

**FY2017 PROGRESS REPORT  
OAK RIDGE NATIONAL LABORATORY'S  
TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA  
(TES SFA)**

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**ABSTRACT**

Understanding responses of ecosystem biogeochemical cycles to environmental 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 environmental change affect the structure and functioning of terrestrial ecosystems at scales from local to global and from decadal to centuries? (2) How to the magnitudes of terrestrial ecosystem biogeochemical processes, mechanisms, interactions and feedbacks control the magnitude and rate of change of atmospheric CO<sub>2</sub> and other greenhouse gases? (3) What are the climate change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of environmental change impacts on ecosystem services and society? The proposed science includes large manipulations, biogeochemical 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<sub>2</sub> on the fundamental organism to ecosystem responses of 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 ecosystem functions, and their response to environmental change including extreme events. The TES SFA aims to integrate experimental and observational studies with model building, parameter estimation, and evaluation to yield reliable ecosystem model projections for application to Earth System models. 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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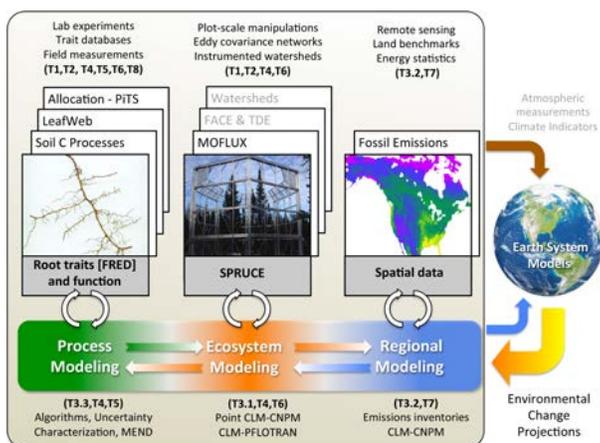
## 1.0 PROGRAM OVERVIEW

ORNL's TES SFA provides fundamental research in support of the DOE BER Earth and Environmental Systems Sciences 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 an 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 environment-biosphere feedbacks. The TES SFA data management and data access activities also contribute real world practice to identified grand challenges in computing.

*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.

TES SFA research is an iterative process (Fig. 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 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.



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

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 Responses Under Changing Environments experiment (SPRUCE), focuses on the combined response of multiple levels of warming at ambient or elevated CO<sub>2</sub> 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 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 Missouri flux (MOFLUX) site while expanding measurements to better interpret responses. Support for the characterization of the fundamental driver of global C emissions is being supplemented.

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).

## 2.0 SCIENCE QUESTIONS, GOALS AND MILESTONES

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

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

### Goals and Milestones

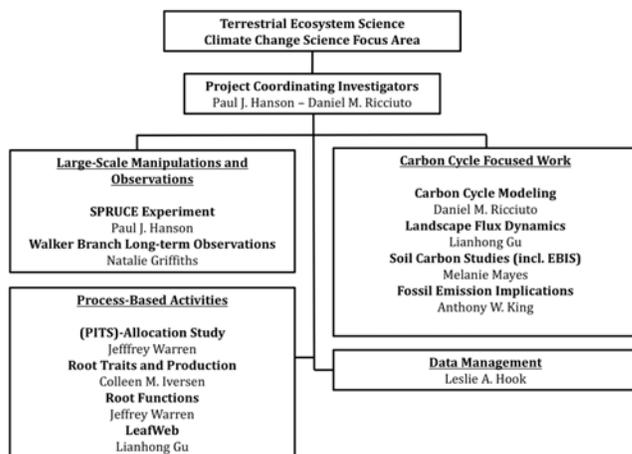
The TES SFA goals and long-term (5 to 10 year) milestones are briefly summarized below. Details on progress are documented in Section 4.

1. Goal 1: Resolve uncertainty in the sign and magnitude of global environment-terrestrial C-Cycle feedbacks under warming and rising CO<sub>2</sub> conditions.
  - 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.
2. Goal 2: Understand and quantify organismal and ecosystem vulnerability to the interactive effects of atmospheric and environmental change using new experimental manipulations employing multi-level warming with appropriate CO<sub>2</sub> 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 environmental change (in a key understudied ecosystem).
3. 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 Earth System Model.
4. **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.
5. **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 environmental change response mechanisms derived from experiments.

### 3.0 TES SFA PROGRAM STRUCTURE AND PERSONNEL

Responsibility for the TES SFA resides within the Climate and Environmental Sciences Directorate and is aligned with associated and related activities of the Climate Change Science Institute (CCSI). The organization chart for the TES SFA is presented in Fig. 2. The TES SFA includes a science and management organization to guide and direct research activities. The TES SFA Leadership Team, comprised of the individuals listed within Fig. 2, provides advice on the yearly SFA plans and budgets, monitors progress, adjusts project plans as appropriate, directs informatics development efforts, and resolves issues in a timely manner.



**Fig. 2. Organizational chart for the TES SFA effective June 2017.**

The TES SFA is supported by 46 dedicated scientific and technical staff at ORNL. Over 50 individuals from the USDA Forest Service, and various other collaborating universities and laboratories are participating in the SPRUCE and MOFLUX projects. 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. Daniel M. Ricciuto is the Coordinating Investigator for terrestrial C-Cycle activities.
- Dr. Leslie A. Hook serves as the Data Management Coordinator. He brings expertise and technical skills for data policy, management, and archive planning and implementation.

Individual Task lead responsibilities are as follows:

## **Task 1 SPRUCE Personnel**

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

Plant growth, NPP and phenology – Paul Hanson is leading tree and shrub growth with the participation of W. Robert Nettles and Jana Phillips. Richard Norby leads characterization of growth and community dynamics of the diverse *Sphagnum* communities. Belowground growth measurements are led by Colleen Iversen in collaboration with current postdoctoral staff, and with technical assistance from Joanne Childs, Deanne Brice, and John Latimer. Vegetation phenology efforts are being led by Andrew Richardson (Harvard).

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 – Plant physiological responses are led by Jeff Warren with the support of Stan Wullschleger and past and current postdoctoral and technical staff. We are actively encouraging external participation in associated tasks: gas exchange, carbohydrate dynamics, C partitioning, 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 assistance from Joanne Childs, Deanne Brice, and John Latimer. C-Cycle observations focused on peat changes and C emissions are coordinated by Paul Hanson. Natalie Griffiths coordinates with Colleen Iversen, Randy Kolka (USFS), and a number of external investigators on extensive decomposition studies.

Modeling of terrestrial ecosystem responses to temperature and CO<sub>2</sub> – 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 an external advisory committee make up the SPRUCE advisory panel. The panel 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. 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 models in collaboration with Jiafu Mao, Dan Ricciuto, Peter Thornton and Anthony King.

**Task 4b** – Colleen Iversen leads the root trait initiative including the development of a global root ecology database to inform the treatment of belowground processes in ecosystem models.

**Task 4c** – Jeff Warren leads the initiative to experimentally link root function to specific root traits in collaboration with Colleen Iversen, post-docs and students, and modelers Scott Painter, Anthony Walker and Dali Wang.

**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.

**Task 6** – Lianhong Gu leads activities in landscape flux of greenhouse gases associated with climate extremes utilizing eddy covariance data and associated experiments. Jeff Wood operates the MOFLUX on-site activities. Other contributing staff include Colleen Iversen, Melanie Mayes, Anthony Walker, and Joanne Childs.

**Task 7** – Anthony King is responsible for the task on implications of fossil emissions for terrestrial ecosystem science.

**Task 8** –Lianhong Gu, Anthony Walker and Dali Wang supported LeafWeb in 2016.

The TES SFA benefits from two advisory panels: ORNL’s CCSI Science Advisory Panel with periodically rotating membership provides annual input on our activities through their annual review of CCSI activities, and a TES SFA panel dedicated to advising the SPRUCE project exists to provide guidance on the science and operation of our flagship experiment. In FY2017 the membership of the SPRUCE Advisory Panel included: Molly Cavaleri (Michigan Technological University); Caitlin Hicks Pries (Lawrence Berkeley National Laboratory); Tim Moore (McGill University); Pat Megonigal (Smithsonian Environmental Research Center); Ted Schuur (Northern Arizona University) and Donald Zak (University of Michigan).

#### **4. PERFORMANCE MILESTONES AND METRICS**

This section represents a summary of TES SFA activities accomplished since our last written document submitted in June 2016. The material is organized by task with parenthetical identification of the goals addressed by each task (Section 2).

Task 1: Spruce and Peatland Responses Under Changing Environments – 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: Implications of Fossil Emissions for Terrestrial Ecosystem Science (Goals 1, 5).

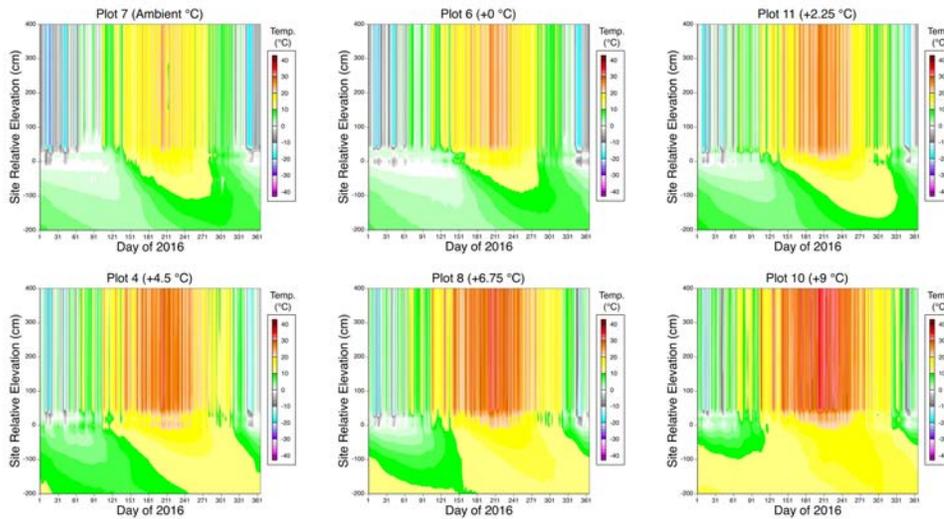
Task 8: LeafWeb data assimilation tool –New Task (Goals 2, 5)

Following the description of progress for each TES SFA science task, a table of anticipated deliverables is provided with annotations regarding progress. Task-specific publications and completed manuscripts are listed by Task. Some citations may be repeated when multiple tasks contributed to the product. The number of new data sets established by each task are also noted with details presented in Appendix B.

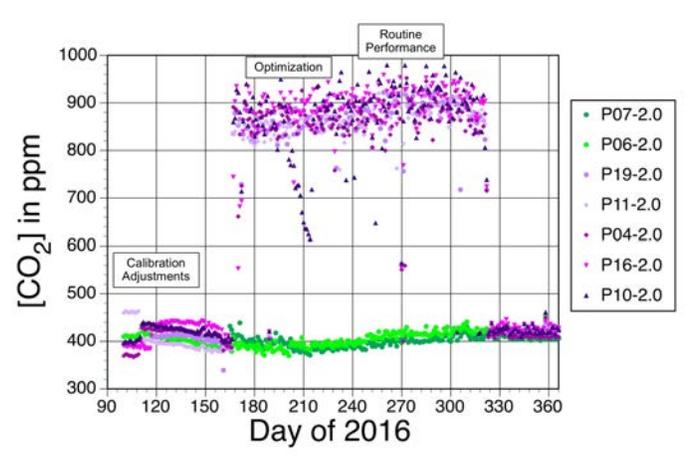
#### **4A1. REVIEW OF SCIENTIFIC PROGRESS BY TASK**

##### **Task 1: SPRUCE Infrastructure**

SPRUCE warming treatments are running full time with limited to no extended interruptions other than those associated with scheduled maintenance. Warming treatments are being maintained day and night throughout the year. Elevated CO<sub>2</sub> exposures initiated on 15 June 2016, are applied only during daytime hours during the active growing season (April through November). The following graphics showcase our ability to sustain whole-ecosystem warming treatments (Fig. 3) and elevated atmospheric CO<sub>2</sub> exposures over time (Fig. 4). Hanson et al. (2017) published a detailed summary of the whole-ecosystem warming and elevated CO<sub>2</sub> treatments of SPRUCE that included a comparison to other warming studies and a full discussion of unique artifacts of the SPRUCE whole-ecosystem warming approach.



**Fig. 3. Temperature contour plots for example ambient and treatment plots that demonstrates our ability to provide whole-ecosystem-warming over the vertical space from +4 m above to -2 m below the peat surface.**

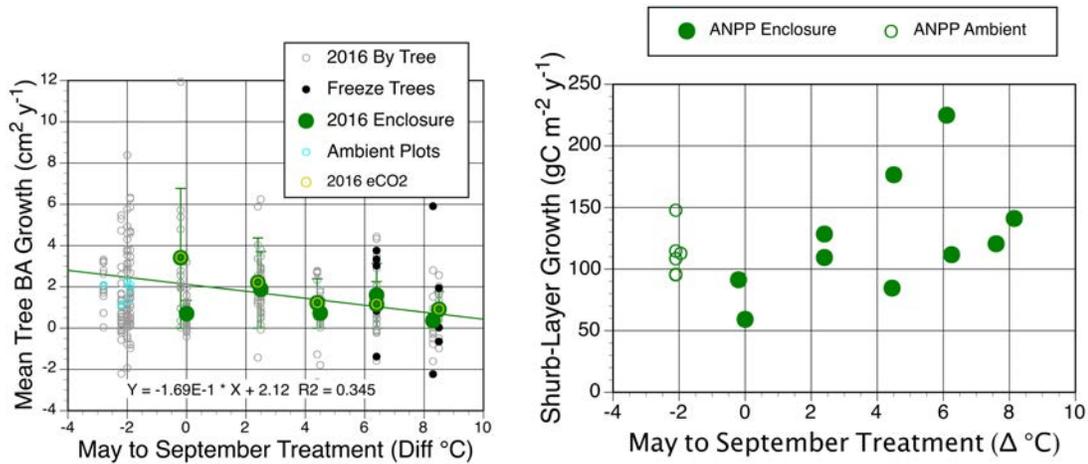


**Fig. 4. Elevated CO<sub>2</sub> treatment performance showing an approximate 500 ppm increase over ambient and constructed control plot concentrations.**

### Task 1: SPRUCE Response Data

*Aboveground production for woody vegetation and forbs* – The first full year of warming (i.e., 2016) revealed a significant pattern of reduced tree growth with warming (Fig. 5 left graph) that was driven primarily by changes in *Picea*. Automated dendrometer bands on a subset of trees captured the species-specific seasonal dynamics of C allocation with *Picea* sustaining growth of stems for a longer period of the growing season (data not shown). Opposite the patterns for trees, the shrub-layer net primary production indicated an increasing trend with warming (Fig. 5 right). No apparent growth changes driven by eCO<sub>2</sub> treatments for trees or shrubs have yet developed.

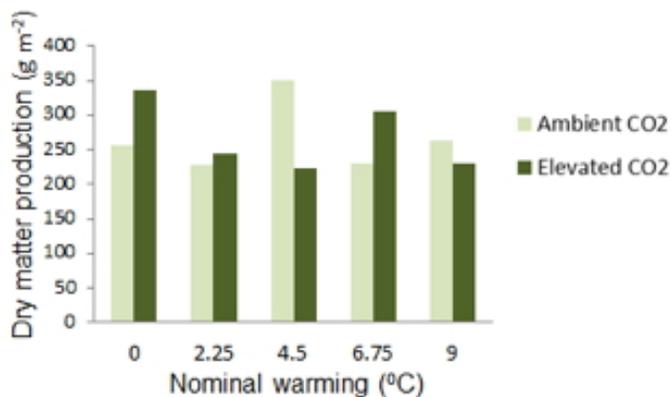
Sustained observations of the growth of tree and shrub-layer vegetation will be an important integrative measure of ecosystem response to warming and elevated CO<sub>2</sub> exposures.



**Fig. 5. Combined tree growth for *Picea* and *Larix* (left) and net primary production for non-tree, shrub-layer vegetation (right) in 2016 under whole-ecosystem warming.**

*Phenology* – Andrew Richardson has prepared a manuscript for *Nature* showing that the warming treatments extend the growing season in spring (as expected), but also in the fall where researchers had concluded that day length was the primary driver. This paper will be submitted very soon once the data sets are appropriately archived and available for review.

*Sphagnum production and Nitrogen Content* - The *Sphagnum* community is dominated by *Sphagnum angustifolium*, *S. fallax* (together comprising 70% cover), and *S. magellanicum* (19%). Will experimental warming and associated drying cause a shift in the community composition of the moss layer, such as replacement *Sphagnum* by *Polytrichum*? Annual assessments across three transects in each plot have not yet shown any change (Fig. 6). Traditional methods of *Sphagnum* growth measurement based on stem elongation, mass per unit stem length, and number of stems per unit ground area, have been problematic. We are using a new and more direct method employing mesh columns embedded in the bog. Initial dry mass is estimated from fresh mass and water content of a paired sample. Net primary productivity of the *Sphagnum* community averaged 267 g dry matter m<sup>-2</sup> or 114 g C ± 6 g m<sup>-2</sup> in 2016. Approximately 30% of the annual production occurred prior to May 9. There were no effects of warming or CO<sub>2</sub> treatments in 2016.



**Fig. 6. *Sphagnum* growth in 2016.**

Nitrogen concentration in *Sphagnum* capitula increased throughout the 2016 growing season. There was no consistent difference due to species, CO<sub>2</sub>, or warming. N concentration in October averaged 13.8 mg g<sup>-1</sup> and C:N ratio was 42.9. Annual N requirement for *Sphagnum* production was 3.7 g m<sup>-2</sup>. Less than 25% of the N needed to support the observed *Sphagnum* production could be accounted for by N deposition, which implies an additional exogenous source of N to this ecosystem.

