We will contract with Dr. Xiaofeng Xu at the University of Texas El Paso to continue incorporating his microbial decomposition and methane module into CLM, and to parameterize and evaluate this model with SPRUCE observations. A second subcontract is planned to Dr. Yiqi Luo (University of Oklahoma) for software development and development of data assimilation techniques at the SPRUCE and MOFLUX sites for ecological forecasting. A third subcontract is planned to Dr. Mingzhou Jin (University of Tennessee) to support the development of statistical methods and application of the detection and attribution technique. We will establish an unfunded collaboration with Joshua Fisher (JPL) to incorporate new methods for modeling nitrogen cycling into CLM. Finally, we will hold a modeling workshop in FY2016 with representatives from several modeling groups to perform and interpret simulations of SPRUCE treatments.

Task 6: – MOFLUX – We will contract with Dr. Jason Hubbart at the University of Missouri for full-time management and support of the operation of the MOFLUX tower. Dr. Hubbart will also manage and execute a variety of science objectives as outline in the description of Task 6 in Section 3.7.

Task 8: LeafWeb – A programmer will be contracted to maintain the web presence of LeafWeb.

INVESTIGATOR-INITIATED SPRUCE COLLABORATIONS (TASK 1)

The following research proposals were developed by the listed investigators and institutions to take advantage of the TES SFA investments in the SPRUCE experiment. Their funding is independent from the TES SFA budget, but their efforts are coordinated with overall SPRUCE project activities through monthly discussions and organized campaign based sampling activities.

1. **The response of soil carbon storage and microbially mediated carbon turnover to simulated climatic disturbance in a northern peatland forest: revisiting the concept of soil organic matter recalcitrance**. Principal Investigators: Joel E. Kostka, Georgia Institute of Technology & Jeff Chanton, Florida State University (2012-2013)
2. **Toward a predictive understanding of the response of belowground microbial carbon turnover to climate change drivers in a boreal peatland**. Principal Investigators: Joel E. Kostka Georgia Institute of Technology & Jeffrey P. Chanton, William T. Cooper Florida State University (2014 to present)
3. **Understanding the mechanisms underlying heterotrophic CO_2 and CH_4 fluxes in a peatland with deep soil warming and atmospheric CO_2 enrichment**. Principal Investigators: Scott D. Bridgham, University of Oregon & Jason Keller, Chapman University (2013 to present, with renewal pending)
4. **Can microbial ecology inform ecosystem level c-n cycling response to climate change?** Principal Investigators: Kirsten Hofmockel, Iowa State University & Erik Hobbie, University of New Hampshire (2014 to present)
5. **Mercury and sulfur dynamics in the spruce experiment.** Principal Investigators: Brandy Toner and Ed Nater, University of Minnesota & Randy Kolka and Steve Sebestyen, USDA Forest Service MN (2103 to present)

6. **Improving models to predict phenological responses to global change**. Principal Investigator: Andrew D. Richardson, Harvard University (2013 to present)
7. **Lichen community responses to warming.** Principal Investigators: Bruce McCune, Oregon State University, Sarah Jovan, USDA Forest Service OR (2013 to present)
8. **Fungal, bacterial, and archaeal communities mediating C cycling and trace gas flux in peatland ecosystems subject to climate change**. Principal Investigator: Erik Lilleskov, Michigan Technological University with Joint Genome Institute Support (2013 to present)
9. **Effects of experimental warming & elevated CO_2 on trace gas emissions from a northern Minnesota black spruce peatland: measurement and modeling**. Principal Investigator: Adrian Finzi, Boston University (2014-present)
10. **Functioning of wetlands as a source of atmospheric methane: a multi-scale and multi-disciplinary approach**. Principal Investigator: Karis McFarlane and Xavier Mayali, Mike Singleton, Ate Visser, Jennifer Pett-Ridge, Brad Esser, Tom Guilderson Lawrence Livermore National Laboratory (2014-present)
11. **Using microbial enzyme decomposition models to study the effects of peat warming and/or CO_2 enrichment on peatland decomposition**. Principal Investigator: Brian H. Hill and Colleen M. Elonen, Terri M. Jicha, Mary F. Moffett US Environmental Protection Agency (2014-present)
12. **Peatland Mercury Cycling in a Changing Climate: A Large-Scale Field Manipulation Study.** Carl Mitchell, University of Toronto - Scarborough (2014-present)
13. **The role of the Sphagnum microbiome in carbon and nutrient cycling in peatlands - JGI's Community Science Program**. Joel E. Kostka and Gen Glass Georgia Institute of Technology, David Weston Oak Ridge National Laboratory, Erik Lilleskov USDA Forest Service – Houghton, MI, Jon Shaw Duke University, and Susannah Tringe at the Joint Genome Institute. (2015-present)
14. **Soil fauna biodiversity sampling at SPRUCE**. Zoë Lindo University of Western Ontario. (starting in 2015)