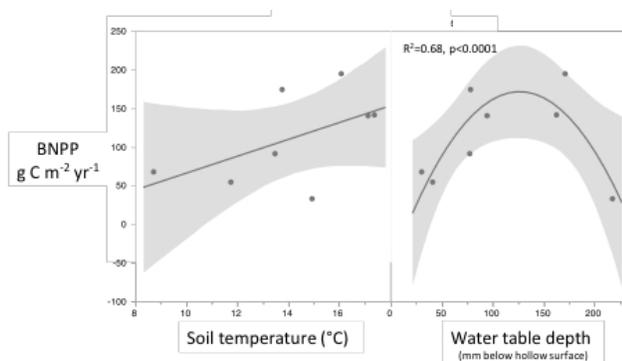
*The distribution and dynamics of fine roots in a forested bog* – Iversen et al. (2017) determined how the amount and timing of fine-root growth in a forested, ombrotrophic bog varied across gradients of vegetation density, peat microtopography, and changes in environmental conditions across the growing season and throughout the peat profile. They quantified fine-root peak standing crop and growth using non-destructive minirhizotron technology over a two-year period, focusing on the dominant woody species in the bog: *Picea mariana*, *Larix laricina*, *Rhododendron groenlandicum*, and *Chamaedaphne calyculata*. The fine roots of trees and shrubs were concentrated in raised hummock microtopography, with more tree roots associated with greater tree densities and a unimodal peak in shrub roots at intermediate tree densities. Fine-root growth tended to be seasonally dynamic, but shallowly distributed, in a thin layer of nutrient-poor, aerobic peat above the growing season water table level.

Building upon the methodology and scientific knowledge gained from the investigation of fine-root distribution and dynamics across the S1 bog, four minirhizotron tubes were installed in each of the SPRUCE experimental plots in early October 2012, and image collection has been on-going weekly during the unfrozen portion of the year since June 2013. Since the onset of aboveground warming in August 2015, warmer peat in the heated plots has allowed minirhizotron image collection to continue throughout the winter months.

**Automated minirhizotrons in SPRUCE experimental plots** - Novel, automated minirhizotron (AMR) technology is also being used to track the dynamics of ephemeral roots in the SPRUCE experimental plots. We have been collecting weekly scans of each AMR system since they came online in June 2014 with a goal of quantifying the phenology of fungal production and mortality in a high-impact paper on root and rhizosphere interactions.

**Root ingrowth cores in SPRUCE experimental plots** - We are also using root ingrowth cores to capture newly-grown fine roots for chemical analyses given the ambiguity of distinguishing between living and dead roots in the anaerobic bog environment where dead tissues are highly preserved. Paired hummock-hollow ingrowth cores constructed of rigid polypropylene mesh and filled with moist, root-free commercial peat are installed in each of two locations in each SPRUCE experimental plot. The cores are collected and replaced two times per year—once in the spring and once in the fall—to better understand seasonal patterns in root growth and chemistry. Chemistry results are in progress but we have been able to gain insight on the temperature responses of fine-root production and traits. Prior to the initiation of warming, we saw no root ingrowth in the winter months between October and June, but this pattern is changing as warming has lengthened the belowground growing season in the treatment plots.

We hypothesized that fine-root production would increase with increased temperature. During the 2015 growing season, when whole ecosystem warming was initiated, we observed greater fine-root production in warmer treatments (Fig. 7 left). However, fine-root production was better predicted by water table depth, suggesting a possible decrease in production related to moisture limitation (Fig. 7 right).

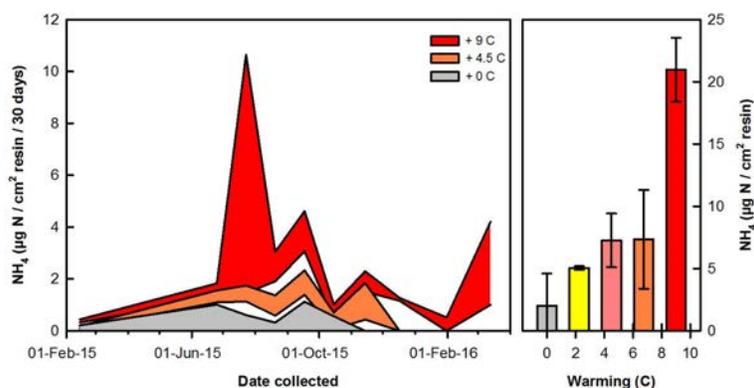


**Fig. 7. Summer 2015 ecosystem-level (pooled across all microtopographical features, plant groups, depths and root orders) relationship between fine-root production as estimated from ingrowth cores. While the relationship between fine-root production and mean growing season soil temperature was non-significant, the mean growing season water table depths and fine-root production had a significant quadratic relationship.**

The initial whole ecosystem warming response of newly grown roots varied by plant functional type (PFT), microtopography, root order and depth. Preliminary analyses suggest that responses to warming were generally stronger for roots growing in hummock microtopography compared with roots growing in

depressed hollows, perhaps due to greater overall root production in hummocks (Iversen *et al.*, 2017). Within hummocks, shallower woody roots showed a stronger response to warming than deeper roots. Conversely, graminoid roots had the strongest response in the deepest sections of the ingrowth cores, due in part to fewer graminoid roots in the shallower sections and as a consequence of aerenchymous tissue in sedge roots. The variability of these responses is useful for informing the belowground components of ALM-SPRUCE.

*Plant Available nutrients* - Ion-exchange resin capsules (WECSA, LLC, Saint Ignatius, MT, USA) are being used to monitor *in situ* changes in plant-available nutrients (i.e.,  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ , and  $\text{PO}_4$ ) in aerobic and anaerobic peat layers in the SPRUCE experimental plots. Resin capsules have been collected every ~28 days from two arrays of resin-access tubes in each experimental plot beginning in the growing season of 2013, and continuing during the non-frozen periods. Since the onset of aboveground warming in August 2015, resin collection has continued in the heated plots throughout the winter months, and it appears that the extension days above freezing has led to an increase in the availability of  $\text{NH}_4\text{-N}$  in the warmest treatment plots (Fig. 8).  $\text{NH}_4\text{-N}$  was by far the most available N source in the bog, with  $\text{NO}_3\text{-N}$  making up a negligible fraction of N (at or near detection limits);  $\text{PO}_4^{3-}$  availability was intermediate.



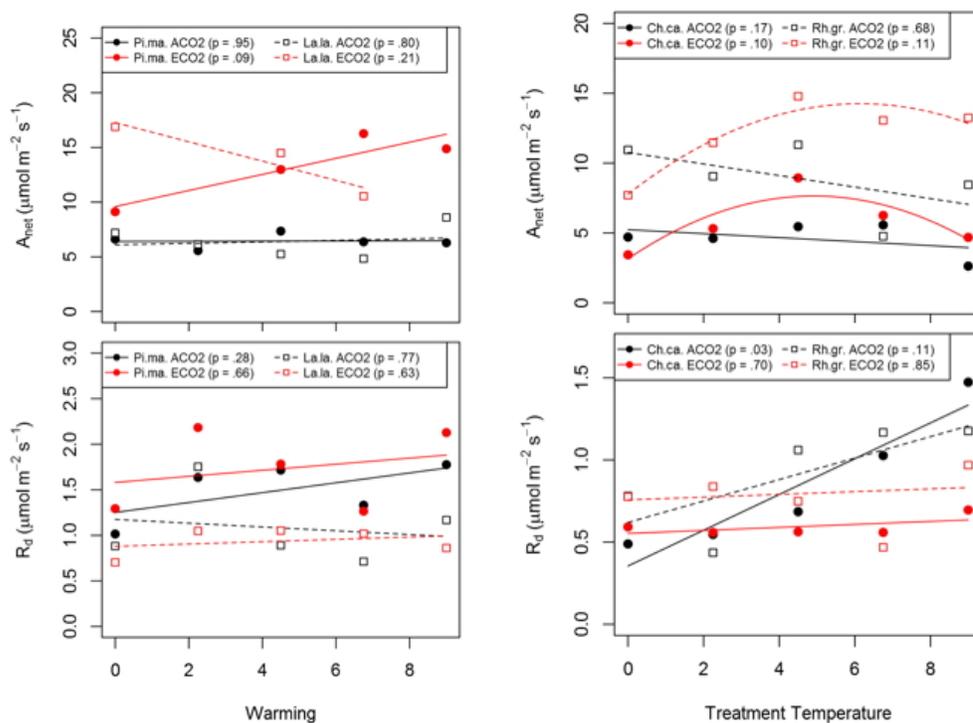
**Fig. 8. Plant-available  $\text{NH}_4\text{-N}$  increased in the warmest treatment plots, in large part because of an extension in the length of time the peat was above freezing in these plots.**

*Woody Plant Physiology* – In Fall 2015 we began long-term automated measurements of sap flow and stem diameter in trees and soil water content within the hummock hollow complex in the 10 chambered SPRUCE plots. In late summer of 2016, we added additional sensors to the two un-chambered SPRUCE control plots. Plant water relations measurements will continue throughout the growing seasons during 2016–2018. The warming treatments create a strong impact on soil, plant and atmospheric water relations through the increase in temperature (~2-11 °C for the +0 and +9 chambers), increased turbulence, increased evaporative losses and shifts in the energy balance that affects the dewpoint. In response to the drier and warmer conditions, we expect shifts in canopy structure, and in leaf area and leaf display through accelerated loss of older foliar cohorts in favor of the new tissue developed under treatment conditions. In summer 2017, we are assessing morphological characteristics of the woody species (traits such as leaf area, leaf size, shoot:area ratio, stomatal density, leaf pubescence) using destructive samples collected during the intensive physiology campaigns (described below). We are also measuring woody branch and root respiratory rates in response to temperature from the different species outside the plots to reduce uncertainty in net C flux from the vegetation. We are able to collect both periodic and opportunistic measurements (e.g., during spring phenology, or during extreme events) to further characterize the morphological and biochemical responses of woody vegetation.

The functions describing response of photosynthesis and respiration to temperature in ALM-SPRUCE depend on two temperatures: standard temperature (25 °C) and the mean temperature over the previous 10 days (T10). We used leaf gas exchange to estimate net photosynthesis ( $A_{\text{net}}$ ) and dark-acclimated respiration ( $R_d$ ) for two conifer tree species (*Picea abies* and *Larix laricina*) and two dominant ericaceous angiosperm shrubs (*Chamaedaphne calyculata* and *Rhododendron groenlandicum*) found at the S1 Bog. We measured  $A_{\text{net}}$  and  $R_d$  at T10 and standard temperature for all species. Measurements were taken in

May (*Picea* only), June, and August. In August, measurements were made at both ambient (400 ppm) and elevated (900 ppm) CO<sub>2</sub> levels for samples from elevated CO<sub>2</sub> treatment plots.

Before CO<sub>2</sub> enrichment began (May, June), we found no evidence for declining A<sub>net</sub> with increasing T10, suggesting either acclimation or a wide thermal niche for photosynthesis in these species. In August, after CO<sub>2</sub> enrichment, we found similar results for the tree species (Fig. 9 left), but that A<sub>net</sub> increased with T10 up to maximum or optimum in the two shrub species (Fig. 9 right). Measurements made at ambient CO<sub>2</sub> (data not shown), indicate some photosynthetic downregulation with CO<sub>2</sub> enrichment in the lower temperature treatments.



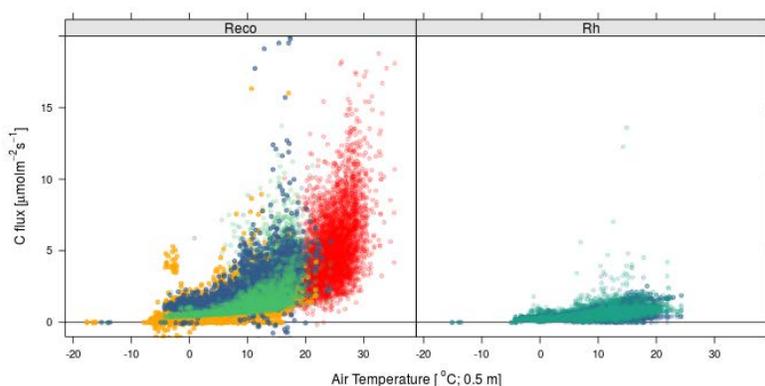
**Fig 9. Net photosynthesis (A<sub>net</sub>) and respiration (R<sub>d</sub>) of carbon for two tree species at the SPRUCE site: *Picea mariana* and *Larix laricina* (Pima and Lala; left graph), and for two ericaceous shrub species at the SPRUCE site: *Chamaedaphne calyculata* and *Rhododendron groenlandicum* (Chca and Rhgr, right graph). Data are presented across 5 temperature treatments ranging from +0 to +9 °C at ambient (aCO<sub>2</sub>) and +500 ppm (eCO<sub>2</sub>) carbon dioxide concentrations. P-values are given for slopes of linear regressions, or for A<sub>net</sub> at eCO<sub>2</sub>, second-order polynomial terms across temperatures.**

We have also been monitoring the soil water content in the plots and the water status of these species, using leaf water potentials taken predawn and midday as indicators of chronic and dynamic water stress, respectively. Due to poor performance in the hummocks, soil water content sensors were removed from hummocks and redeployed into hollow positions, where patterns of drying and relationship to water table depth will facilitate measurements of vegetation response to drought stress. In 2016, we observed a clear pattern of increasing predawn water potentials with treatment temperature in *Larix*, indicating increasing chronic water stress. Such water stress could lead to earlier stomatal closure during the diurnal cycle and thus, reduce photosynthesis, even if photosynthetic potential (as estimated from gas exchange) remained constant. This hypothesis will be further explored with the use of sap flux data, the pretreatment data of which is being prepared for publication later this year. In late summer 2017, we will assess initial sap flux results and examine sap flux sensor performance. Based on this information, we will potential deploy a new set of sap flow sensors in targeted trees that can be used to assess sap flow through 2019.

*Sphagnum Physiology* – The vegetation of the S1 bog is dominated by peat mosses (*Sphagnum* spp.) that contribute substantially to bog NPP (~53%) and together with their associated microbiome contribute to ecosystem C and N cycling. Research in 2016 marks the start of treatment relevant data. During the

growing season, we measured net CO<sub>2</sub> with clear-top LiCOR 8100s. Two sets of 6 chambers each were deployed at the SPRUCE site. One set was deployed at the ambient CO<sub>2</sub> and ambient +9 °C enclosure, and another set deployed at the ambient CO<sub>2</sub> and ambient +2.25 °C enclosure. At both locations, two 8100's were deployed in hollow locations within the enclosures, while the remaining four chambers were deployed outside the enclosures within S1 bog hollows. To assess the relative contributions of autotrophic and heterotrophic respiration, two of the outside chambers were clipped of all vegetation, and were compared with residual chambers with intact *Sphagnum* carpets.

Two notable results are emerging from the 2016 data. First, the C flux difference between clipped and unclipped plots is substantial, differing by up to 7X depending of the air temperature and time of year (Fig. 10). This suggests that autotrophic (*Sphagnum*) respiration is higher than anticipated, or that peat respiration is more tightly coupled with *Sphagnum* photosynthate than previously thought. Both possibilities have direct implications on peatland C dynamics. 2017 field campaigns are designed to partition autotrophic from heterotrophic respiration.



**Fig 10. Relationship between C flux from clear top soil surface gas-exchange chambers to temperature contrasting intact *Sphagnum* carpets (left) and chambers with bare peat (all vegetation removed).**

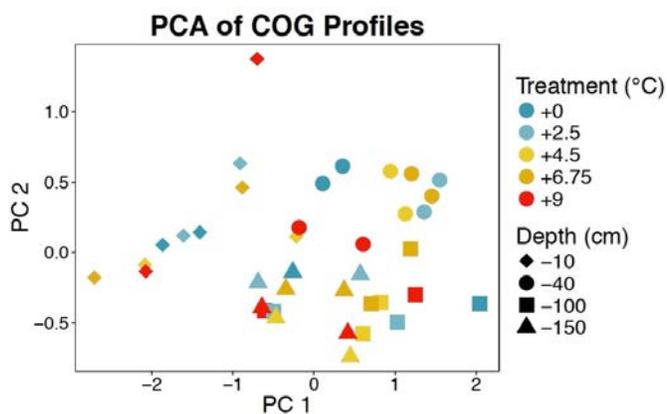
The emerging role of the *Sphagnum*- associated microbiome on peatland nitrogen and carbon interactions is also a notable 2016 outcome. *Sphagnum* production and wet deposition estimates indicate that less than 25% of the N needed to support *Sphagnum* growth is accounted for at the SPRUCE site. To investigate whether the *Sphagnum*-associated microbiome is contributing to this “missing N”, SPRUCE investors determined that N<sub>2</sub> fixing bacteria are present at the site (Glass et al. 2017), and that the abundance and composition of N<sub>2</sub> fixing bacteria respond to warming conditions. Initial results indicate that both the diversity of N<sub>2</sub> fixing bacteria and the rate of N<sub>2</sub> fixation (estimated from acetylene reduction) decrease with warming. These preliminary results highlight a potentially novel role for warming to decrease plant production through disruption of plant microbe interactions. 2017 field campaigns will substantiate these preliminary results throughout the entire growing season.

Microbial Communities and Processes – Recent work on *in situ* experimental heating the SPRUCE chambers, indicated that the deep peat microbial communities and decomposition rates were resistant to elevated temperatures in the first year of experimental warming (Wilson et al., 2016). To follow up on that work we conducted, an *ex-situ* microcosm incubation to understand how nutrient and pH limitations may also interact with temperature to limit microbial community composition and activity.

Anaerobic microcosms of peat collected from 1.5 to 2 meters in depth were incubated at 6 °C and 15 °C with elevated pH, nitrogen (NH<sub>4</sub>Cl) and/or phosphorus (KH<sub>2</sub>PO<sub>4</sub>) addition treatments in a full factorial design. Our results indicated that the production of CO<sub>2</sub> and CH<sub>4</sub> was significantly greater in microcosms incubated at 15 °C, although the structure of the microbial community did not differ between the two temperatures. By elevating the ambient pH of the peat from ~3.5 to ~5.5, CH<sub>4</sub> production increased and altered the microbial community structure. Contrary to expectations, N and P additions did not increase CO<sub>2</sub> and CH<sub>4</sub> production, indicating that nutrient availability is not limiting decomposition. N addition in the form of NH<sub>4</sub> suppressed both microbial abundance and activity in the peat, as well as dramatically altered microbial community composition and reduced microbial diversity. Our findings indicate that temperature is a key factor limiting the decomposition of deep peat, however the availability of O<sub>2</sub> or alternative electron donors, and increased concentrations of phenolic compounds and recalcitrance with

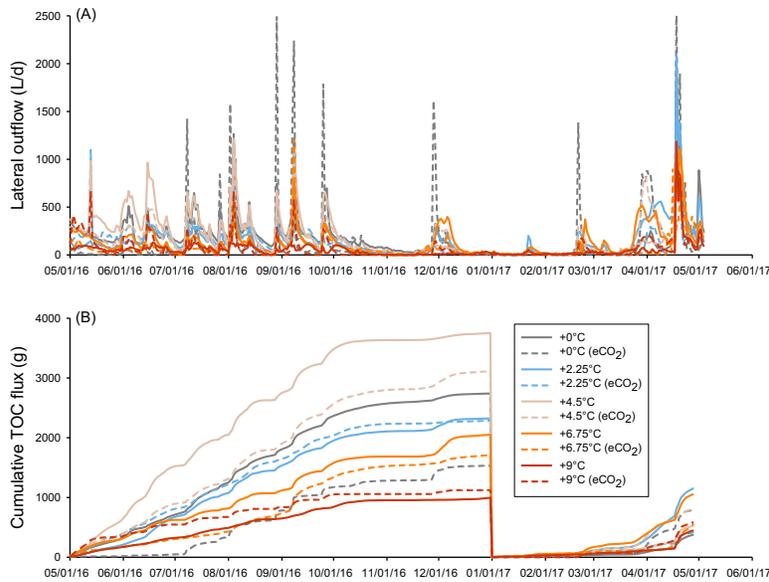
depth, may also exert constraints. Continued study of experimental warming plots will be necessary to assess if the deep peat carbon bank is susceptible to increased temperatures over the decadal course of the SPRUCE field-based experiment, as compared to the 70 days of this incubation study. A paper describing the results of this experiment is under review at *Global Change Biology*.

*rRNA and Metagenomic analyses of microbial responses to SPRUCE treatments* –In addition to the QPCR and rRNA gene sequence based analyses contributed to the Wilson et al (2016) paper, 38 samples for the first year Deep Peat Heating experiment were extracted and metagenome (shotgun) sequencing completed in collaboration with the DOE-Joint Genome Institute (JGI). Results show that like rRNA gene and QPCR examinations, these metagenomes show striking changes in phylogenetic and functional composition with depth, however responses to treatments were not yet evident (Fig. 11). These data, along with other environmental data on the peat samples, have been summarized in a series of published data sets (Kluber et al. 2016a&b) and are available to all collaborators working at the SPRUCE experiment to support other efforts in their projects. An additional 45 metagenome samples from the second year (under whole ecosystem warming) were extracted and submitted in March to JGI for metagenome sequencing. We anticipate the results from these combined samples sets will be published together in the coming year.



**Fig. 11. Principal coordinates analysis of the abundance of functional gene types (COG-based gene classes) from SPRUCE metagenome sequencing shows strong grouping by depth, but not temperature after one year of belowground warming.**

*Hydrology and Water Chemistry* – The subsurface corral and collection basin system is used to measure lateral flow (i.e., stream flow) and solute fluxes from each enclosed plot. In spring 2016, the outflow system was operational, and the autosamplers began collecting flow-weighted water samples for chemical analyses. Solute concentrations in outflow were variable across enclosures, but there was a general pattern of higher total organic carbon (TOC) and cation (i.e., calcium, potassium, sodium) concentrations from the warmer plots. These elevated concentrations may reflect increased decomposition and leaching of recently produced organic matter. There were clear differences in water fluxes (outflow) across enclosures, with lower outflow from the warmer enclosures (Fig. 12A) likely due to increased evapotranspiration. However, there were no differences in outflow between ambient and elevated CO<sub>2</sub> treatments. Despite the higher TOC concentrations in outflow from warmer enclosures, TOC fluxes were lower (especially from the +6.75 °C and +9 °C treatments) because of lower outflow (Fig. 12B). Overall, the first year of outflow and solute flux data suggest that chemical fluxes from the S1 bog to downstream ecosystems may decrease under increasing temperatures.



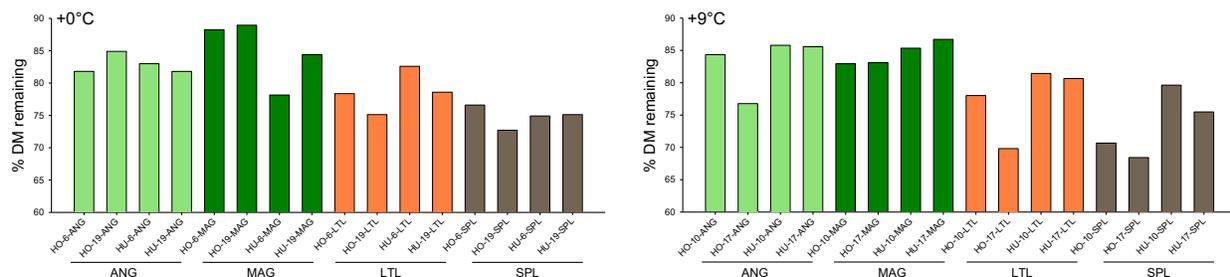
**Fig. 12 – (A) Lateral outflow (L/d) of water from each enclosure from May 2016 to May 2017 and (B) cumulative yearly TOC fluxes (g) from each enclosure.**

**Porewater:** After whole-ecosystem warming began in August 2015, TOC and cation (calcium, potassium) concentrations increased in near-surface porewater (0 m); however, there was considerable among-enclosure variability. Like the outflow chemistry responses, the higher TOC and cation concentrations may be due to increased mineralization and leaching from recently produced organic matter and surface peats. In 2016, TOC concentrations in near-surface porewater continued to increase, with concentrations in some enclosures reaching >160 mg C/L, but the effects of temperature were less apparent. There have been no clear changes in nutrient (i.e., nitrate, ammonium, phosphate) or other solute (i.e., anions) concentrations with temperature treatments thus far. At slightly deeper peat depths (0.3 m), similar patterns of increasing TOC and cation concentrations after whole-ecosystem warming were observed. At deeper depths (0.5 to 3 m), porewater chemistry was very consistent across years, with no major changes after deep peat heating or whole-ecosystem warming.

**Decomposition** - Multiple decomposition studies are being conducted by ORNL within SPRUCE. The main decomposition study is examining the breakdown rates of above- and belowground litter types [*Picea mariana* needles and fine roots, *Rhododendron groenlandicum* leaves and fine roots, *Sphagnum angustifolium*, and *S. magellanicum*] in the SPRUCE enclosures. A second experiment is examining the effect of litter mixtures (*S. angustifolium* with either *Picea mariana* needles or *Rhododendron groenlandicum* leaves) on breakdown rates. Meter-long cotton strips are also deployed twice a year to examine seasonal, inter-annual, and depth-specific variation in decomposition of a labile material (95% cellulose). Lastly, a study is being designed to measure the decomposition of peat at different depths in the SPRUCE enclosures (0-10, 10-20, 20-30, and 30-40 cm), and peat decomposition ladders will be installed in fall 2017. All experiments are evaluating the effect of temperature and CO<sub>2</sub> treatments on decomposition rates.

There were no clear patterns in decomposition rates of various litter types across temperature treatments after 0.5 years (Fig. 13). Breakdown rates varied among litter types, with *Rhododendron groenlandicum* leaves and *Picea mariana* needles decomposing at a faster rate than both *Sphagnum* species (Fig. 13). In the mixed species bags, *Picea mariana* needles and *Rhododendron groenlandicum* leaves broke down at a faster rate when mixed with *Sphagnum*, and slower when mixed with polyester. This finding is opposite our hypothesis of a slower breakdown rate due to the known inhibitory effect of *Sphagnum* on decomposition rates. Faster decomposition may be due to differences in the ability of *Sphagnum* vs. polyester to hold moisture in the litterbags, and we will measure differences in moisture in litterbags during the next retrieval. The cotton strip experiment revealed that labile C decomposition increased with temperature, but there was no clear pattern with depth. The first cotton strip deployment

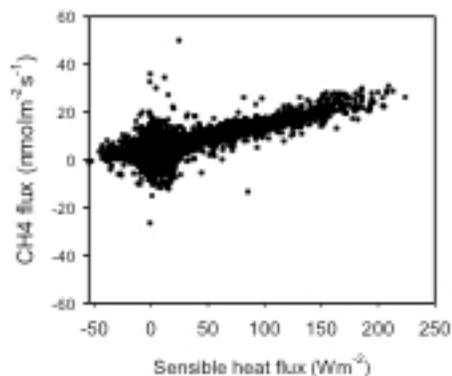
resulted in very rapid decomposition rates, so future cotton strip deployments will be conducted seasonally (spring and fall) instead of yearly.



**Fig. 13 – Dry mass (DM) remaining (%) of *Sphagnum angustifolium* (ANG), *Sphagnum magellanicum* (MAG), Labrador tea leaves (LTL), and spruce needles (SPL) in hollow (HO) and hummock (HU) locations within the two +0 °C (left figure) and two +9 °C (right figure) enclosures after 0.5 years. Note that the two enclosures per temperature treatment are considered replicates here, as CO<sub>2</sub> treatments had not yet been initiated.**

Net CO<sub>2</sub>/CH<sub>4</sub> efflux – The first full season of large-collar CO<sub>2</sub> and CH<sub>4</sub> flux measurements under whole-ecosystem warming was completed in 2016. Data for net CO<sub>2</sub> efflux do not increase with warming, but appear to show a pattern consistent with “acclimation” or substrate limitation. Net CH<sub>4</sub> efflux does increase with warming as expected. Elevated CO<sub>2</sub> responses are not yet fully developed, but there are indications that eCO<sub>2</sub> is providing additional substrate for use by belowground root/microbial systems to periodically enhance net CO<sub>2</sub> and CH<sub>4</sub> efflux rates.

An interesting but unexplained observation from the SPRUCE eddy covariance (EC) study is that the net ecosystem exchange of CH<sub>4</sub> is closely correlated with the sensible heat flux (Fig. 14). To our knowledge, this close relationship has not been reported previously. We are continuously gathering EC observations and conduct analyses in conjunction with other data streams to understand whether such a correlation has a mechanistic basis and if so how to take advantage of this observation for modeling and scaling up CH<sub>4</sub> fluxes from wetlands.



**Fig. 14. CH<sub>4</sub> flux as a function of sensible heat flux as observed at the Plot 2 with an eddy covariance system.**

Carbon Cycle Assessments for the S1-Bog – Griffiths et al. (2017) combined data from numerous SPRUCE measurement tasks to produce a comprehensive analysis of error propagation and uncertainty analysis for the S1-Bog C cycle (Fig. 15). The results showed a very small net gain of C of 8 gC m<sup>-2</sup> y<sup>-1</sup>. However, the combined error terms from this analysis do not allow us to conclude that these data are different than a no change conclusion. Unless changes are very large, conclusions on whole-ecosystem C cycle responses to warming and elevated CO<sub>2</sub> will need to employ isotopic tracer or discrimination techniques to resolve direction and magnitude of change.

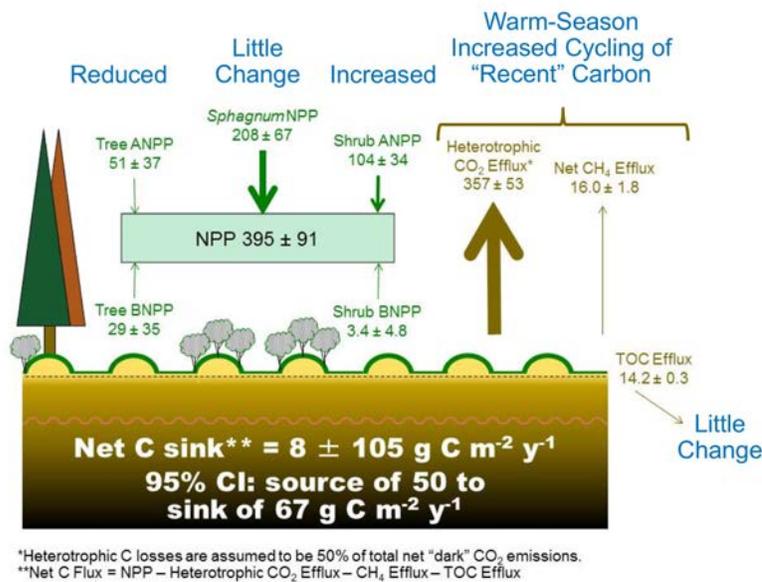


Fig. 15. Full uncertainty analysis of the S1-Bog carbon cycle (Griffiths et al. 2017) showing an average net sink of C with very large error bars. Directions of change for key fluxes inferred from first-year whole ecosystem warming results are shown in blue text.

### SPRUCE Deliverable Progress

The SPRUCE project is now in full operational model with science measurement and modeling tasks representing the dominant effort. The following deliverables cover SPRUCE activities for FY2016 and FY2017.

#### Task 1 – SPRUCE Deliverable Status

Date	Deliverable	Status
<b>FY 2016 Deliverables</b>		
Jan 2016	Whole-Ecosystem Warming Technique Paper	Completed
Jan 2016	Draft manuscript detailing spatial variation in porewater profiles in S1	Published as part of the Griffiths and Sebestyen 2016 paper.
Oct 2016	Full season of task measurements under whole-ecosystem warming	Completed
Oct 2016	Manuscript on root-fungal interactions using AMR technology	Planned
<b>FY 2017 Deliverables</b>		
Aug 2017	Submission of baseline SPRUCE water relations manuscript. Submit sap flow and water potential data to TES SFA data archive.	In progress
Sept 2017	Submission of baseline SPRUCE carbon physiology MODEX manuscript for all major woody species. Submit A-Ci and A-Q data to TES SFA data archive.	In progress
Sept 2017	Submission of SPRUCE manuscript describing initial response of photosynthesis and respiration of <i>Picea mariana</i> and <i>Larix laricina</i> under whole ecosystem warming and elevated [CO <sub>2</sub> ], and TES SFA data archive.	In progress
<b>FY 2018 Deliverables</b>		
Oct 2017	Full season of task measurements under whole-ecosystem warming	Ongoing
Oct 2017	Submission of SPRUCE manuscript describing initial response of photosynthesis and respiration of <i>Chamaedaphne calyculata</i> and <i>Rhododendron groenlandicum</i> under whole ecosystem warming and elevated [CO <sub>2</sub> ], and TES SFA data archive.	In progress
Nov 2017	Submission of SPRUCE manuscript describing initial response of sap flux and canopy conductance responses of <i>Picea mariana</i> and <i>Larix laricina</i> to environmental drivers in an ombrotrophic bog	In progress

Summer 2018	Complete draft manuscript on the moss decomposition study.	Litterbag retrieval in 2018. Manuscript in 2019.
Jan 2017	Draft manuscript comparing porewater chemistry across peatlands (S1 bog, S2-bog, Bog Lake Fen).	Paper is in progress for 2018.

#### Task 1 SPRUCE Publications in FY2016

- Furze M, Jensen A, Warren J, Richardson A (2017) Seasonal patterns of nonstructural carbohydrate reserves in four woody boreal species. *Botany* (being revised)
- Griffiths NA, Sebestyen SD (2016) Dynamic vertical profiles of peat porewater chemistry in a northern peatland. *Wetlands* 36:1119-1130.
- Griffiths NA, Hanson PJ, Iversen CM, Malhotra A, McFarlane KJ, Norby RJ, Ricciuto DM, Sebestyen SD, Walker AP, Ward E, Warren JM, Weston DJ (2017) Temporal and spatial variation in peatland carbon cycling and implications for interpreting responses of an ecosystem-scale warming experiment. *Soil Science Society of America Journal* (in press).
- Hanson PJ, Gill AL, Xu X, Phillips JR, Weston DJ, Kolka RK, Riggs JS, Hook LA (2016) Intermediate-scale community-level flux of CO<sub>2</sub> and CH<sub>4</sub> in a Minnesota peatland: Putting the SPRUCE project in a global context. *Biogeochemistry* 129: 255-272. DOI: 10.1007/s10533-016-0230-8.
- Hanson PJ, Riggs JS, Nettles WR, Phillips JR, Krassovski MB, Hook LA, Richardson AD, Aubrecht DM, Ricciuto DM, Warren JM, Barbier C (2017) Attaining whole-ecosystem warming using air and deep soil heating methods with an elevated CO<sub>2</sub> atmosphere. *Biogeosciences* 14: 861–883, doi: 10.5194/bg-14-861-2017
- Hobbie EA, Chen J, Hanson PJ, Iversen CM, McFarlane KJ, Thorp NR, Hofmockel KS (2017) Long-term Carbon and Nitrogen Dynamics at SPRUCE Revealed through Stable Isotopes in Peat Profiles. *Biogeosciences Discussion* 14: 2481-2494, doi:10.5194/bg-14-2481-2017.
- Huang Y, Jiang J, Ma S, Ricciuto D, Hanson PJ, Luo Y (2017) Soil thermal dynamics, snow cover and frozen depth under five temperature treatments in an ombrotrophic bog: Constrained forecast with data assimilation. *Journal of Geophysical Research* (submitted 18 March 2017).
- Iversen CM, Childs C, Norby RJ, Ontl TA, Kolka RK, Brice DJ, McFarlane KJ, Hanson PJ (2017) Fine-root growth in a forested bog is seasonally dynamic, but shallowly distributed in a nutrient-poor peat. *Plant and Soil* ([early online](#)), doi:10.1007/s11104-017-3231-z.
- Kluber LA, Allen SA, Hendershot JN, Hanson PJ, Schadt CW (2017) Constraints on microbial communities, decomposition 1 and methane production in deep peat deposits. *Global Change Biology* ([in review](#)).
- McFarlane KJ, Iversen CM, Phillips JR, Brice DJ, Hanson PJ (2016) Temporal and spatial heterogeneity of carbon accumulation in an ombrotrophic bog in northern Minnesota over the Holocene. ([being revised for new submission](#)).
- Richardson AD, Furze ME, Hufkens K, Aubrecht DM, Milliman T, Krassovski MB, Latimer J, Nettles WR, Hanson PJ. Photoperiod does not constrain phenological response to experimental whole-ecosystem warming in a Boreal peatland forest. [Intended for Nature](#).
- Smith RJ, Nelson PR, Jovan S, Hanson PJ, McCune B (2017) Decline of the boreal lichen *Evernia mesomorpha* over one year of whole-ecosystem warming. ([being revised for a new journal](#))
- Walker AP, Carter KR, Gu L, Hanson PJ, Malhotra A, Norby RJ, Sebestyen SD, Wullschleger SD, Weston DJ (2016) Biophysical drivers of seasonal variability in *Sphagnum* gross primary production in a northern temperate bog. *Journal of Geophysical Research - Biogeosciences* (in press).
- Wilson RM, Hoppole AH, Tfaily MM, Sebestyen S, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane K, Kostka JE, Kolton M, Kolka R, Kluber L, Keller J, Guilderson T, Griffiths N, Chanton JP, Bridgham S, Hanson PJ (2016) Stability of peatland carbon to rising temperatures. *Nature Communications* 7:13723, doi: 10.1038/NCOMMS13723.