APPENDIX A: TES SFA Publications

Published, accepted and in print papers since January 2012

1. Andres RJ, Boden TA, Bréon F-M, Ciais P, Davis S, Erickson D, Gregg JS, Jacobson A, Marland G, Miller J, Oda T, Olivier JGJ, Raupach MR, Rayner P, Treanton K (2012) A synthesis of carbon dioxide emissions from fossil fuel combustion. *Biogeosciences* 9:1845-1871, doi:10.5194/bg-9-1845-2012.
2. Andres RJ, Boden TA, Higdon D (2014) A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission. *Tellus B*. 66:23616, doi:10.3402/tellusb.v66.23616.
3. Bailey V, Hanson PJ, Jastrow J, Torn M, Stover D and workshop participants (2014) *Data-Model Needs for Belowground Ecology - A Summary Report* from the TES Mini-Workshop held in Potomac, MD, May 8, 2014. 31 pp.
4. Bandaru B, West TO, Ricciuto DM, Izaurralde C (2013) Estimating crop net primary production using inventory data and MODIS-derived parameters. *ISPRS Journal of Photogrammetry and Remote Sensing* 80:61-71, doi:10.1016/j.isprsjprs.2013.03.005.
5. Barbier C, Hanson PJ, Todd DE Jr, Belcher D, Jekabson EW, Thomas WK, Riggs JS (2012) Air Flow and Heat Transfer in a Temperature Controlled Open Top Enclosure, *ASME International Mechanical Engineering Congress and Exposition*, 2012, Houston, TX, Paper #IMECE2012-86352.
6. Barr AG, Richardson AD, Hollinger DY, Papale D, Arain MA, Black TA, Bohrer G, Dragoni D, Fischer M, Gu L, Law BE, Margolis HM, McCaughey JH, Munger J, Oechel W, Schaeffer K (2013) Use of change-point detection for friction-velocity threshold evaluation in eddy-covariance studies. *Agricultural and Forest Meteorology* 171:31-45, doi:10.1016/j.agrformet.2012.11.023.
7. Bauerle WL, Oren R, Way A, Qian SS, Stoy PC, Thornton PE, Bowden JD, Hoffman FM, Reynolds RF (2012) Photoperiodic regulation of the seasonal pattern of photosynthetic capacity and the implications for carbon cycling. *Proceedings of the National Academy of Sciences of the United States of America* 109(22):8612-8617, doi:10.1073/pnas.1119131109.
8. Blanco G, Gerlagh R, Suh S, Barrett J, de Coninck H, Felix Diaz Morejon C, Mathur R, Nakicenovic N, Ofosu Ahenkorah A, Pan J, Pathak H, Rice J, Richels R, Smith SJ, Stern D, Toth FL, Zhou P, Andres R, Baiocchi G, Hanemann M, Jakob M, Kolp P, la Rovere E, Michielsen T, Nansai K, Rogner M, Rose S, Santalla E, Wiedmann T, Wilson T, Ürge-Vorsatz D (2014) Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC (eds.)] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Released online 17 Dec 2013.
9. Cheng CL, Kang M, Perfect E, Bilheux HZ, Horita J, Voisin S, Warren JM, Hussey D (2012) Average soil water retention curves measured by neutron radiography. *Soil Science Society of America Journal* 76:1184–1191, doi:10.2136/sssaj2011.0313.
10. Chinnasamy P and Hubbart JA (2014a) Stream and shallow groundwater nutrient concentrations in an Ozark forested riparian zone of the central USA. *Environmental Earth Sciences*, doi:10.1007/s12665-014-3880-7.
11. Chinnasamy P and Hubbart JA (2014b) Potential of MODFLOW to model hydrological interactions in a semikarst floodplain of the Ozark border forest in the central United States. *Earth Interactions* 18:1–24, doi: http://dx.doi.org/10.1175/EI-D-14-0015.1.
12. Chinnasamy P and Hubbart JA (2014c) Measuring and modeling shallow groundwater flow between a semi-karst border stream and Ozark forested riparian zone in the central USA. *Journal of Scientific Research and Reports* 3(6):844-865, doi:10.9734/JSRR/2014/7711#sthash.hc3dzq8i.dpuf.
13. Ciais P, Dolman AJ, Bombelli A, Duren R, Peregon A, Rayner PJ, Miller C, Gobron N, Kinderman G, Marland G, Gruber N, Chevallier F, Andres RJ, Balsamo G, Bopp L, Bréon F-M, Broquet G,

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15. De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze M, Wang Y-P, Luo Y, Jain AK, El-Masri B, Hickler T, Wårlind D, Weng E, Parton WJ, Thornton PE, Wang S, Prentice IC, Asao S, Smith B, McCarthy HR, Iversen CM, Hanson PJ, Warren JM, Oren R, Norby RJ (2014) Where does the carbon go? A model-data intercomparison of vegetation carbon allocation and turnover processes at two temperate forest free-air CO_2 enrichment sites. *New Phytologist* 203:883-899, doi:10.1111/nph.12847.
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17. Dong X, Patton J, Gu L, Wang J, Patton B (2014) Leaf photosynthesis and plant competitive success in a mixed-grass prairie: With reference to exotic grasses invasion. *Journal of Ecosystem and Ecography* 4:9, doi: 10.4172/2157-7625.1000152.
18. Fisher JB, Sikka M, Oechel WC, Huntzinger DN, Melton JR, Koven CD, Ahlstrom A, Arain MA, Baker I, Chen JM, Ciais P, Davidson C, Dietze M, El-Masri B, Hayes D, Huntingford C, Jain AK, Levy PE, Lomas MR, Poulter B, Price D, Sahoo AK, Schaefer K, Tian H, Tomelleri E, Verbeeck H, Viovy N, Wania R, Zeng N, Miller CE (2014) Carbon cycle uncertainty in the Alaskan Arctic. *Biogeosciences* 11:4271-4288, doi: 10.5194/bg-11-4271-2014
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35. Jagadamma S, Mayes MA (2013a) The role of sorption on mineralization of carbon in soils. *JSM Environmental Science & Ecology* 1:1005.
36. Jagadamma S, Steinweg JM, Mayes MA, Wang G, Post WM (2013b) Mineral control on decomposition of added and native organic carbon in soils from diverse eco-regions. *Biology and Fertility of Soils* 49, doi:10.1007/s00374-013-0879-2.
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Completed manuscripts in the peer review process

1. Eberhardt, TL, N Labbé, C-L So, K Kim, KG Reed, D Leduc, JM Warren (2014) Effects of Free-Air CO_2 Enrichment (FACE) on extractives and ash contents of the inner and outer bark of sweetgum (*Liquidambar styraciflua* L.) trees. *Trees – Structure and Function* (under review).
2. Griffiths NA, Tiegs SD (2014) Organic matter decomposition along a temperature gradient in a forested headwater stream. *Freshwater Science* (in review).
3. Griffiths NA, Sebestyen SD (2015?) Temporal dynamics in the vertical profiles of peat porewater nutrients in a northern peatland. Prepared for March submission to *Biogeochemistry.*
4. Gu L, Pallardy SG, Hosman KP, Sun Y (2015a) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. Agricultural and Forest Meteorology (in review).
5. Gu L, Pallardy SG, Hosman KP, Y Sun (2015b) Predictors and mechanisms of the drought-influenced mortality of tree species along the isohydric to anisohydic continuum in a decade-long study of a central US temperate forest. *Biogeosciences Discussions* 12:1285-1325.
6. Gu L, Pallardy SG, Hosman KP, Mao J, Ricciuto D, Shi X, Yang B (2015c) Observed and modeled ecosystem functional relationships of carbon and water exchanges driven by a wide range of precipitation regimes in a central US forest (manuscript in preparation).
7. Hanson PJ, Phillips JR, Riggs JS, Hook LA, Weston DJ, Xu X, Kolka RK (2014) Plot-scale observations of community CO_2 and LA CH_4 carbon flux from a high-carbon peatland in northern Minnesota. *Journal of Geophysical Research – Biogeosciences (being revised).*
8. Jensen AM, Warren JM, Hanson PJ, Childs J, Wullschleger SD (2015) Needle age and season influence photosynthetic temperature response in mature black spruce trees: Do we overestimate the importance of new needles? *Annals of Botany* (being revised).
9. Mao JF, Fu W, Shi X, Ricciuto DM, et. al, (2015b) How the anthropogenic effects modulate the climate-dominated land evapotranspiration trends. Prepared for *Geophysical Research Letters.*
10. Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2015) Evaluating the Community Land Model in a pine stand with $^{13}CO_2$ and shading manipulations. *JGR-Biogeosciences* (submitted).

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APPENDIX B: TES SFA DATA SETS

ORNL TES-SFA Data Policy: Archiving, Sharing, and Fair-Use

The open sharing of ORNL TES-SFA data, modeling products, and documentation among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE's Program of Terrestrial Ecosystem Science. The policy is applicable to all TES-SFA participants including ORNL, cooperating independent researchers, and to the users of data products. Data collected by TES-SFA researchers, results of analyses and syntheses of information, and model algorithms and codes will be quality assured, documented, and archived and will be made available to the public. Archived data products are freely available to the public. Users should acknowledge the contribution of the data provider with the citation (with DOI) as provided in the documentation and acknowledge the U.S. DOE Program for Terrestrial Ecosystem Science.