Wilson RM, Tfaily MM, Rich VI, Keller JK, Bridgham SD, Medvedeff C, Meredith L, Hanson PJ, Hines M, Pfeifer-Meister L, Saleska SR, Crill P, Cooper WT, Chanton JP, Kostka JE, Hydrogenation of Organic Matter as a Terminal Electron Sink Sustains High CO<sub>2</sub>:CH<sub>4</sub> Production Ratios Regulating Climate Feedbacks in Boreal Peatlands and Thawing Permafrost. Biogeochemistry (submitted).

#### Task 1 Data Sets

Twenty new Task 1 data sets have been prepared and posted as outlined in Appendix B.

#### Task 2: Walker Branch Watershed Long-Term Monitoring (publication activity)

Walker Branch Watershed research focused on finalizing publications and long-term datasets. A paper on estimating uncertainty in stream nutrient uptake methods was published in *Limnology and Oceanography: Methods* (Brooks et al. 2017), and a paper on snail contributions to total stream nitrogen cycling was published in *Freshwater Biology* (Hill and Griffiths 2017). A paper on dual N and P uptake in streams has been drafted, and is being revised by a co-author (Follstad et al.). Work on developing a stream metabolism model to examine the effects of climate change on stream C cycling is currently on hold as the modeling collaborator has moved institutions. Instead of developing a model, we will focus on summarizing the longer-term dataset in a publication.

Collection of long-term hydrology (precipitation, stream flow), stream chemistry, and climate data in Walker Branch Watershed ended in 2013, and datasets have been available for public download via the Walker Branch website (walkerbranch.ornl.gov). In 2016, these datasets were revised (e.g., for consistent formatting, notation for missing datapoints, coding to denote detection limits, etc.) following standard data archiving protocols. More comprehensive data guides were completed from existing metadata and institutional knowledge. These updated datasets and data guides are now available on the ORNL TES-SFA website (<http://tes-sfa.ornl.gov/node/80>) and are accessible via the Walker Branch website.

#### Publications/Manuscripts

Brooks SC, Brandt CC, Griffiths NA (2017) Estimating uncertainty in ambient and saturation nutrient uptake metrics from nutrient pulse releases in stream ecosystems. In Revision at *Limnology and Oceanography: Methods*. 15:22-37.

Follstad Shah JJ, Kominoski JS, Ardón M, Dodds WK, Gessner MO, Griffiths NA, Hawkins CP, Lecerf A, LeRoy CJ, Manning DWP, Johnson SL, Rosemond AD, Sinsabaugh RL, Swan CM, Webster JR, Zeglin LH. (2017) Global synthesis of the temperature sensitivity of leaf litter breakdown in streams and rivers. *Global Change Biology* (in press) doi: 10.1111/gcb.13609.

Hill WR, Griffiths NA (2017) Nitrogen processing by grazers in a headwater stream: riparian connections. *Freshwater Biology* 62:17-29.

#### Task 2 Deliverables

Date	Deliverable	Status
Fall 2016	Complete development of stream metabolism model and analyze various climate change.	Model development on hold. Will focus on a paper summarizing the longer-term metabolism dataset?
Fall 2017	Manuscript on effects of climate change on stream C cycling.	Model development on hold. Will focus on a paper summarizing the longer-term metabolism dataset?

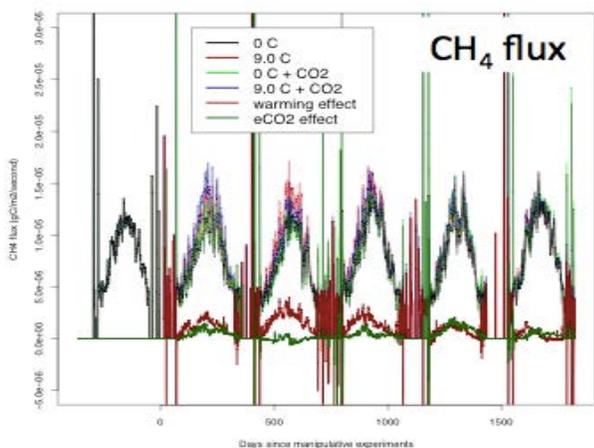
#### Task 3: Mechanistic Carbon Cycle modeling

This task incorporates model development and MODEX activities at the point scales (task 3.1), regional to global scales (task 3.2), and at the level of mechanistic functional units (task 3.3) to identify process contributions to the global climate C cycle forcing from terrestrial ecosystems. Brief summaries of progress are presented along with tabular summaries of progress on proposed deliverables.

### Task 3.1 – Improving ecosystem models with site-level observations and experiments

We have continued model development for SPRUCE and transitioned from CLM-SPRUCE to ALM-SPRUCE (using the ACME version 0 framework). We are continuing to use a GitHub repository for ALM-SPRUCE, which serves as the central point for model development there. ALM-SPRUCE improvements, along with other wetland modeling tasks, are on the ACME version 2 roadmap for integration in 2017 and 2018 with joint TES SFA and ACME support. We are also using the point version of ALM (version 1) at a number of sites relevant for the TES SFA. An uncertainty quantification study is underway at the Missouri Flux eddy covariance site, and we are collaborating with task 5 on model evaluation at this site for ALM-MEND development. New model parameter optimization and sensitivity analysis algorithms are being applied to ALM, substantially improving model predictions, both for the full model and for model functional units (task 3.3). Task 3.1 also supports a SPRUCE model intercomparison: 10 modeling teams have agreed to participate, and pre-treatment simulations have been completed by several teams.

ALM SPRUCE model development - Progress continues for the incorporation of a mechanistic CH<sub>4</sub> model, a moss submodel and methods for model-data fusion and ecological forecasting using pre-treatment observations, include large collar flux measurements (Task 1). A model parameter optimization algorithm (Lu et al., in review) is improving predictions of carbon cycling in these mechanistic models; Fig. 16 shows the optimized model predictions in simulating CH<sub>4</sub> fluxes under different treatment scenarios. The *Sphagnum* submodel developed by Xiaoying Shi includes moss-specific representations of internal and external water, conductance and photosynthesis. For other plant functional types, including *Picea*, *Larix*, and shrubs, we are using measurements and allometric relationships to optimize model growth and allocation parameters. In addition, leaf-level measurements are being used in the functional testing task (3.3) to optimize photosynthesis and leaf respiration parameters. We have also engaged a new sensitivity analysis framework developed for ACME (Ricciuto et al., in review; Lu et al., in review) to identify model parameters and processes that most strongly influence predictions of net carbon fluxes under different treatment scenarios (Griffiths et al. 2017). This sensitivity analysis framework is also being applied to estimate key sensitivities at the Missouri flux site, and for model development in the root function and trait tasks (Task 4).



**Fig. 16. Impact of warming and elevated CO<sub>2</sub> on methane fluxes as simulated by ALM-SPRUCE, after optimization of methane model parameters using pre-treatment flux and concentration dataset.**

EcoPAD, an ecological forecasting framework for the SPRUCE site has been completed using the terrestrial Ecosystem (TECO) model (University of Oklahoma). EcoPAD has been successfully integrated with the SPRUCE Vista Data Vision software to provide continuously updated hindcasts of selected variables (<http://sprucedata.ornl.gov/>). This framework is currently being extended to ALM-SPRUCE. This forecasting system uses a Markov Chain Monte Carlo data assimilation framework with near real-time data streams to estimate the relative contributions of predictive uncertainty from model drivers (e.g. meteorology) and model parameters. Parametric and forcing uncertainties drive the prediction

uncertainty. Model predictions are continuously updated with new data and simulations at [http://ecolab.cybercommons.org/ecopad\\_portal/](http://ecolab.cybercommons.org/ecopad_portal/).

*Formal Model Structural Uncertainty Analysis: Tools and Methods* - This subtask is to develop methods that formally assess model structural uncertainty, i.e. the uncertainty that arises in modelling a system when multiple competing hypotheses exist for the mechanistic representation of a process in question. Given the unique approach to formalising model structural uncertainty and its potential, this work has been elevated to the position of sub-task within the carbon cycle modeling task. This sub-task is to develop agile software and novel algorithms which will be used to formalise model structural uncertainty analysis.

In collaboration with Ming Ye (FSU) and colleagues at PNNL, a sensitivity analysis method based on Sobol's method has been developed to formally analyse process-representation uncertainty and published in *Water Resources Research* (Dai et al., 2017). The Multi-Assumption Architecture and Testbed (MAAT) is the novel software framework designed specifically for formal model structural (i.e. process representation) uncertainty analysis. The MAAT software system, written in R, was developed in the early part of FY16 as a flexible and automated object oriented software framework to be a formalised flexible wrapper around modularised code that can simply and efficiently switch between multiple representations of the same process, sometimes referred to as multi-physics. The MAAT allows full global process-representation and parameter uncertainty analysis based on Sobol's method and that of Dai et al., (2017).

Anthony Walker was selected to give a plenary presentation of MAAT and MAAT research in the **Emerging Technologies from the Local to Global Scale session** at the NACP and AmeriFlux PI Meeting in Washington DC, March 2017. The presentation was competitively selected from a large group of applicants and was viewed by the selection committee as novel and exciting enough to be presented alongside Berrien Moore's presentation of NASA's Geostationary Carbon Cycle Observatory (GeoCARB) mission.

*Sphagnum* photosynthesis has been modelled within the MAAT framework and evaluated against the 8100 data (Walker et al., 2017) as described in the SPRUCE *Sphagnum* task section. MAAT allowed very flexible specification of alternative hypotheses within the *Sphagnum* photosynthesis model to link seasonality in *Sphagnum* GPP to environmental dynamics. The evaluation of alternative hypotheses enabled the discovery of an interaction of *Sphagnum* photosynthesizing tissue area with the water table that described a key feature of seasonality in GPP.

Future plans for this sub-task of the TES-SFA are to further develop the process-representation uncertainty analysis method to improve computational efficiency thus expanding the range of problems that can be addressed using this method. The MAAT leaf-scale and canopy-scale photosynthesis routines are supporting NGEE-Tropics RO2 model uncertainty analysis tasks and further development of these routines (i.e. the actual process) has been handed off to NGEE-Tropics. This SFA sub-task will focus on development of uncertainty analysis methods and application of these and the MAAT to answer TES-SFA science questions.

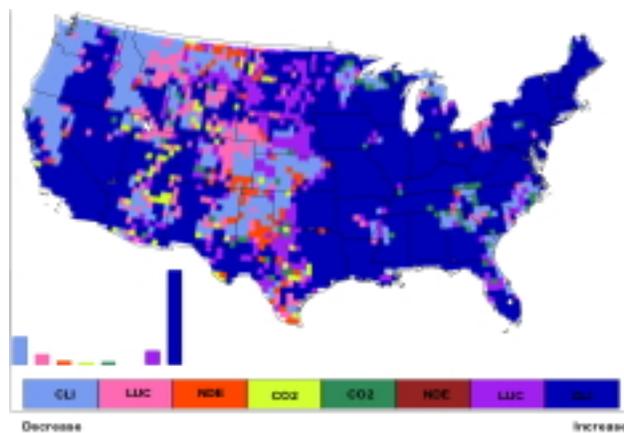
### Task 3.1 Deliverable status

2017	- Completion of CLM_SPRUCE model with improved <i>Sphagnum</i> photosynthesis	<i>Underway</i>
	- Complete 3D PFLOTRAN simulations	<i>Underway</i>
2018	- Document ecological forecasting system	<i>Underway (Huang et al., in prep)</i>
	- Deliver model to ACME	<i>Underway</i>

### Task 3.2 - Regional and global land ecosystem modeling

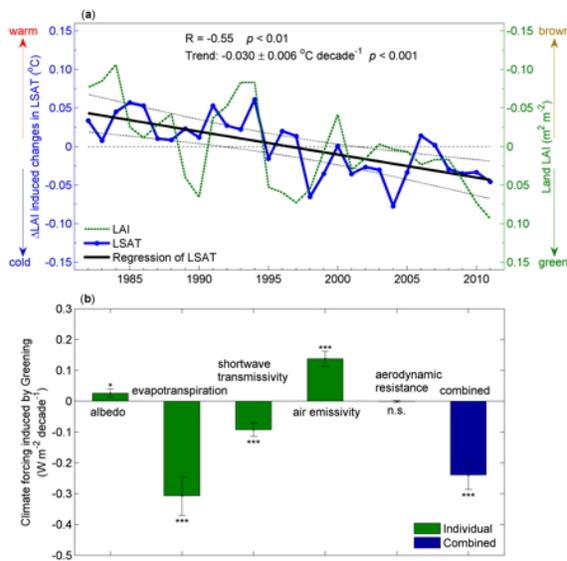
*Detection and attribution of the terrestrial runoff in the conterminous United States* - With the recent availability of long-term runoff observations and multiple factorial model simulations in continental U.S., we are in a unique position to detect and attribute multi-year changes of terrestrial runoff from local to continental scales. To disentangle the natural and anthropogenic drivers (e.g., climate change, elevated

CO<sub>2</sub>, and land use/land cover change) underlying spatiotemporal changes in US runoff, we carried out modified statistical analysis of Detection and Attribution (D&A) using single-factor simulations from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) project. We found that in addition to climate change effects, particularly the precipitation, observed runoff trends were also attributed to individual and combined human effects. Specifically, we identified that the conterminous US experienced an enhancement of runoff for the 1950–2010 period diagnosed in USGS WaterWatch observations and MsTMIP offline historical simulations. Changing climate, mainly the precipitation, was assessed to be the dominant driver controlling variations in annual and seasonal runoff (Fig. 17). The net CO<sub>2</sub> fertilization and physiological effects induced increased runoff for most regions, and nitrogen deposition slightly decreased US runoff via enhanced plant growth. The land-use-induced runoff responses were pronounced locally and even outweighed the climate impacts in central and central north US. Based on simplified D&A analysis, we demonstrated that the runoff D&A results were quite regionally and seasonally dependent. For example, the climate change effects were detected and attributed for autumn across three of the four US big regions. For the summer season, however, the climate change effects were significantly detected and attributed only over two big regions. Compared to the dominant role of changing climate on long-term runoff changes, the CO<sub>2</sub> and land use impacts were identified over few regions and seasons and with wide scaling factors. More detailed analysis and datasets are still needed, including the use of pre-industrial control simulations from fully coupled Earth system models to estimate the internal variability of simulated runoff and the synthesis of more observed runoff data to reduce observational uncertainties. One manuscript on this research is under preparation.



**Fig. 17. Spatial distribution of dominant environmental driver for the annual changes of US runoff for the period 1950–2010. The insets show the frequency distribution of the corresponding change. Factorial results of the MsTMIP multi-model are CLI: the impact from historical climate only, LUC: the historical land use/land cover change impact only, NDE: the historical nitrogen deposition impact only, and CO<sub>2</sub>: the historical CO<sub>2</sub> impact only.**

*Climate mitigation from vegetation biophysical feedbacks during the past three decades* – The observed widespread “greening” trend, especially in the northern extratropical latitudes, over the past 30 years has been attributed to human effects, particularly the well-mixed greenhouse gases. Responses of surface air temperature to this human-induced enhanced vegetation growth, however, have never been well quantified. We participated in an international collaborative research to isolate the fingerprint of increasing leaf area index (LAI) on surface air temperature using a coupled land–atmosphere global climate model prescribed with satellite LAI observations. We found that the global greening slowed down the rise in global land-surface air temperature by  $0.09 \pm 0.02$  °C since 1982 (Fig. 18). This net cooling effect was the sum of cooling from increased evapotranspiration (70%), changed atmospheric circulation (44%), decreased shortwave transmissivity (21%), and warming from increased longwave air emissivity (29%) and decreased albedo (6%). The global cooling originated from the regions where LAI has increased, including boreal Eurasia, Europe, India, northwest Amazonia, and the Sahel. Increasing LAI did not, however, significantly change surface air temperature in eastern North America and East Asia, where the effects of large-scale atmospheric circulation changes mask local vegetation feedbacks. Overall, the sum of biophysical feedbacks related to the greening of the Earth mitigated 12% of the observed global land-surface warming for the past 30 years. This work was partially supported by the TES SFA project and recently accepted by Nature Climate Change (Zeng et al., 2017a).



**Fig. 18. LAI-induced trends in annual average land-surface air temperature (LSAT), (a) temporal variation of global land average LAI (green dotted line) and LAI -induced variation in LSAT (blue solid line). The black line is the least squares regression of LSAT against time. (b) LAI-induced trends in surface radiative forcing over the land surface associated with the changes in surface albedo.**

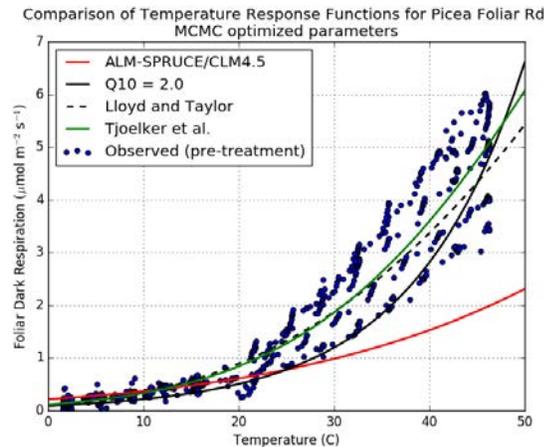
### Task 3.2 Deliverable status

2017	- CLM-SIF model validation; experimental design and model ensemble simulations	Planned
	- D&A study of the NDVI and river flow	Planned
2018	- Finish global optimization framework with GPP reanalysis time series	Planned
	- D&A of global GPP	Planned

### Task 3.3 – Functional testing

Using our functional testing framework, we continue to explore the functional representation of photosynthesis and  $R_d$  in CLM-SPRUCE and ALM. We have focused on the representation of foliar dark respiration ( $R_d$ ) and pre-treatment (2010–2013) observations of the temperature response of  $R_d$  for black spruce (*Picea mariana*) at the SPRUCE site. In the functional unit testing framework, functional representations at the finest level of code granularity and the scale of observations are isolated as modular units, in this case  $R_d$  and its accompanying temperature response functions. We have found that the observed temperature response of black spruce foliar  $R_d$  is not duplicated by the foliar  $R_d$  module of CLM-SPRUCE. The model simulates a reduction in  $\ln R_d$  at temperatures  $> 30$  °C not seen in the observations where  $\ln R_d$  increases approximately linearly over the range 5-40 °C (Fig. 19). Substituting in a more conventional Q10 temperature response module improves the fit with observations. The “acclimation” of  $R_d$  coded into the model may not appear in the observations because historically, black spruce at the site experience the warmer temperatures infrequently and only briefly, and we are pursuing the investigation of this hypothesis with Jeff Warren (Task 4c) and others. We are also utilizing the functional unit testing framework in the  $^{13}\text{C}$  modeling of Task 7 (work described there).