TES-SFA data policies are consistent with the most recent DOE policies for "Public Access to the Results of DOE-Funded Scientific Research"
http://mnspruce.ornl.gov/system/files/DOE_Public_Access%20Plan_FINAL.pdf
and the "Statement on Digital Data Management"
http://science.energy.gov/funding-opportunities/digital-data-management/
A complete copy of our data policy may be found at:
http://tes-sfa.ornl.gov/sites/default/files/TES_SFA_Data_Policy_20130510_Ver_1_approved.pdf

SPRUCE Public Data Sets:

1. Hanson PJ, Riggs JS, Dorrance C, Nettles WR, Hook LA (2015) **SPRUCE Environmental Monitoring Data: 2010-2014.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.001. (Includes recent additions of annual data files.)
2. Slater L, Hanson PJ, Hook LA (2012) **SPRUCE S1-Bog Peat Depth Determined by Push Probe and GPR: 2009-2010.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.002.
3. Hanson, PJ, U.S. Forest Service Staff, and SPRUCE Team (2012) **SPRUCE S1-Bog Vegetation Survey and Peat Depth Data: 2009.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.003.
4. Lin X, Tfaily MM, Steinweg JM, Chanton P, Esson K, Yang ZK, Chanton JP, Cooper W, Schadt CW, Kostka JE (2014) **Microbial metabolic potential in carbon degradation and nutrient (nitrogen and phosphorus) acquisition in an ombrotrophic peatland.** Applied and Environmental Microbiology 80:3531-3540, doi:10.1128/AEM.00206-14. [**Access SPRUCE Microbial Community Metagenome** (SPRUCE Metagenome Lin *et al.* 2014)]

SPRUCE Project-only Access Data Sets (to be made public following article publications):

1. Hanson PJ, Brice D, Garten CT, Hook LA, Phillips J, Todd DE (2012) **SPRUCE S1-Bog Vegetation Allometric and Biomass Data: 2010-2011**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.004.
2. Iversen CM, Hanson PJ, Brice DJ, Phillips JR, McFarlane KJ, Hobbie EA, Kolka RK (2014) **SPRUCE Peat Physical and Chemical Characteristics from Experimental Plot Cores, 2012**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.005.
3. Hanson PJ, Phillips JR, Riggs JS, Nettles WR, Todd DE (2014) **SPRUCE Large-Collar In Situ CO_2 and CH_4 Flux Data for the SPRUCE Experimental Plots**. Carbon Dioxide Information Analysis

Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.006.

4. Hanson PJ, Riggs JS, Hook LA, Nettles WR, Dorrance C (2015) SPRUCE S1-Bog Phenology Movies, 2010-2104. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.011.

Other TES SFA Public Data Sets and Tools:

1. Warren JM, Iversen CM, Garten Jr CT, Norby RJ, Childs J, Brice D, Evans RM, Gu L, Thornton P, Weston DJ (2013) PiTS-1: **Carbon Partitioning in Loblolly Pine after ^{13}C Labeling and Shade Treatments**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.001.
2. Jagadamma, S, Mayes MA, Steinweg JM, Wang G, Post WM (2014) **Organic Carbon Sorption and Decomposition in Selected Global Soils.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.002.
3. **Tool for Evaluating Mesophyll Impact on Predicting Photosynthesis (TEMIPP).** TEMIPP is a Microsoft Excel spreadsheet-based tool used for demonstrating the impact of lacking an explicit representation of mesophyll diffusion in a photosynthetic model on the predicted response of photosynthesis to the increase in CO_2 partial pressures. TEMIPP is provided as a supplement to the recent publication: Sun Y, Gu L, Dickinson RE, Norby RJ, Pallardy SG, Hoffman FM (2014) Impact of mesophyll diffusion on estimated global land CO_2 fertilization. *Proceedings of the National Academy of Sciences of the United States of America* 15774–15779, doi: 10.1073/pnas.1418075111. Download TEMIPP at http://tes-sfa.ornl.gov/node/80.
4. **LeafWeb.** LeafWeb is a TES SFA-funded web-based tool for the automated numerical analyses of leaf gas exchange measurements. LeafWeb is a SErvice-in-Exchange-for-Data-Sharing (SEEDS) Project. With the approval of the user, the data LeafWeb receives are preserved and added to a global database of biochemical, physiological, and biophysical properties of single leaves to support studies of plant functions and terrestrial carbon cycle modeling. Access LeafWeb at http://leafweb.ornl.gov/.
5. **Walker Branch Watershed Long-Term Data Archive.** Repository for TES SFA-funded data collections of long-term hydrology, stream ecology, chemistry, and biogeochemistry measurements and research. Data can be accessed at http://walkerbranch.ornl.gov/.
6. **Missouri Ozark Flux (MOFLUX) Measurement Data.** TES SFA-funded site characterization and flux measurement data, starting in 2004 and continuing, are archived by the AmeriFlux Program. Data and can be accessed at http://ameriflux.ornl.gov/fullsiteinfo.php?sid=64.
7. Shi X, Wang D (2014) **GSOD Based Daily Global Mean Surface Temperature and Mean Sea Level Air Pressure** (1982-2011)", doi: 10.15149/1130373. (Landing page under development.)

TES SFA Data Sets in the Carbon Dioxide Information Analysis Center (CDIAC):

1. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.ndp058.2013.
2. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyMass.2013.
3. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.AnnualIsomass.2013.
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5. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.db1013.2013.
6. Boden TA, Marland G, Andres RJ (2013) **Global, Regional, and National Fossil-Fuel CO_2 Emissions.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi 10.3334/CDIAC/00001_V2013.
7. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.ndp058.2012.
8. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyMass.2012.
9. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.AnnualIsomass.2012.
10. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyIsomass.2012.
11. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2009.** ORNL/CDIAC, electronic database. doi: 10.3334/CDIAC/ffe.db1013.2012.
12. Boden TA, Andres RJ, Marland G (2012) **Global, Regional, and National Fossil-Fuel CO_2 Emissions: 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/00001_V2012.
13. Maksyutov S, Takagi H, Belikov DA, Saeki T, Zhuravlev R, Ganshin A, Lukyanov A, Yoshida Y, Oshchepkov S, Bril A, Saito M, Oda T, Valsala VK, Saito R, Andres RJ, Conway T, Tans P, Yokota T (2012) **Estimation of regional surface CO_2 fluxes with GOSAT observations using two inverse modeling approaches.** Proc. SPIE 8529, Remote Sensing and Modeling of the Atmosphere, Oceans, and Interactions IV, 85290G. doi:10.1117/12.979664.
14. Global Carbon Project (2013) Global Carbon Atlas. http://www.globalcarbonatlas.org.

TES SFA Data Sets in the NASA Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC):

1. Barr AG, Ricciuto DM, Schaefer K, Richardson A, Agarwal D, Thornton PE, Davis K, Jackson B, Cook RB, Hollinger DY, van Ingen C, Amiro B, Andrews A, Arain MA, Baldocchi D, Black TA, Bolstad P, Curtis P, Desai A, Dragoni D, Flanagan L, Gu L, Katul G, Law BE, Lafleur P, Margolis H, Matamala R, Meyers T, McCaughey H, Monson R, Munger JW, Oechel W, Oren R, Roulet N, Torn M, Verma S (2013) **NACP Site: Tower Meteorology, Flux Observations with Uncertainty, and Ancillary Data.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA http://dx.doi.org/10.3334/ORNLDAAC/1178.
2. Huntzinger DN, Schwalm CR, Wei Y, Cook RB, Michalak AM, Schaefer K, Jacobson AR, Arain MA, Ciais P, Fisher JB, Hayes DJ, Huang M, Huang S, Ito A, Jain AK, Lei H, Lu C, Maignan F, Mao J, Parazoo N, Peng C, Peng S, Poulter B, Ricciuto DM, Tian H, Shi X, Wang W, Zeng N, Zhao F, Zhu Q (in press). **NACP MsTMIP: Global 0.5-deg Terrestrial Biosphere Model Outputs (version 1) in Standard Format.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1225.
3. Ricciuto DM, Schaefer K, Thornton PE, Davis K, Cook RB, Liu S, Anderson R, Arain MA, Baker I, Chen JM, Dietze M, Grant R, Izaurralde C, Jain AK, King AW, Kucharik C, Liu S, Lokupitiya E, Luo Y, Peng C, Poulter B, Price D, Riley W, Sahoo A, Tian H, Tonitto C, Verbeeck H (2013) **NACP Site: Terrestrial Biosphere Model and Aggregated Flux Data in Standard Format.** Data set.

Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1183.

4. Ricciuto DM, Schaefer K, Thornton PE, Cook RB, Anderson R, Arain MA, Baker I, Chen JM, Dietze M, Grant R, Izaurralde C, Jain AK, King AW, Kucharik C, Liu S, Lokupitiya E, Luo Y, Peng C, Poulter B, Price D, Riley W, Sahoo A, Tian H, Tonitto C, Verbeeck H (2013) **NACP Site: Terrestrial Biosphere Model Output Data in Original Format.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1192.
5. Wei Y, Hayes DJ, Thornton MM, Post WM, Cook RB, Thornton PE, Jacobson A, Huntzinger DN, West TO, Heath LS, McConkey B, Stinson G, Kurz W, de Jong B, Baker I, Chen J, Chevallier F, Hoffman F, Jain A, Lokupitiya R, McGuire DA, Michalak A, Moisen GG, Neilson RP, Peylin P, Potter C, Poulter B, Price D, Randerson J, Rodenbeck C, Tian H, Tomelleri E, van der Werf G, Viovy N, Xiao J, Zeng N, Zhao M (2013) **NACP Regional: National Greenhouse Gas Inventories and Aggregated Gridded Model Data.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA http://dx.doi.org/10.3334/ORNLDAAC/1179.
6. Wei Y, Liu S, Huntzinger D, Michalak AM, Viovy N, Post WM, Schwalm C, Schaefer K, Jacobson AR, Lu C, Tian H, Ricciuto DM, Cook RB, Mao J, Shi X (2014) **NACP MsTMIP: Global and North American Driver Data for Multi-Model Intercomparison.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1220.
7. Yang X, Post WM, Thornton PE, Jain A (2014) **Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1223.
8. Yang X, Post WM, Thornton PE, Jain A (2014) **A Global Database of Soil Phosphorus Compiled from Studies Using Hedley Fractionation.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1230.