The functional unit testing of the temperature response of black spruce foliar dark respiration has been expanded to include alternative temperature functions and integrated with MCMC UQ/calibration. Results show that non-exponential formulations better represent the SPRUCE pre-treatment observations (Fig 19). In a MODEX application these results are being used in the planning a June 2017 campaign of plant physiology measurements, particularly the temperatures and time spent at higher temperatures in respiration and photosynthesis measurements.



**Fig. 19. Dark respiration as a function of temperature: modeled vs. observed responses at the SPRUCE site.**

The functional unit testing of ALM-SPRUCE is also being employed in an analysis of pre-treatment photosynthesis measurements, comparing observed A-Ci curves and light response curves with functional unit simulations with and without calibration and with and without acclimation to growth temperature. Early results indicate that the functional units are more sensitive to calibration than the acclimation algorithm.

### Task 3.3 Deliverable status

2017	Functional testing for ecosystem dynamics and hydrological components and model structure UQ development	Underway
2018	Regional CLM functional testing and multiscale UQ with observational datasets	Planned

### Task 3 Publications

- Dai H, Ye M, Walker AP, Chen X (2017) A new process sensitivity index to identify important system processes under process model and parametric uncertainty. *Water Resources. Research* 53:2577-3522, doi:10.1002/2016WR019715
- Fang Y, Michalak AM, Schwalm C, Huntzinger D, Berry JA, Ciais P, Piao S, Poulter B, Fisher JB, Cook RB, Hayes D, Huang M, Ito A, Lei H, **Mao J**, Parazoo N, **Shi X**, Tao B, Wang W, Wei Y, Yang J (2017) Global land carbon sink response to temperature and precipitation varies with ENSO phase. *Environmental Research Letters*. ([accepted in press](#)).
- Huntzinger DN, Michalak AM, Schwalm C, Ciais P, Schaefer K, King AW, Wei Y, Cook RB, Fisher JB, Hayes D, Huang M, Ito A, Jain AK, Lei H, Lu C, Maignan F, **Mao J**, Parazoo N, Peng S, Poulter B, **Riccuito D**, **Shi X**, Tian H, Wang W, Zeng N, Zhao F (2017) Multiple drivers important for controlling trends in net land sink since 1959. *Scientific Reports*. ([accepted in press](#)).
- Lu D, Ricciuto D, Walker A, Safta C, Munger W (2017) Bayesian calibration of terrestrial ecosystem models: A study of advanced Markov chain Monte Carlo methods, *Biogeosciences Discuss.*, doi:10.5194/bg-2017-41, ([in review](#))
- Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM4.5). *Biogeosciences* 13:5183-5204, doi:10.5194/bg-13-5183-2016, 2016.
- Walker AP, Carter KR, Gu L, Hanson PJ, Malhotra A, Norby RJ, Sebestyen SD, Wullschlegel S, Weston DJ (2017) Biophysical drivers of seasonal variability in *Sphagnum* gross primary production in a northern temperate bog. *Journal of Geophysical Research*. - *Biogeosciences* 2016JG003711. doi:10.1002/2016JG003711
- Zeng ZZ, Piao SL, Li LZ, Zhou LM, Ciais P, Wang T, Li Y, Lian X, Wood ER, Friedlingstein P, **Mao J**, Estes LD, Myneni RB, Pen SS, **Shi XY**, Seneviratne SI, Wang YP (2017) Climate mitigation from

vegetation biophysical feedbacks during the past three decades. *Nature Climate Change* 7:432-436, doi: 0.1038/NCLIMATE3299.

#### Model and Data Archiving

The first publications containing ALM- SPRUCE model results (Shi et al, 2015; Griffiths et al., in press) highlight the need for a consistent archiving framework for model products. We are pursuing a strategy similar to that used in NGEE-Arctic to arrive model code and datasets used for model validation. A model-data package for the Shi et al. manuscript has been made available (<http://dx.doi.org/10.3334/CDIAC/spruce.031>). A repository is also set up for code archiving, development and sharing ([https://github.com/dmricciuto/CLM\\_SPRUCE/](https://github.com/dmricciuto/CLM_SPRUCE/)), and has enabled efficient collaboration within the project.

#### Task 4a: Synthesis of the Partitioning in trees and soils studies.

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 ALM and other terrestrial biosphere models. PiTS data analysis and modeling efforts continued in the past year based on existing data from the three PiTS studies – the dogwood <sup>13</sup>CO<sub>2</sub> labeling and shading dataset and manuscript is in development, and modeling activities are planned. Once the modeling runs are complete, we will reassess the utility of this MODEX, and in context of the primary goal of improving C partitioning model routines to evaluate if additional modeling or experimental studies are warranted.

#### Task 4a. Deliverable status

Date	Deliverable	Status
Oct 2017	Submission of final PiTS dogwood <sup>13</sup> CO <sub>2</sub> labeling and shading data manuscript. Submit data to TES SFA data archive.	In progress, but pushed back
Jan 2018	Submission of final PiTS dogwood <sup>13</sup> CO <sub>2</sub> labeling and shading modeling manuscript	In progress, but pushed back

#### Publication

Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016) Evaluating the Community Land Model in a pine stand with shading manipulations and <sup>13</sup>CO<sub>2</sub> labeling, *Biogeosciences* 13:641-657, doi:10.5194/bg-13-641-2016

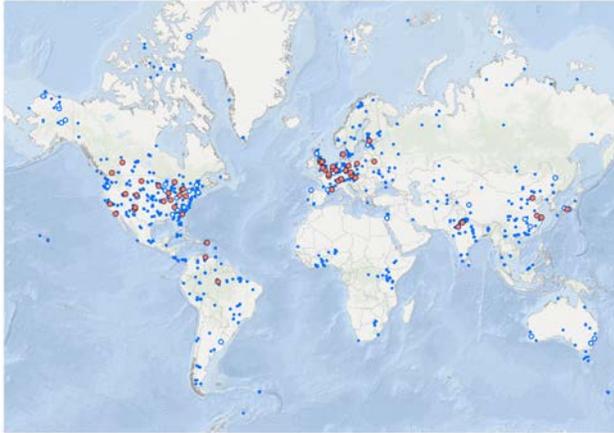
#### Task 4b: Leveraging root traits to inform terrestrial biosphere models

Task 4c is broadly focused on understanding the variation in root traits and function across the globe, which is the scale at which land surface models like ALM operate. In a Viewpoint in *New Phytologist* (Iversen *et al.*, 2017), we note that variation and tradeoffs within and among plant traits are increasingly being harnessed by empiricists and modelers to predict ecosystem processes in response to current and future environmental conditions. While fine roots play an important role in ecosystem processes, most fine-root traits are extremely underrepresented in global trait databases. The lack of available and centralized data has hindered efforts to analyze fine-root trait variation at a global scale, and limited meaningful linkages among above- and belowground traits. Together, these limitations have contributed to the coarse representation of fine-root processes and associated parameters in terrestrial biosphere models.

**FRED 1.0** - To address the need for a centralized fine-root trait database, we compiled the Fine-Root Ecology Database (*FRED*) from published literature and datasets as well as unpublished sources; data collection is ongoing and will continue for the foreseeable future (Iversen *et al.*, 2017). *FRED* 1.0 contains ~50,000 species-specific trait observations from 1213 species, and ~20,000 trait observations collected from mixed plant communities, compiled from nearly 800 data sources. In total, these observations encompass more than 300 root traits.

**The FRED website** - *FRED* 1.0 is now available to the broader public via the *FRED* website (<https://roots.ornl.gov>), developed in collaboration with the Data Theme in the Climate Change Science

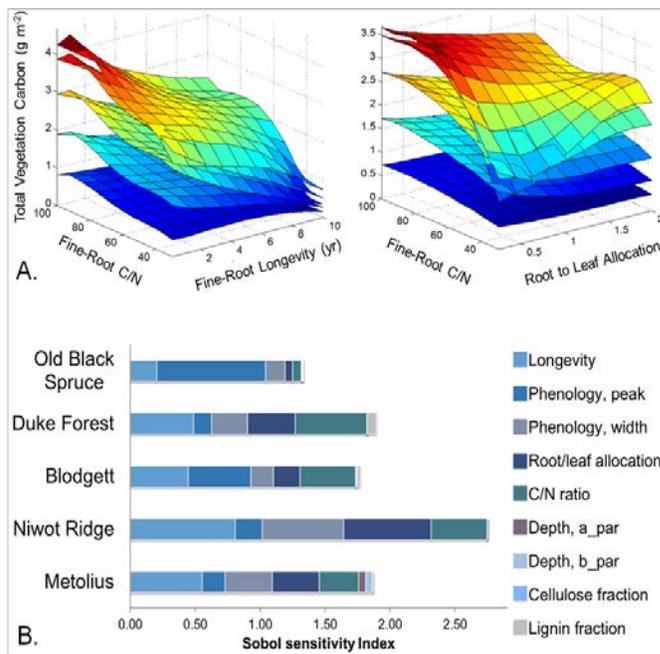
Institute at ORNL. When you request to download data from *FRED*, you are asked to confirm that you have read and agree to the Data Use Guidelines (<https://roots.ornl.gov/guidelines>), provide your name, a valid email address, and basic location information, and describe the way in which you plan to use the data in *FRED*. These metrics are used in aggregate to track the number of data products downloaded, what types of users are downloading data, and their general locations, but individual users are not identified in these summary statistics (see the *FRED* Privacy Policy, <https://roots.ornl.gov/privacy-policy>). Since its release on February 28, 2017, *FRED* 1.0 has been downloaded 102 times (as of June 20, 2017), by users in 22 countries across 5 continents (Fig. 20).



**Fig. 20. Observation and download locations for *FRED* 1.0. Closed blue dots are the locations of studies reporting root trait data for plants growing outdoors, not in pots (979 locations) and open circles are from plants grown in more artificial conditions (54 locations). Meta-data on fine-root characteristics, species taxonomy, treatments, and growing conditions are linked with each data point, as well as notes and ancillary data on site, vegetation, edaphic, and climatic conditions. Closed red dots indicate distinct locations where *FRED* 1.0 was downloaded from March 1 to April 10, 2017.**

**Improving our understanding of above- and belowground plant traits --** The widely-used global plant trait “TRY” database ([www.try-db.org](http://www.try-db.org)) reports that < 1% of the data deposited describes fine-root functional traits. To facilitate better quantification of relationships or tradeoffs between and among above- and belowground traits as suggested in a recent DOE-sponsored workshop (Koven *et al.*, 2016, *Workshop Report*; Kueppers *et al.*, 2016, *Eos*), the *FRED* database will be submitted annually to TRY under the ‘public (open access)’ data status. *FRED* 0.0 has been submitted to TRY, and will become available with the release of TRY 4.0. *FRED* 0.0 is among the major contributions of trait data to TRY, adding about 250 new root traits to TRY and roughly doubling the number of root records compared to TRY Version 3.0.

**Sensitivity analyses -** ALM 0.0 includes a number of root parameters that will benefit from being informed with empirical data from *FRED* 1.0. In collaboration with Task 3 (D. Ricciuto and D. Lu), we are using sensitivity analyses to inform which observations and experiments are necessary to improve our understanding of roots and root processes (Fig. 21). Our initial focus is on: (1) fine-root longevity, a fixed, PFT-specific parameter that is directly related to leaf longevity in ALM, (2) fine-root phenology, which is currently parameterized as a one-to-one relationship with leaf phenology, and (3) fine-root C/N ratios (currently equal to 42 for all plant functional types). Preliminary results indicate that fine-root C/N ratio, allocation ratio between fine roots and leaves, timing of peak production and width, and fine-root longevity are important controls over site-level gross primary production, while rooting depth distribution and root cellulose and lignin fractions are less important, at least in the current configuration of ALM 0.0.



**Fig. 21. Sensitivity of total vegetation C in ALM 0.0 from variation in *FRED*-informed fine-root parameters in evergreen conifer sites. (A) Changes due to variation in 2 parameters at Duke Forest in years 10, 20, 50, 100, and 200, respectively from bottom to top. (B) Relative sensitivity due to each fine-root parameter at year 100 across 5 evergreen conifer sites in North America.**

#### Task 4b. Deliverable status

Date	Deliverable	Status
Dec 2016	Fine-root ecology database ( <i>FRED</i> ) – Accessible through TES SFA and TRY.	<i>Completed</i> (Released in February 2017) ( <a href="http://roots.ornl.gov">http://roots.ornl.gov</a> )
August 2017	Synthesize and highlight global patterns and trends in root traits, and root trait variation within and among model-defined plant functional types.	<i>Paper Completed</i>
April 2018	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 ( <i>SPRUCE</i> , <i>NGEES</i> , <i>PiTS</i> , <i>FACE</i> , <i>AmeriFlux</i> )	<i>Planned</i> (Virtual meeting held by <i>ORNL</i> in June 2017)
Sep 2017	Sensitivity analyses linking PFT root parameterizations with ecosystem function using <i>FRED</i> and <i>ALM</i> .	<i>Underway</i>
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 <i>FRED</i> and <i>ALM</i> will be conducted based on new model structure.	<i>Planned</i>

#### Publications/Manuscripts

- Freschet GT, Valverde-Barrantes OJ, Tucker CM, Craine JM, McCormack ML, Violle C, Fort F, Blackwood CB, Urban-Mead KRU, Iversen CM, Bonis A, Comas LH, Cornelissen JHC, Dong M, Guo D, Hobbie SE, Holdaway RJ, Kembel SW, Makita N, Onipchenko VG, Picon-Cochard C, Reich PB, De la Riva EG, Smith SW, Soudzilovskaia NA, Tjoelker M, Wardle DA, Roumet C (2017) Climate, soil and plant functional types as drivers of global fine-root trait variation. *Journal of Ecology*, DOI: 10.1111/1365-2745.12769.
- Iversen CM, McCormack ML, Powell AS, Blackwood CB, Freschet GT, Kattge J, Roumet C, Stover DB, Soudzilovskaia NA, Valverde-Barrantes OJ, van Bodegom PM, Violle C (2017a) Viewpoints: A global Fine-Root Ecology Database to address belowground challenges in plant ecology. *New Phytologist* 215: 15-26.
- Koven C, Kueppers L, Iversen CM, Reich P, Thornton PE. 2016. Expanding the use of plant trait observations and ecological theory in Earth system models: DOE Workshop Report. **A summary**

**report from the Terrestrial Ecosystem Science (TES) and Earth System Modeling (ESM) Workshop on Trait Methods for Representing Ecosystem Change;** Rockville, MD, 18-19

November 2015. Report Date: May 31, 2016. Access on-line at:

[http://science.energy.gov/~media/ber/pdf/workshop%20reports/Trait\\_workshop\\_report\\_05\\_31\\_2016.pdf](http://science.energy.gov/~media/ber/pdf/workshop%20reports/Trait_workshop_report_05_31_2016.pdf)

- Kueppers LM, Iversen CM, Koven CD (2016) Expanding the use of plant trait observations in Earth system models. *Eos* 97, DOI:10.1029/2016EO049947.
- McCormack ML, Guo D, Iversen CM, Chen W, Eissenstat DM, Fernandez CW, Li L, Ma C, Ma Z, Poorter H, Reich PB, Zadworny M, Zanne A (2017) Viewpoints: Building a better foundation: Improving root-trait measurements to understand and model plant and ecosystem processes. *New Phytologist* 215: 27-37.
- McCormack ML, Iversen CM, Eissenstat DM (2016) Moving forward with fine-root definitions and research. *New Phytologist* 212: 313.
- Norby RJ, Iversen CM (2017) Introduction to a Virtual Special Issue on root traits. *New Phytologist* 215: 5-8.
- Xu Y, Wang D, Iversen CM, Walker A, Warren J (2017) Building a virtual ecosystem dynamic model for root research. *Environmental Modelling & Software* 89: 97-105.

*Data Sets*

A root traits database has been initiated (Iversen et al. 2017; Appendix B).

**Task 4c. Linking Root Traits to Function**

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. The scope of this task has depended on results from current FY17 modeling and uncertainly analyses led by D. Ricciuto and D. Lu (manuscript in prep). Based on these analyses, the *FRED* database, and discussions with other SFA and BER-TES scientists and modelers, we have identified dynamics of water uptake to be a key root process to assess mechanistically, and in a modeling environment. Water uptake dynamics are a key driver of ecosystem function that links the roots to the shoots, and rooting depth and distributions are key traits linked to this process.

Our initial focus has been to link these root traits to their functional water uptake. While we are exploring representation of depth-dependent bulk water dynamics and hydraulic redistribution in the models using published data (e.g., the ORNL FACE data), we are also looking at linking specific root ages, sizes and order to root uptake in situ. This is first principle mechanistic work that can provide function to form. Along these lines, we are working on different woody and grass seedlings at the HFIR neutron facility to assess root water uptake under drying and wetting conditions. We found that newer, younger roots have greater uptake capacity per unit surface area, but that total water uptake depended on the larger roots, with lower uptake rates (Fig. 22). This work has engaged ORNL reactive-transport modeler Scott Painter to develop an explicit model focused on root water extraction and we discovered that the roots themselves cause substantial changes in soil hydraulic properties, such that the commonly used soil hydraulic properties used by models are not correct.