APPENDIX C: Progress-to-Date Deliverables Tables

Table C1 – SPRUCE deliverable progress since January 2012.

Date	Deliverable	Status
FY2012 Deliverables		
Mar/Apr 2012	Hire ORNL staff technologist to reside in Minnesota	Completed
May 2012	Complete specifications for data service to experimental plots, (2) scope specifications for data systems for data acquisition, storage, and transfer to ORNL, and (3) scope specification for site telecommunications.	Completed
May 2012	Complete engineering for field facilities including office buildings, data system office space, storage, sample prep space, telecommunications.	Completed
May 2012	Complete installation of boardwalks	Completed
Apr to Oct 2012	Conduct pretreatment measurements and archiving of time-zero samples for the full range of disciplinary tasks at all defined experimental plots.	Completed
Jun 2012	Complete engineering and drawings for final aboveground warming chambers	Completed 2013
Jul 2012	Complete the addition of electric, CO_2, propane and data service to all experimental plots.	Postponed for rebid process; Completed 2015
Sep 2012	Environmental and observational monitoring in all planned treatment plots.	Completed 2014
Sep 2012	Submit manuscripts on full-scale warming prototype performance, and on seasonal CH_4/CO_2 flux observations using new methods.	Postponed to include MN performance data
FY 2013 Deliverables		
Oct 2012	Prepare pads for CO_2 tanks.	Completed 2014
Mar 2013	Produce manuscript on baseline woody plant foliar physiology for the S1-Bog.	Submitted 2014
Mar 2013	Data system fully operational.	Completed 2014
April/May 2013	Complete construction of all above- and belowground infrastructures, and initiate treatments.	In progress
2013	Conduct measurements for all SPRUCE tasks for all defined experimental plots employing any refined methods indicated by pretreatment studies.	Completed 2013
Sep 2013	Manuscripts on seasonal and depth variation of microbial populations and other peat characteristics	Lin *et al.* 2014ab Tfaily *et al.* 2014
FY 2014 Deliverables		
Summer 2014	Conduct measurements for all SPRUCE tasks for all defined experimental plots.	Completed 2014
Summer 2014	New Initiative – Deep Peat Heating Test and Experiment	June 2014
Sep 2012	Complete the addition of environmental and observational monitoring systems to all planned treatment plots.	Completed 2014
Sept 2014	Submit manuscript on fine-root production in relation to topography and tree density	In progress Iversen et al.
FY2015 Deliverables		
Spring 2015	Complete chamber construction, initiate treatments	June 2015

Table C2 – Task 2 Walker Branch deliverable progress since January 2012.

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

Table C3 – Task 3a Improve ecosystem process models with site-level observations and experimental data progress on deliverables since January 2012.

Date	Deliverable	Status
2013	Complete development of CLM-PiTS and CLM-SPRUCE and integrate structural changes into main CLM-CN code.	Completed
2013	Perform model-data comparison for PiTS experiments 1-3	PiTS 1 complete, 2 and 3 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	Underway
2014	Evaluate CLM-SPRUCE with initial SPRUCE hydrology data	Complete
2015	Perform a full parameterization of all CLM-CN PFTs using an emulator-based method with all available flux tower and experimental data	Ongoing

Table C4 – Task 3b Improve ecosystem process models with regional observations deliverable progress since January 2012.

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	Completed for CLM-SP, CN underway Underway
2015	Perform CLM-CN global simulations with assimilation of point and gridded observations	Underway

Table C5 – Task 3c Earth System model process integration and evaluation deliverable progress since January 2012.

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
2015	Set up and submit a standard observation database, metrics and diagnostic package for biogeochemical model and ESM evaluation at global and continental.	Underway

Table C6 – Task 4a Partitioning in Trees and Soil (PiTS) deliverables progress since January 2012.

Date	Deliverable	Status
Jan 2013	PiTS-1 manuscript submission. Submit data to TES SFA data archive.	Completed
May 2013	Simulations of PiTS-1 site using CLM4 using observed meteorology and ^{13}C data.	Completed
June 2014	Collect additional seasonal experimental data as requested by the modelers	Completed
Nov 2014	Complete manuscript detailing CLM4 modeling for PiTS-1	Completed
Sep 2015	Finalize data analysis and manuscript preparation for the PiTS-3 field study. Begin PiTS-3 simulations.	In Progress

Table C7 – Task 4b Integrating Root Functional Dynamics into Models deliverable progress since January 2012.

Date	Deliverable	Status
Oct 2013	Build team for review on root functional representation in models	Completed
Apr 2014	Submit review manuscript	Completed
Jun 2014	Work with models and data to explore sensitivity and uncertainty, and root function	Underway
Oct 2014	Refocus task into Task 4b) trait data collation and Task 4c) root function	Completed
Oct 2015	Resolve list of key root traits that require further measurement to resolve function	Underway

Table C8– Task 5 Modeling of Microbial Processing of Soil C deliverables progress since January 2012.

Date	Deliverable	Status
Jun 2013	Calibration of MEND model using lab-scale incubation data	Completed
Sep 2014	Relationship between proxies for microbial biomass	Underway
Aug 2015	Short-term decomposition experiments for model validation	Underway
Sep 2015	MEND is linked with CLM and tested against existing CLM model	Underway

Table C9 – Task 6 Terrestrial impacts & feedbacks of climate variability, extreme events & disturbances deliverables progress since January 2012.

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

Table C10 – Task 7 Fossil Emissions deliverable progress since January 2012 (expressed in abbreviated form):

Date	Deliverable	Status
Due annually	Create monthly emission inventories at the scale of states and months at a global scale	Completed
Due annually	Create annual and monthly distributions of emissions	Completed
October 2012	Explore and publish uncertainty estimates associated with annual emissions	Completed

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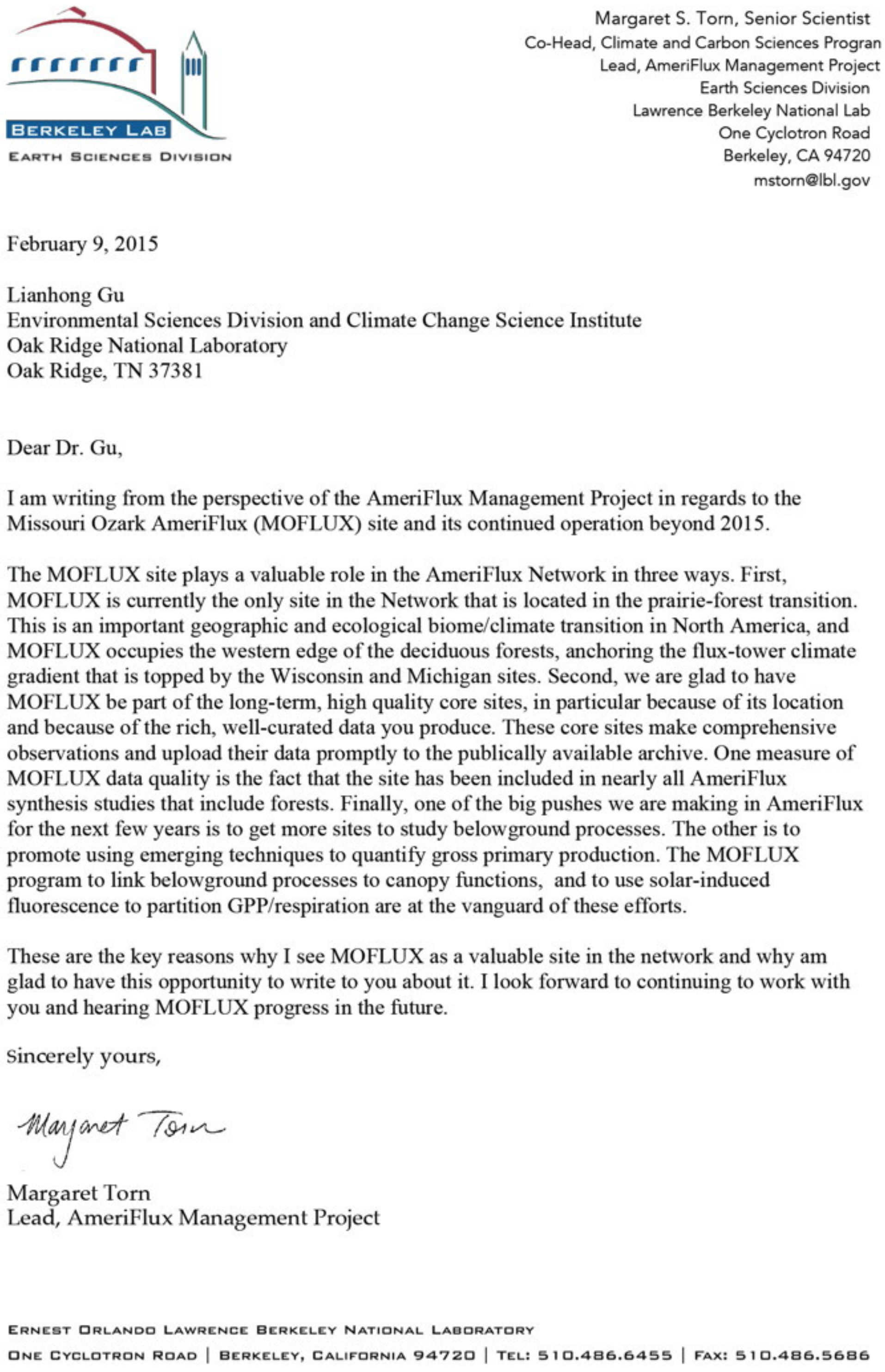
APPENDIX D: AmeriFlux Letter of Support



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February 9, 2015

Lianhong Gu
Environmental Sciences Division and Climate Change Science Institute
Oak Ridge National Laboratory
Oak Ridge, TN 37381

Dear Dr. Gu,

I am writing from the perspective of the AmeriFlux Management Project in regards to the Missouri Ozark AmeriFlux (MOFLUX) site and its continued operation beyond 2015.