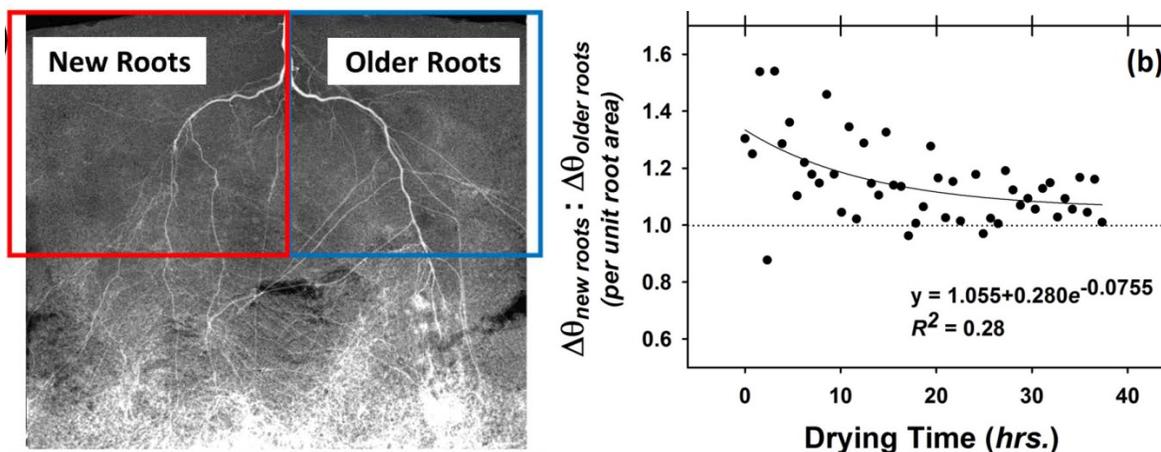


Fig. 22. (a) Neutron image of a poplar root system after recovery from extreme drought, indicating older larger roots, and newer smaller roots. (b) Ratio of water uptake by the young:old root systems during a drying cycle, indicating relative rates of water uptake approach 1:1 as the soil dries.

#### Task 4c. Deliverable status

Date	Deliverable	Status
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	In progress
Dec 2016	Leverage existing data sets (e.g., FACE water content, water use, root distribution) and apply root uptake models for uncertainty and sensitivity analyses	Completed
May 2017	Submission of manuscript focused on root age and size versus water uptake following drought	Completed
Sep 2017	Submit HFIR beamline proposal for advanced root nutrient or water uptake measurements to assess root function under dynamic conditions	Planned
Dec 2017	Data analysis and submission of manuscript focused on linking root morphology and age to water uptake across multiple species	In progress
Dec 2017	Begin deployment of Rhizosphere Ecology Laboratory for integrative assessment of belowground dynamics	In progress

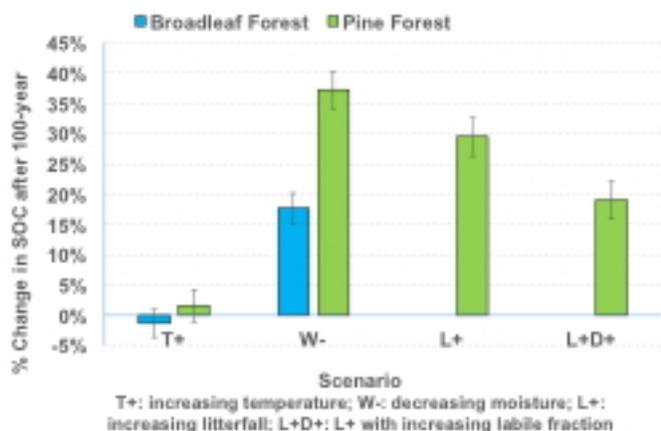
#### Publication

Dhiman, I, HZ Bilheux, KF DeCarlo, SL Painter, LJ Santodonato, JM Warren. Quantifying root water extraction after drought recovery using sub-mm in situ empirical data. *Plant and Soil* (under review).  
 Johnson, DM, R Wortemann, KA McCulloh, L Jordan-Meille, E Ward, JM Warren, S Palmroth, JC Domec. 2016. A test of the hydraulic vulnerability segmentation hypothesis in angiosperm and conifer tree species, *Tree Physiology* doi: 10.1093/treephys/tpw031.

#### Task 5: Microbial Processing of Soil C

This year we focused on the role of soil moisture on facilitating microbial decomposition of soil organic carbon (SOC). First, we improved the Microbial ENzyme Decomposition (MEND) model by representing dormancy, resuscitation and mortality of the soil microbial community in response to changes in soil moisture. We successfully parameterized MEND against heterotrophic respiration and microbial biomass carbon from three years of field experiments in two subtropical forests. The calibrated model projects significant increases in SOC in response to decreasing soil moisture and increasing litterfall over the next 100 years, and only minor changes in SOC in response to increasing soil temperature (Fig. 23). Our results imply that the future trajectory of SOC may be more responsive to

changes in soil moisture than to temperature, particularly in tropical and subtropical environments (Wang et al, submitted).



**Fig. 23. Percent (%) change in soil organic carbon (SOC) after 100 years, under 4 different scenarios.**

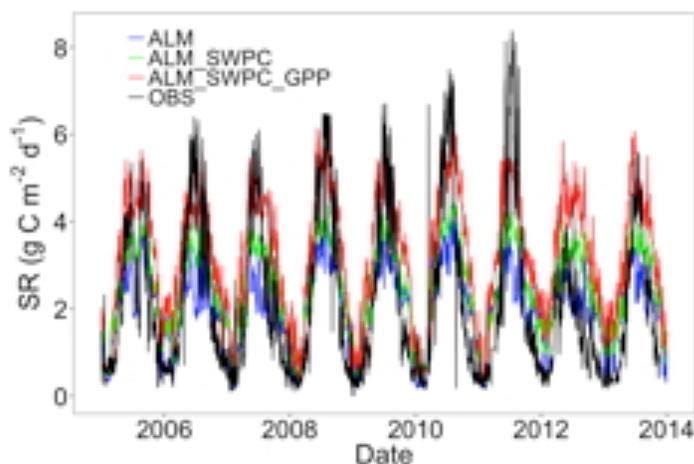
We also developed carbon and nitrogen coupling in MEND that allows for flexible C:N ratios in soil organic matter and microbes. The C-N coupled MEND is under testing against the above subtropical sites with additional field data including N deposition, microbial C:N ratios, nitrate, and ammonium concentrations.

We completed an intense series of laboratory incubation experiments involving respiration and soil microbial biomass with  $^{13}\text{C}$  labeled substrates to examine how edaphic properties, and plant and microbial communities influence C cycling and the long-term fate of C in soil systems, and we prepared the data for public posting (Kluber et al. 2017). Paired forest and grassland soils from four locations were incubated with  $^{13}\text{C}$  labeled glucose in the short-term (144 hours) study while  $^{13}\text{C}$  labeled cellulose was added in the long-term (729 days) study. Soil respiration, microbial biomass, and soil  $^{13}\text{C}$  values were monitored throughout the study.

We are using MEND to model the Kluber et al. (2017) dataset through a subcontract to Jianwei Li of Tennessee State University (TSU) for a PhD student (Siyang Jian). So far, preliminary model calibration and simulations are obtained for one site and ongoing for multiple sites and treatments. For the coming year, TSU will complete the model parameterization and tuning in order to employ the calibrated model, and thereby improve short-term and long-term projections of soil carbon and microbial responses to climate change. TSU also performed a 6-month long laboratory incubation investigating temperature and nitrogen effects on  $\text{CO}_2$  releases, and drafted a manuscript for *Biogeosciences* to be submitted in summer of 2017. In addition, through the DOE Visiting Faculty Program (to ORNL) in 2015 and 2016, Dr. Li developed a data assimilation method to use MEND to model the Harvard Forest warming experiment, focusing on carbon use efficiency and microbial turnover. The manuscript will soon be submitted to *Nature Climate Change* for review.

Soil moisture exerts an important influence on carbon cycling at the AmeriFlux site in Missouri (MOFLUX), which is consistent with the findings of Wang et al. (submitted). Using the ACME Land Model (ALM) and in collaboration with Dan Ricciuto, Lianhong Gu, Avni Malhotra, Colleen Iversen, Jeff Warren, and Jeff Wood at the University of Missouri (MU), new postdoc Junyi Liang is attempting to diagnose the performance of soil C dynamics in ALM, by focusing on key aspects that determine soil respiration, including soil temperature, soil moisture, SOC, leaf area index (LAI), and gross primary production (GPP). Preliminary results show that ALM significantly underestimated soil respiration (i.e., blue line in Fig. 24), which was related to underestimations of both soil water content and GPP (derived by the NEE partitioning method). First, we improved the simulation of soil water content by using new measurements of soil texture from the University of Tennessee (UT). The simulation of soil respiration was slightly improved but still underestimated (i.e., green line in Fig. 24). Then, we improved the simulation of GPP by tuning parameters in ALM's photosynthetic module. Applying these two steps significantly improved the simulation of soil respiration (red line in Fig. 24). The preliminary results indicate that better simulations of soil moisture and GPP are necessary to derive more realistic  $\text{CO}_2$  fluxes

from soils, but there are at least three potential aspects that need further efforts. First, the ALM still underestimates soil water potential, which is the direct scalar that determines the water availability for plant growth and microbial respiration. Second, the ponding effect on water infiltration (field observations by Lianhong Gu) is not represented in the ALM. Third, while the two steps improved GPP simulation, ALM significantly overestimates LAI, suggesting that there may be uncertainty in the derived GPP and we may need to calibrate ALM against observed leaf carbon or litterfall instead of derived GPP. We will focus on these aspects in the future.



**Fig. 24. Comparison of ALM simulated and observed soil respiration (SR) from soil chambers at MOFLUX. The ALM default run significantly underestimated SR, which was improved by improving the simulations of soil moisture and GPP. Data courtesy Lianhong Gu.**

The strong seasonal signal of precipitation and the importance of periodic droughts make MOFLUX appropriate for testing moisture sensitivity in MEND and ALM. To enable the connection between MEND and ALM, we need to separate heterotrophic and autotrophic respiration. Therefore, we began a model-inspired experiment (MODEX) study at MOFLUX to determine the respective contributions through redundant methods of trenching and isotopic separation. In February, Jana Phillips and Melanie Mayes joined Shikha Singh of UT, and Jeff Wood of MU to dig 1 m x 1 m x 0.6 m depth trenches around 4 autochambers at the MOFLUX site, and wrapped the remaining pedons in landscape cloth to prevent root ingrowth (also see MOFLUX Task for details). Samples from each trench were collected ( $n = 4$ ) and sent to TSU for measurements of soil and root respiration. The respiration of  $\delta^{13}\text{C}$  of the soils was -19 per mil and respiration rate was  $1.5 \mu\text{g CO}_2/\text{g/h}$ , while root respiration was -27 per mil and the rate was  $19 \mu\text{g CO}_2/\text{g/h}$ , which suggests that root and soil respiration can be isotopically separated. Samples ( $n = 4$ ) were collected from 0-5, 5-20, and 20-55 cm depths and analyzed for gravimetric moisture content, bulk density, moisture retention, pH, microbial biomass carbon and nitrogen, dissolved organic carbon, total organic carbon, total nitrogen and soil texture at UT through a subcontract to Dr. Sindhu Jagadamma. PhD student Shikha Singh is beginning a laboratory incubation experiment to understand the moisture sensitivity on carbon cycling and microbial community using MOFLUX soils and other soils with contrasting textures.

In the coming year, we will work on simulating below-ground processes at MOFLUX. We will initiate monthly field-scale measurements of  $\delta^{13}\text{CO}_2$  from the four trenched plots at MOFLUX and from four paired untrenched plots (with Jeff Wood). Additionally, measurements (about 5/y) will be taken from cores of soil and root samples to understand the seasonally varying  $\delta^{13}\text{C}$  signature of soil and root respiration (with TSU), as well as of the bulk soil and roots themselves (through collaboration with Avni Malhotra and Colleen Iversen). This work will facilitate using MEND to model heterotrophic respiration and will improve its sensitivity to soil moisture, as will the incubations at UT focusing on soil moisture effects on  $\text{CO}_2$  emissions. We will use both MEND and ALM to model soil chamber data at MOFLUX and thereby improve response to soil moisture in both models, as well as to improve connections between ALM and MEND (which has, until now, only been able to model heterotrophic respiration). Finally, one of the Kluber et al. (2017) sites is also MOFLUX, so the modeling of her dataset at TSU will also strengthen our understanding of C cycling at MOFLUX. Further, the Kluber et al. (2017) dataset was designed to use short-term incubations to determine microbial parameters of the MEND model, and then those parameters can be applied to the long-term incubations. Using the dataset will further strength MEND's capabilities to model below ground soil carbon cycling.

### Task 5. Deliverable Status

Date	Deliverable	Status
05/17	Complete temperate grassland v forest, short-term, long-term isotope study (revised, delayed again)	In progress
03/17	Incorporate soil moisture effects into MEND model (note, this is complete) and test against field scale experimental data (revised, moved up)	Complete
12/17	Model temperate grassland v forest short-term, long-term isotope study (added)	12/17
5/18	Complete the proposed moisture sensitivity experiments and model test against experimental data	5/18
9/18	Incorporate flexible C:N ratio into MEND (completed)	9/18

Future endeavors that might be proposed for the next TES SFA cycle could involve building a coupled soil-root respiration module. The current activities at MOFLUX, which will certainly not reach completion in a year, could be better connected with the mini-rhizotrons installed at the MOFLUX site, for example. Alternatively, or in the outyears, we could move to the SPRUCE site to improve capacity for coupled root-soil respiration.

#### *Publications/Manuscripts*

- Abramoff R, Xu X, Hartman M, O'Brien S, Feng W, Davidson E, Finzi A, Moorhead D, Schimel J, Torn M, Mayes M (2017) The Millennial Model: in search of measurable pools and exchanges in soil carbon cycling for the new century. *The Journal of Advances in Modeling Earth Systems* (in review).
- Jian S, Li J, Chen J, Wang G, Mayes MA, Dzantor KE, Hui D, Luo Y (2016) Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. *Soil Biology and Biochemistry* 101: 32-43. DOI:10.1016/j.soilbio.2016.07.003
- Li J, Wang G, Mayes MA, Allison SD, Frey SD, Shi Z, Hu XM, Luo Y, Mellilo JM (2017) Reduced carbon use efficiency and increased microbial turnover with soil warming. *Nature Climate Change* (submitted).
- Mayes MA, Lajtha K, Bailey V (2016) Advancing Soil Carbon Cycle Science: Workshop to celebrate 2015–2024 International Decade of Soil; Boulder, Colorado, 14–16 March 2016. *EOS Meeting report* <https://eos.org/meeting-reports/advancing-soil-carbon-cycle-science>
- Wang G, Huang W, Mayes MA et al. (2017) Soil moisture drives microbial controls on carbon decomposition in subtropical forests. *Nature Geoscience* (in review).

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

*Root dynamics and relations to soil CO<sub>2</sub> efflux* – Task goals are as follows:

- 1) Characterize the spatial and temporal variability in soil respiration at the MOFLUX site.
- 2) Characterize the spatial and temporal variability in root traits (length, diameter, biomass, specific root length, root tissue density, branching patterns, carbon and nitrogen concentrations, etc.) and root production.
- 3) Characterize moisture sensitivity of soil respiration and root dynamics, both within seasons and during intermittent wetting events during the dry season.
- 4) Investigate how soil respiration variability over space and time relates to root growth and phenology.

Soil respiration variability is being investigated using data measured at 16 auto-chambers from 2004 to present. Analyses include soil temperature and moisture data to evaluate seasonality and spatial variability in temperature and moisture sensitivity of soil respiration. Root phenology and growth are being measured using minirhizotron tubes installed at 10 of the 16 soil chambers.

In September 2016, ORNL staff (C. Iversen, J. Childs, A. Malhotra) travelled to MOFLUX for field activities in support of the root dynamics subtask. Tree vouchers were collected from multiple individuals of the major tree species in the MOFLUX forest (*Quercus alba*, *Q. velutina*, *Carya ovata*, *Acer saccharum*, *Juniperus virginiana*, *Fraxinus americana*). Analyses are underway to investigate the link between root dynamics and ecosystem respiration. These vouchers will also be used to convert linear root growth from

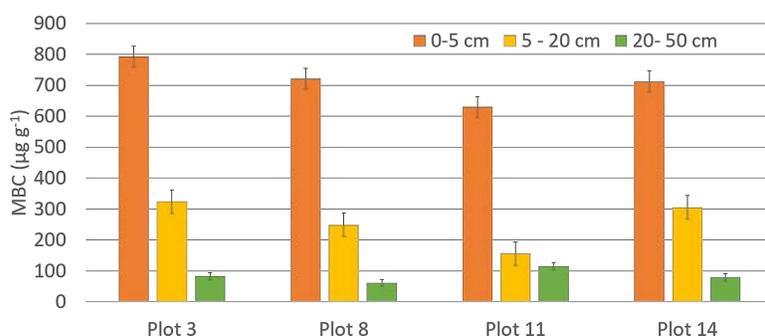
minirhizotrons into biomass and production estimates. To further characterize spatial variability in root biomass and traits, we collected 16 soil cores near 4 of the chamber sites. Roots within these cores will be analyzed for all traits mentioned in goal 2 above and will be used to estimate fine-root biomass per unit area. This biomass estimate will also be used to upscale results from a study partitioning heterotrophic and autotrophic respiration led by Melanie Mayes (Task 5).

Lastly, to get at the key goal of linking soil respiration and root dynamics, and assess the moisture sensitivity of soil respiration and root growth, we will develop statistical models of soil respiration as a function of temperature and moisture, and test the relationship between soil respiration and root growth over space and time. We will also test hypotheses focused on intermittent wetting events during the dry season. Specifically, we hypothesize that the increased soil respiration during these wetting periods as observed in our study (data not shown) are unrelated to root growth but related to microbial activity.

***Partitioning soil respiration into heterotrophic and autotrophic component*** - In coordination with TES-SFA Task 5, new effort was directed towards partitioning soil heterotrophic and autotrophic respiration. In February 2017, ORNL staff (M. Mayes, J. Phillips) and a collaborating UT student (S. Singh) visited MOFLUX to trench around long-term soil chambers. Four chambers, not paired with minirhizotrons, were used for this effort. A  $\sim 1 \times 1$  m trench was excavated to the bottom of the root zone and landscape geotextile was installed to prevent ingrowth of new roots into the isolated soil column (Fig. 25), and the trenches backfilled. At the time of trenching, detailed soil sampling was conducted to characterize profiles of soil biological (microbial biomass, e.g., Fig. 26), chemical (pH, N, C) and physical properties (soil water retention).