The MOFLUX site plays a valuable role in the AmeriFlux Network in three ways. First, MOFLUX is currently the only site in the Network that is located in the prairie-forest transition. This is an important geographic and ecological biome/climate transition in North America, and MOFLUX occupies the western edge of the deciduous forests, anchoring the flux-tower climate gradient that is topped by the Wisconsin and Michigan sites. Second, we are glad to have MOFLUX be part of the long-term, high quality core sites, in particular because of its location and because of the rich, well-curated data you produce. These core sites make comprehensive observations and upload their data promptly to the publically available archive. One measure of MOFLUX data quality is the fact that the site has been included in nearly all AmeriFlux synthesis studies that include forests. Finally, one of the big pushes we are making in AmeriFlux for the next few years is to get more sites to study belowground processes. The other is to promote using emerging techniques to quantify gross primary production. The MOFLUX program to link belowground processes to canopy functions, and to use solar-induced fluorescence to partition GPP/respiration are at the vanguard of these efforts.

These are the key reasons why I see MOFLUX as a valuable site in the network and why am glad to have this opportunity to write to you about it. I look forward to continuing to work with you and hearing MOFLUX progress in the future.

Sincerely yours,

Margaret Torn

Margaret Torn
Lead, AmeriFlux Management Project

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APPENDIX E: Task 3.2 Supplemental Text (J. Mao)

As stated in the IPCC's fourth and fifth assessment reports, detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense without providing a reason for that change; attribution of causes of climate change is the process of establishing the most likely cause for the detected change with some defined level of statistical confidence. Detection and Attribution (D&A) has mainly been used to analyze climate change in the sense of surface temperature, precipitation, surface humidity, extreme events, etc. (Allen and Tett, 1999; Allen and Scott, 2003; Ribes *et al.* 2013). The factor, which is usually attributed to these changes, is an anthropogenic forcing.

The statistical methods used in D&A are based on linear regression and are of the form $Y = \sum_i \beta_i X_i + \varepsilon$ where Y is the observational data, $\sum_i \beta_i X_i$ is the sum of external forcings X_i multiplied by scaling factors β_i, and ε is the internal variability (IV). The covariance matrix of the internal variability $Cov(\varepsilon) = \sum_{\mathrm{IV}}$ is also needed and can be estimated from unforced simulations. Both Ordinary Least Squares (OLS) and Total Least Squares (TLS) methods can be used for the estimation. The primary difference in these two methods is the form of the forcing variables, X_i. While OLS assumes each X_i is perfectly known from the model, TLS allows for variability due to noise in these variables (Ribes and Terray, 2013). A third model, which is more complicated, is the Error in Variables (EIV) model. Like the TLS, EIV allows for variability in the forcing variables X_i (Huntingford *et al.* 2006). Unlike the TLS, however, EIV no longer assumes the model to be perfect and allows for variability due to errors in the model.

Our goal is to complete a D&A analysis on the selected ecosystem variables, such as GPP, NDVI and river flows. In order to do so, methods mentioned above need to be adapted and improved. As stated by Ledoit and Wolfe (2004), in the Ledoit estimation of the covariance matrix of the internal variability ($\hat{C}_I = \gamma \hat{C} + \rho I$), there is a possibility that the accuracy could be improved by using something other than the identity matrix I or establishing a better way to estimate γ and ρ, the coefficients to linearly combine $\hat{C}$ and I. It is possible that there is a better way than used in the classical fingerprint to reduce the dimensionality of the data without losing the regional spatial properties. A recent idea would be establishing a modified multiple factor ANOVA test, which could be used to detect interactions among models with different forcings. The different combinations of forcings can be considered different factors in an experiment. Most of the methods used for D&A are for the fully coupled simulations, which have internal climate variability. In recent years, there is a push to move towards off-line simulations, driven by prescribed historical meteorological forcings, because they consume less computational time (Gedney *et al.* 2014). Therefore, another goal of this task would be to modify D&A for off-line simulations. Without any internal variability, the least squares methods mentioned above may not be applicable for off-line simulation but EIV may be adapted to this. In the regression equation above, the variability lies within the observations. For off-line simulations, this variability is embedded in the model errors, i.e. in the X_i's. As for data used in detection, the linearity of the forcings could be explored to determine if nonlinear combinations could be more appropriate.

Appendix E References

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