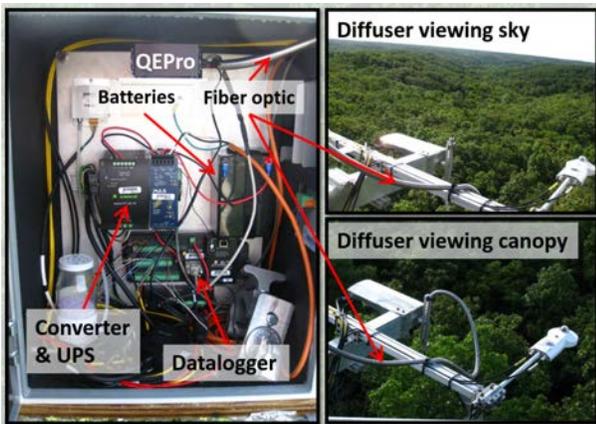
**Fig. 25. Trenching around soil chambers at MOFLUX, showing the excavation of a trench (left) and installation (right).**



**Fig. 26. Profiles of microbial biomass carbon (MBC) for each of the chambers that were trenched in winter 2017. Each bar represents the mean ( $N = 3$ ) and error bars denote 1 SE.**

***Solar-induced fluorescence observations***- The Fluorescence Automated Measurement Equipment (FAME) was developed specifically for observing SIF from fixed towers (Fig. 27). The FAME system is based around a spectrometer (model QEPro, Ocean Optics Inc., Dunedin FL) that is controlled by a datalogger (model CR1000, Campbell Scientific Inc., Logan UT). An all-wave net radiometer (model CNR4, Kipp and Zonen Inc., Bohemia NY), and PAR sensors (model PSQ1, Kipp and Zonen Inc.) are used to measure broad band radiation components at the same instant that spectral measurements are made. The broad band radiation, as well as atmospheric pressure and air temperature and humidity are measured at the same instant as spectral observations to aid with the interpretation of spectral information.

The FAME system prototype was deployed on the MOFLUX tower in September 2016 (J.S. Riggs, M, Bowling, L. Gu, and J.D. Wood). The system was operated through the end of the growing season, at which point it was winterized to avoid possible damage due to freezing rain. The system was redeployed in the spring of 2017. Since the initial deployment, troubleshooting activities have been completed in order to optimize data acquisition and facilitate easier field operation (e.g., calibration). Through this iterative process, the onboard program for data acquisition and control has gone through numerous iterations and improvements. A single datalogger can now control two spectrometers, which permits the simultaneous retrieval of SIF in the red and far-red regions. SIF retrieval algorithms are under development to decouple reflectance and SIF using spectral fitting methods and the measured radiances. The research and development activities regarding SIF measurements at MOFLUX will facilitate new observations at SPRUCE and as part of LDRD research. A description of the FAME system and preliminary results were presented at the 2016 AmeriFlux PI meeting and the 2017 joint NACP/AmeriFlux PI meeting. Furthermore, a manuscript is currently in preparation for a submission to the AmeriFlux 20<sup>th</sup> Anniversary special issue in Agricultural and Forest Meteorology (submission, June 2017).



**Fig. 27. Photographs of the Fluorescence Automated Measurement Equipment (FAME) system deployed at MOFLUX. The left panel shows the interior of the thermostatically controlled enclosure that houses the spectrometer (QEPro) datalogger (CR1000), and power supplies. The right-most panel shows the fiber optic to which a cosine diffuser (180° FOV) is affixed viewing the sky (upper) and canopy (lower). A smart motor is used to alternate the position of the diffuser. The net all wave radiometer (CNR4) is also visible at the right of both panels at right.**

Spectral fitting methods were used to decouple the fluorescence ( $F$ ) and reflectance ( $\rho$ ) contributions to the upwelling radiance ( $L$ ). Assuming that both  $F$  and  $\rho$  vary linearly as a function of wavelength over the fitting window around the O<sub>2</sub>A band gives the following bilinear model (Eq. 1a):

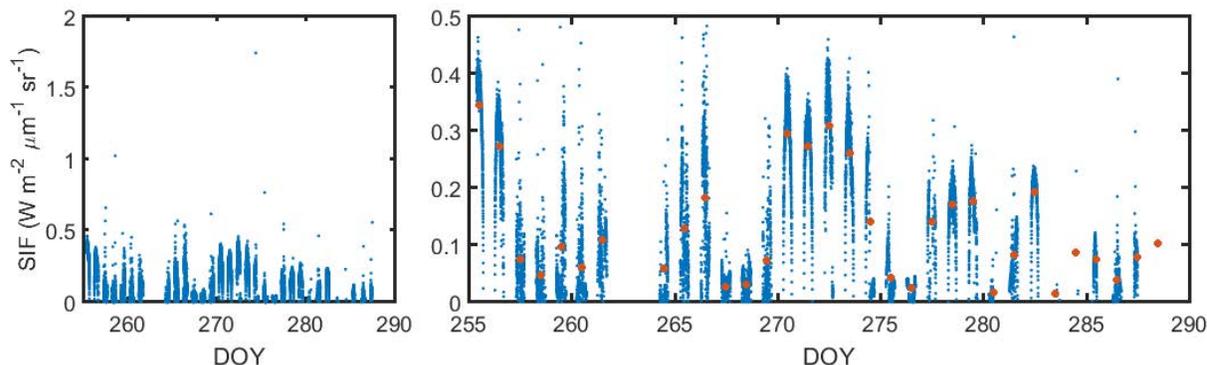
$$L(\lambda_0 + \Delta\lambda) = F_0 + \Delta\lambda \frac{dF}{d\lambda} + E \left( \rho_0 + \Delta\lambda \frac{d\rho}{d\lambda} \right) \quad [1a]$$

$$= b_1 + \Delta\lambda b_2 + E(b_3 + \Delta\lambda b_4) \quad [1b]$$

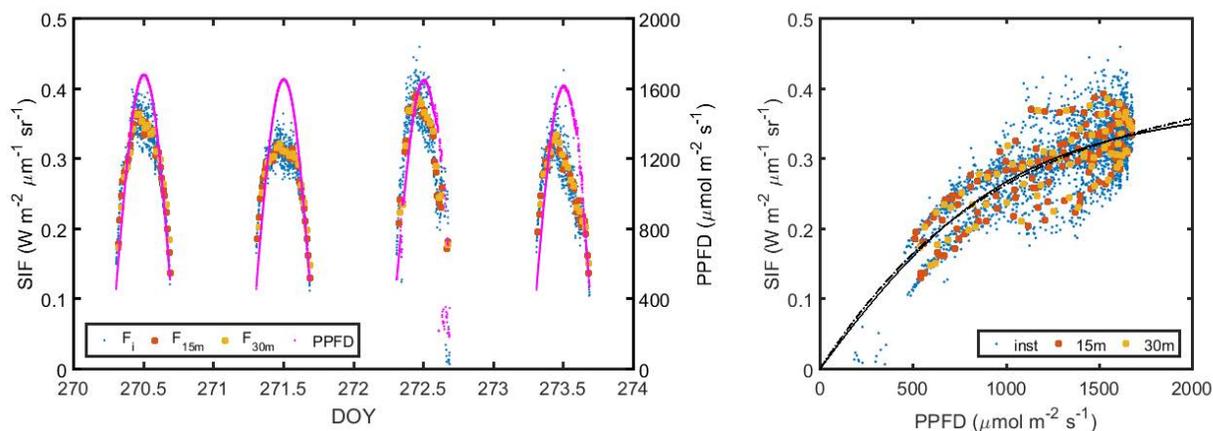
where  $\lambda_0$  is the wavelength at the lower end of the fitting window,  $\Delta\lambda$  is the width of the fitting window,  $F_0$  is fluorescence at  $\lambda_0$ ,  $\rho_0$  is reflectance at  $\lambda_0$ ,  $E$  is the down welling radiance, and  $dF/d\lambda$  and  $d\rho/d\lambda$  are the rate of changes of  $F$  and  $\rho$  with respect to wavelength, respectively. Rewriting Eq. 1a and substituting  $b_i$  for the relevant model terms gives Eq. 1b, which was solved using nonlinear least squares fitting procedures. The fitting window included wavelengths ranging from 758.5 to 764 nm, and included the leftmost shoulder of the O<sub>2</sub>A band well, the entire well, and some of the higher frequency features.

Example time series of SIF (at 760.5 nm) from autumn 2016 are provided in Fig. 28. The light environment varied markedly over the time period represented in Fig. 28, with days characterized by clear-sky, variable cloudiness, and consistent thick clouds. There were clear skies on DOY 270–274, and these data are highlighted in Fig. 29, which shows the time series of SIF and PPFD, as well as ecosystem SIF light response curves with various levels of temporal aggregation. There was excellent agreement among SIF at different levels of temporal aggregation (Fig. 29). In the panel showing the ecosystem light response, the small cluster of instantaneous observations at PPFD < 500  $\mu\text{mol m}^{-2} \text{s}^{-1}$  occurred during conditions of short term variable cloudiness at the end of the day. Interestingly, hysteresis in the SIF signal was evident in the time series and the light response curves (Fig. 29). In general, the observations above and below the light response model fits (Fig. 29 right panel) tended to occur in the morning and

afternoon, respectively. *A more thorough analysis of the SIF light response for other light environments and relationships between SIF and gross primary production (GPP) from eddy covariance is under way.*



**Fig. 28.** Time series of SIF retrieved in the O<sub>2</sub>A band in 2016. The data are the same in both panels except that for the right, the y-scale has been compressed. Blue dots are individual retrievals and the red dots in the right panel are daily means.



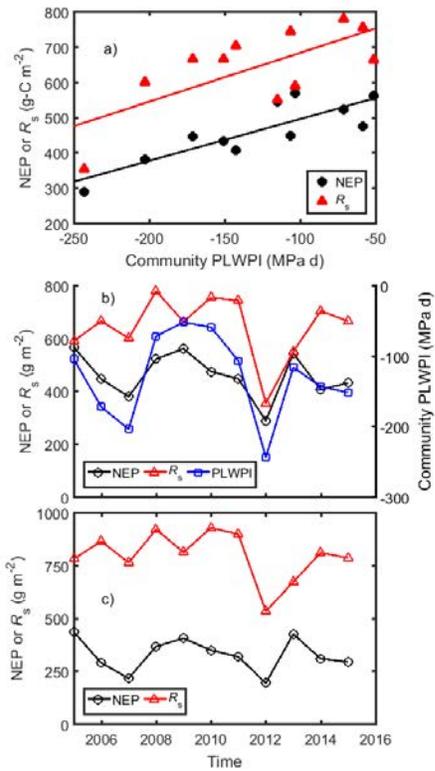
**Fig. 29.** Time series of instantaneous ( $F_i$ ), 15 minute mean ( $F_{15m}$ ) and 30 minute mean ( $F_{30m}$ ) SIF, and instantaneous PPF (left panel); and ecosystem SIF light response curves for instantaneous (inst), 15 minute means (15m) and 30 minute means (30m) (right panel). In the right panel, there are 3 model fits shown by solid, dashed and dotted black lines, each representing a different temporal resolution.

In 2017, Leaf-level observations of photosynthesis parameters will be collected and used to parameterize a simple model that describes the fraction of PSII reaction centers that are open. The ultimate goal is to relate fluorescence directly to electron transport through PSII.

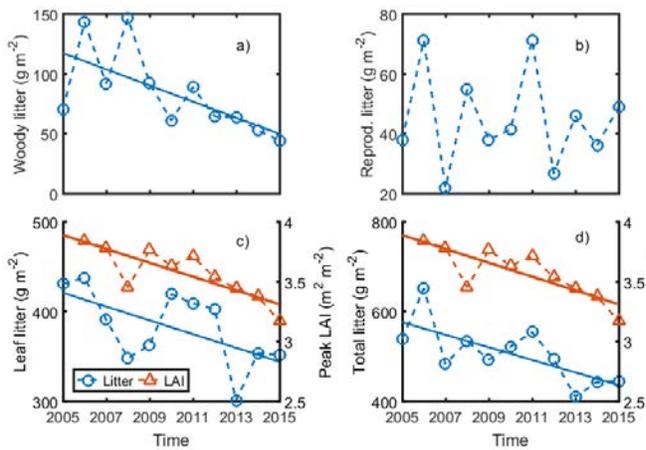
*MOFLUX Data curation and Synthesis* - Historical MOFLUX data products that have been curated, archived and posted have been limited to (i) the standard AmeriFlux product (<https://ameriflux.lbl.gov/>) and (ii) predawn leaf water potential (<http://tes-sfa.ornl.gov/>). Efforts are underway to curate additional historical data products for archival and posting including litter (leaf, woody and reproductive; 2005–2015) and coarse woody debris (2005–2015). The data have been formatted and user guides drafted.

Over the 2005–2015 time period, growing season net ecosystem productivity (NEP) and ( $R_s$ ) were largely controlled by plant water stress, as evidenced by significant linear relationships with community predawn leaf water potential integrals (PLWPI; Fig. 30a). Water stress (i.e., PLWPI) was largely governed by precipitation patterns. The tight coupling of C fluxes with water stress and the combination of high inter-annual precipitation variability gave rise to significant variations in C fluxes over time for both growing season (Fig. 30b) and annual periods (Fig. 30c). Variability was such that significant temporal trends could not be detected for either NEP or  $R_s$ . It is, however, noteworthy that over the same time period there have been significant declines in litter production and leaf area index (LAI) (Fig. 31).

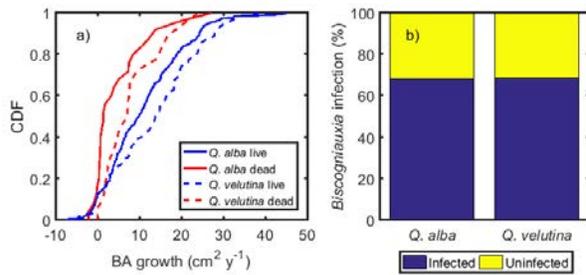
Both woody and leaf litter components declined over the period of record (Fig. 31 a&c). Reduced peak LAI and litter production supports other observations of high levels of *Hypoxylon* fungi on many of the white and black oak individuals that died in 2013. *Hypoxylon*, a weak pathogen that is only pathogenic when trees are stressed, can cause slow canopy decline. It may be that over the last decade that *Hypoxylon* was slowly affecting weaker trees and that the exceptional drought of 2012 triggered an infection sufficient to induce elevated oak mortality in 2013 (Fig. 32; Gu et al. 2015). *Continued monitoring to track the trajectory of ecosystem function is critical to determine whether the forest is at a tipping point.*



**Fig. 30.** Growing season a) net ecosystem productivity (NEP) and soil respiration ( $R_s$ ) as a function of community predawn leaf water potential integral (PLWPI) and the significant linear fits, and time series of b) growing season NEP,  $R_s$ , and PLWPI and c) annual NEP and  $R_s$ .



**Fig. 31.** Time series of a) woody, b) reproductive, c) leaf and d) total litter production. In the c) and d) panels time series of peak growing season leaf area index (LAI) are also shown. Significant temporal trends are represented by solid lines.



**Fig. 32.** The a) empirical cumulative distribution functions (CDF) of basal area (BA) growth rates (2005–2015) of live (blue) and individuals that died in 2013 (red) after the exceptional drought of 2012, for *Q. alba* (solid lines) and *Q. velutina* (dashed lines).

**MOFLUX Synergistic Activities** - On August 21, 2017, a total solar eclipse will pass over MOFLUX. Total obscuration will last approximately 2m40s, with the partial eclipse lasting for ~1.5 h before and after totality, and is approximately centered about solar noon. There is minimal effort associated with observing the eclipse aside from adding high frequency (5 s scan rate) radiation and standard meteorology measurements. This will offer exceptional opportunities to learn about SIF due to the predictable and “controlled” variation of direct and diffuse solar radiation during the eclipse. Further, **JD Wood** is the PI of a NASA funded grant (1 year) in collaboration with other researchers from MU. MOFLUX observations will be synthesized with eddy covariance data from three other towers located in corn, soybean and prairie systems, Dual-Pol Doppler radar data, and radiosonde atmospheric profiles to examine the land-atmosphere responses to the eclipse. A major emphasis will be comparing differences in responses among ecosystems due to inherent structural and physiological differences. *Furthermore, the project will support enhanced public outreach that will help underscore the importance of general MOFLUX research to a wider audience.*

MOFLUX researchers are also involved with a USDA funded project (PI: Kim Novick, IU) that will involve a multi-site (MOFLUX, Morgan Monroe State Forest IN, Coweeta NC). The goals are to investigate the implications of different water use strategies (anisohydric/isohydric) on tree to ecosystem-scale carbon uptake and growth during drought. *This project represents the first steps towards greater collaborative efforts among AmeriFlux sites that span a hydroclimatological gradient in the Eastern US forests.*

**JD Wood** is a co-Investigator on a NASA Interdisciplinary Science research project (PI: Dylan Millet) that will focus on the methane budget of the Upper Midwest. The project will use top-down approaches that use satellite, aircraft and tall tower observations to drive atmospheric inversions to constrain the net regional flux, with ecosystem-scale micrometeorological measurements that obtain process-level information and bottom-up constraints. The overall goal is to better understand the magnitude and seasonality of the net regional flux and the contributions from important sources within the domain. *SPRUCE eddy covariance observations will play a key role in constraining methane fluxes in wetland systems.*

In collaboration with MU faculty member, B. Svoma, **JD Wood** facilitated the hosting of Bill Massman, an AmeriFlux site-PI. Bill gave an invited seminar on his work at the GLEES site in Wyoming, met with MU faculty and visited the MOFLUX site for a tour.

#### Task 6. Deliverable status

Date	Deliverable	Status
FY2016	Complete and submit the manuscript ‘The impacts of precipitation variability and drought on tree species and community mortality in a central US forest’	Published
March 2016	Submit 2015 MOFLUX data to AmeriFlux Due to PI changes at University of Missouri, this work was complete by August	Submitted
FY 2016	Once the USFS completes the installation of the planned tower at the Bog Lake Fen Site in the Marcell Experimental Forest, we will instrument the eddy flux observation system for methane, carbon dioxide, sensible heat and latent heat. “Integration of this site with SPRUCE is in progress”	EC system installed.
August 2016	Test Installation of MOFLUX Solar Induced Fluorescence Measurement System	FAME installed

December 2016	Complete and submit the manuscript ‘The impacts of precipitation variability and drought on leaf area display in a central US forest’	Published
May 2017	Submit 2016 MOFLUX data to AmeriFlux	Submitted in June
August 2017	MOFLUX SIF system operational	In progress

### *Publications/Manuscripts*

- Gu L, Pallardy SG, Yang B, Hosman KP, Mao J, Ricciuto D, Shi X, Sun Y (2016) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a central USA forest. *Journal of Geophysical Research - Biogeosciences* 121, 1884-1902.
- Gu L, Pallardy SG, Hosman KP, Y Sun (2016) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. *Agricultural and Forest Meteorology* 217: 120-136.
- Gu L, Norby RJ, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Winter K (2016) Photosynthetic parameters and nutrient content of trees at the Panama crane sites. OSTI Identifier:1255260.
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- Kravitz B, Guenther AB, Gu L et al. (2016) A new paradigm of quantifying ecosystem stress through chemical signatures. *Ecosphere* 7:DOI: 10.1002/ecs2.1559.
- Liu S, Zhuang Q, Chen M, Gu L (2016) Quantifying spatially and temporally explicit CO<sub>2</sub> fertilization effects on global terrestrial ecosystem carbon dynamics. *Ecosphere*, DOI: 10.1002/ecs2.1391.
- Liu S, Zhuang Q, Chen J, Gu L, Noormets A (2016) Evaluating atmospheric CO<sub>2</sub> effects on gross primary productivity and net ecosystem exchanges of terrestrial ecosystems in the conterminous United States using the AmeriFlux data and an artificial neural network approach. *Agricultural and Forest Meteorology* 220: 38-49.
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- Shao J et al. (2016) Direct and indirect effects of climatic variations on the interannual variability in net ecosystem exchange across terrestrial ecosystems. *Tellus B* 2016, 68, 30575, <http://dx.doi.org/10.3402/tellusb.v68.30575>.
- Sun Y, Frankenberg C, Wood JD, Schimel DS, Jung M, Guanter L, Drewry DT, Porcar-Castell A, Griffis TJ, Gu L, Magney TS, Köhler P, Evans B, Yuen K (2017) OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. *Science*. Manuscript # aam5747 ([revised manuscript submitted](#)).
- Wood JD, Griffis TJ, Baker JM, Frankenberg C, Verma M, Yuen K (2017) Multiscale analyses of solar-induced fluorescence and gross primary production. *Geophysical Research Letters* 44:533-541.
- Zhang J, Gu L (Corresponding Author), et al. (2017) The interaction between nitrogen and phosphorous is a strong predictor of intra-plant variation in nitrogen isotope composition in a desert species. *Biogeosciences*, 14, 1–14. doi:10.5194/bg-14-1-2017.

### *Data Sets*

In addition to the annual posting of MOFLUX site data to the AmeriFlux network data bases, a physiological data set was generated:

- Pallardy SG, Gu L, Hosman KP, Sun Y (2015) Predawn Leaf Water Potential of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2014. 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.004>

## Task 7: Implications of Fossil Emissions for Terrestrial Ecosystem Science

Through FY2016, Task 7 contributed to maintaining and improving a publicly available data base on carbon dioxide emissions from fossil fuel consumption, examining and confronting the uncertainty in emissions estimates, and utilizing the carbon dioxide emissions database in terrestrial carbon budgets. Beginning in FY2017, Task 7 was reformulated to focus on analysis and understanding of the implications of fossil-fuel emissions for terrestrial ecosystems and the terrestrial biosphere. The new subtasks are:

**Task 7a.** Implications of variation and uncertainty in fossil fuel emissions for terrestrial biosphere research, and in turn implications of uncertainty in terrestrial carbon fluxes on the global carbon budget.

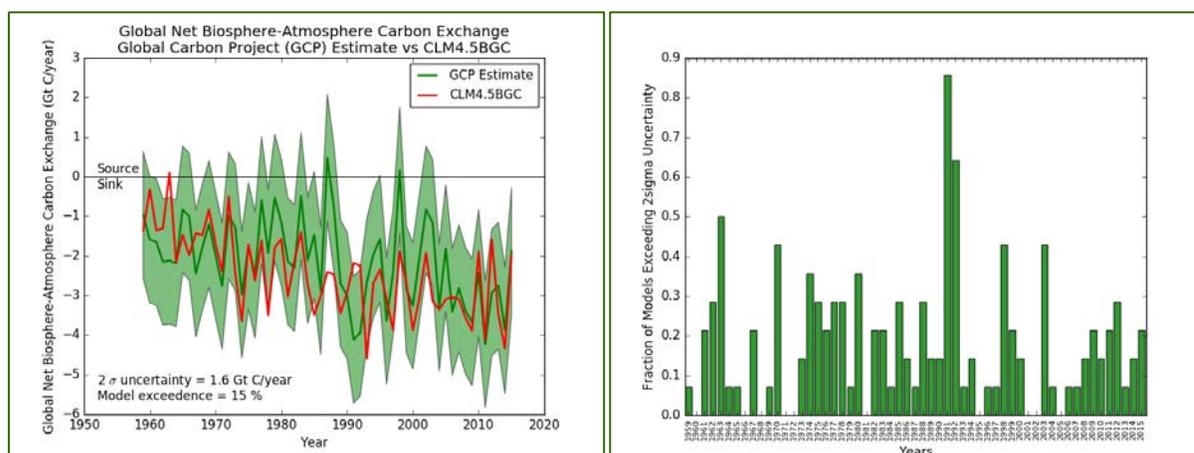
1. A synthesis of the implications of uncertainty in the global terrestrial biosphere flux estimated by closure of the global carbon budget for terrestrial biosphere research, modeling and observation.

2. Application of uncertainty methods developed within the TES-SFA to estimating uncertainty in total global and spatially distributed fossil fuel emissions. This item is something of a continuation of the current Item 3 in TES-SFA Task 7, but explores the use of tools of uncertainty analysis developed as part of the TES-SFA for terrestrial ecosystem application in estimating uncertainty in fossil fuel emissions.

**Task 7b.** Development of high precision  $^{13}\text{C}$  and  $^{14}\text{C}$  modeling in CLM-SPRUCE and ALM for application to isotopic tracer studies at the SPRUCE site and in connecting observed variations in  $^{13}\text{C}/^{14}\text{C}$  in fossil fuel emissions with observations of  $^{13}\text{C}/^{14}\text{C}$  in the terrestrial biosphere.

**Task 7c.** Exploration of terrestrial-landscape drivers of anthropogenic emissions at the scale of geographically distributed emissions.

Towards Task 7a, given observations of the increase in atmospheric  $\text{CO}_2$ , estimates of anthropogenic emissions and models of oceanic  $\text{CO}_2$  uptake, it is possible to estimate net global  $\text{CO}_2$  exchange between the atmosphere and the terrestrial biosphere as the residual of the balanced (closed) global carbon budget. These calculations show that global terrestrial ecosystems are a growing sink for atmospheric  $\text{CO}_2$  (averaging 2.12 Gt C  $\text{y}^{-1}$ ) but with considerable year-to-year variability (Fig. 33a). Within the uncertainty of the observations, emissions estimates and ocean modeling, this residual calculation is a robust, current best estimate of the global terrestrial sink for  $\text{CO}_2$ . A task of terrestrial ecosystem science is to explain the trend and variability in this estimate of the global terrestrial biosphere carbon sink. We are examining how well global terrestrial biosphere models from both the TRENDY and MsTMIP model



**Fig. 33. Comparison of model simulated biospheric sink with estimate from balancing the global carbon budget and its uncertainty. B. Fraction of GCP/TRENDY models exceeding  $2\sigma$  uncertainty in the carbon-budget estimate of the global terrestrial sink in a given year.**

intercomparison projects simulate the trend and interannual variability of the estimated terrestrial carbon sink within the context of this uncertainty (e.g., which fall within  $1\sigma$  or  $2\sigma$  of the estimate). The models, with CLM4.5, the precursor of ACME's ALM, are generally capable of reproducing the trend in net

atmosphere-biosphere carbon exchange, but are less able to capture interannual variability. Models differ in the frequency in which they err in exceeding the uncertainty bounds with only 1 of the 14 TRENDY models achieving the less than 5% exceedance by chance. Where a model exceeds the uncertainty bounds is a target for detailed process examination to determine why the model fails to capture the timing or magnitude of interannual variability. For example, most models fail to capture the terrestrial biosphere's response to the 1991 Mt Pinatubo eruption (Fig. 33b). We are preparing a manuscript reporting these results with plans to extend both the MIPS considered and the diagnostics.

Towards Task 7b, we have determined that consideration of  $^{13}\text{C}$  in terrestrial ecosystems provided an appropriate link between previous fossil fuel research and ongoing terrestrial biosphere research as part of Task 7.  $^{13}\text{C}$  (and  $^{14}\text{C}$ ) are frequently used as tracers in site-scale studies (and are part of the SPRUCE experiment). Can variations in global fossil-fuel  $^{13}\text{C}$  be used as a tracer of terrestrial biosphere activity? Answering that question will require adapting and advancing existing models of plant and ecosystem  $^{13}\text{C}/^{14}\text{C}$  discrimination within the context of understanding fossil fuel  $^{13}\text{C}/^{14}\text{C}$  as a terrestrial biosphere tracer. This model development as part of Task 7 will include determining the precision in models and experimental observations needed for the purpose of using fossil fuel  $^{13}\text{C}/^{14}\text{C}$  as a biosphere tracer. The SPRUCE  $^{13}\text{C}/^{14}\text{C}$  observations are an ideal platform for evaluating model performance, and the linkage between ALM-SPRUCE and ALM (both derived from CLM4.5) facilitates transfer of understanding and modeling from the site-scale to the global terrestrial biosphere.

#### Task 7. Deliverable status

Date	Deliverables	Status
FY 2017-18	Manuscript synthesizing consequences of fossil-fuel and carbon-cycle uncertainty for understanding of the terrestrial biosphere C sink	Poster presented; manuscript in preparation
FY 2017-18	Improved representation of $^{13}\text{C}/^{14}\text{C}$ in CLM-SPRUCE	Early code development
FY 2017-19	Initial assessment of terrestrial landscape drivers of anthropogenic emissions, and current availability of data for quantification with uncertainty	In formulation, with a focus on drivers of land-use change emissions

#### *Publications/Manuscripts*

Andres RJ, Boden TA, Higon DM (2016) Gridded uncertainty in fossil fuel carbon dioxide emission maps, a CDIAC example. *Atmos. Chem. Phys.* doi:10.5194/acp-2016-258.

Hogue S, Marland E, Andres RJ, Marland G, Woodward D (2016) Uncertainty in gridded CO<sub>2</sub> emissions estimates. *Earth' Future* 4:225-239, doi: 10.1002/2015EF000343

#### Task 8: LeafWeb

LeafWeb is an automated online tool ([www.leafweb.org](http://www.leafweb.org)) that has two primary objectives: to provide plant physiologists and photosynthesis researchers a reliable, convenient tool for analyzing leaf gas exchange and Pulse Amplitude Modulated fluorescence measurements for key biochemical and physiological photosynthetic parameters, and to develop a global database of plant biochemical and physiological parameters needed for large-scale plant biological studies and cross-climate and cross-ecosystem modeling.

*Progress for FY2016* - We have successfully re-developed LeafWeb background processing software which is now much faster than the old version. A parallel processing capability has been added to the new LeafWeb. The LeafWeb user interface has also been redesigned for easier data upload and results retrieval (Fig. 34a) and graphics display (Fig. 34b). Finally, LeafWeb has been migrated from [leafweb.ornl.gov](http://leafweb.ornl.gov) to [www.leafweb.org](http://www.leafweb.org) so that LeafWeb does not physically depend on any particular computer which makes LeafWeb much more stable.

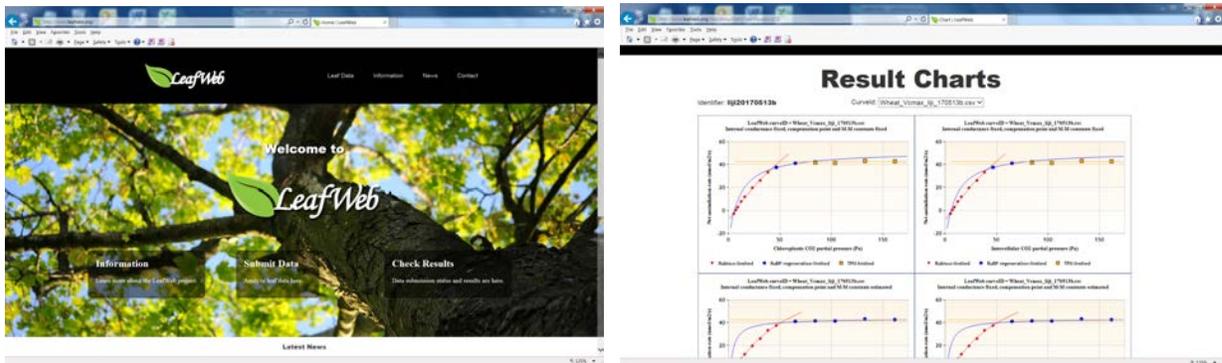


Fig. 34. Screenshots of LeafWeb user interface ([www.leafweb.org](http://www.leafweb.org))

**Ongoing Activities** - We are organizing the writing of the book Our Photosynthetic Planet. The book outline has been completed, and we are continuing the software development of joint analysis of A/Ci/PAR/Temperature/PAM curves.

Publications -

Gu L, Norby RJ, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Winter K (2016) Photosynthetic parameters and nutrient content of trees at the Panama crane sites. OSTI Identifier:1255260.

Norby RJ, Gu L, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Xu C, Winter K. (2016) Informing models through empirical relationships between foliar phosphorus, nitrogen and photosynthesis across diverse woody species in tropical forests of Panama. *New Phytologist* doi: 10.1111/nph.14319.

### TES SFA Data Systems, Management, and Archiving Update

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. Active data sharing facilitates delivery of SFA products to our stakeholders. TES SFA researchers continue to develop and deploy the data systems, repositories, tools, and integration capabilities needed for the collection, QA, storage, processing, sharing, analysis, and archiving of data and model products.

These capabilities facilitate model-data integration and provide accessibility to model output and benchmark data for analysis, visualization, and synthesis activities in support of the TES SFA Vision. Task specific web sites (e.g., FRED: <http://roots.ornl.gov>), access to web-based tools (e.g., LeafWeb: <http://leafweb.org>), links to external products (e.g., microbial metagenomes), and value-added products (<http://tes-sfa.ornl.gov>) enable these interactions.

The SPRUCE experiment is a key component of the SFA. SPRUCE has implemented an experimental platform for the long-term testing of the mechanisms controlling the vulnerability of organisms, ecosystems, and ecosystem functions to increases in temperature and exposure to elevated CO<sub>2</sub> treatments within the northern peatland high-carbon ecosystem. All data collected at the SPRUCE facility, all results of analyses or synthesis of information, and all model algorithms and codes developed in support of SPRUCE will be submitted to the SPRUCE Data Archive in a timely manner such that data will be available for use by SPRUCE researchers and, following publication, the public via the recently updated SPRUCE website (<http://mnspruce.ornl.gov>).

Data acquisition and real time display of SPRUCE experimental plot monitoring data are fully implemented. More than 1,100 sensors are deployed across 16 instrumented plots. Real-time visual displays of selected monitoring and infrastructure operational control parameters are provided using Campbell Scientific's Real-Time Monitor and Control (RTMC) software. Vista Data Vision (VDV) software has been implemented for performance monitoring, data visualization, and data review by the

SPRUCE Team. Data are stored and will be accessible through web-based search and download applications to the project and public.

In addition, ongoing SFA task data products continue to be archived at program-specific archives (e.g., MOFLUX at AmeriFlux). North American Carbon Program (NACP) data synthesis products are archived at the ORNL Distributed Active Archive Center (ORNL DAAC). New SFA task data products are publicly available on the ORNL TES-SFA web site: <http://tes-sfa.ornl.gov>.

#### **Affiliated TES SFA Supported Publications**

Staff supported by the TES SFA continue to collaborate and complete work funded by US DOE BER in prior fiscal years that may not explicitly be funded under Tasks 1 through 8. The following listing shows additional manuscripts completed since the February 2016 with limited TES SFA support.

- Deng Y, He Z, Xiong J, Yu H, Xu M, Hobbie SE, Reich PB, Schadt CW, Kent A, Pendall E, Wallenstein M and Zhou J (2016) Elevated carbon dioxide accelerates the spatial turnover of soil microbial communities. *Global Change Biology* 22:957-64.
- Jia Q, Li G, Köllner TG, Fu J, Chen X, Xiong W, Crandall-Stotler BJ, Bowman JL, **Weston DJ**, Zhang Y, Chen L (2016) Microbial-type terpene synthase genes occur widely in nonseed land plants, but not in seed plants. *Proceedings of the National Academy of Sciences*, 113(43), pp.12328-12333.
- Phillips RP, Ibanez I, D'Orangeville L, **Hanson PJ**, Ryan MG, McDowell N (2016) A belowground perspective on the drought sensitivity of forests: towards improved understanding and simulation. *Forest Ecology & Management* 380:309-320, <http://dx.doi.org/10.1016/j.foreco.2016.08.043>
- Porras RC, Hicks Pries CE, McFarlane KJ, **Hanson PJ**, Torn MS (2017) Association with pedogenic iron and aluminum: effects on soil organic carbon storage and stability in four temperate forest soils. *Biogeochemistry* (in press).

Also completed were the following:

Funded Rapid Access proposal EMSL proposal: The metabolite exchange within a tri-partite plant – fungus – cyanobacterium interaction system using a Maldi FT-ICR Mass Spectrometry imaging. PI Weston

Funded ORNL CNMS user proposal: Determining the elemental and small molecule signatures of a plant - cyanobacteria symbiosis using TOF-SIMS, PI Weston

JGI Community Supported Science: The *Sphagnum* genome project. We are continuing to work with JGI on the largest plant genome sequencing project specific to carbon cycling.

#### **4AII. SCIENCE HIGHLIGHTS SINCE FEBRUARY 2015**

- ORNL TES SFA staff completed 59 articles including submissions to *Science*, *Nature Communications*, *Nature Climate Change* and *Nature Geoscience* since June of 2016.
- TES SFA scientists sustained SPRUCE whole ecosystem warming (WEW) treatments throughout 2016 and 2017 to date with very minor interruptions for maintenance or system error. A major paper describing the SPRUCE experimental system and performance was published.
- A paper describing temporal and spatial variation in peatland carbon cycling parameters was published in a special issue on uncertainty in forest ecosystem studies in the *Soil Science Society of America Journal* (Griffiths et al. In Press).
- For Walker Branch Watershed research, the historical precipitation, climate, stream discharge, and stream chemistry datasets were finalized, and were made available on the ORNL TES SFA website. Two papers on stream biogeochemistry were published (Brooks et al. 2017; Hill and Griffiths 2017).
- Pretreatment analysis and characterization papers for SPRUCE continue to be produced and published (Jensen et al. 2015, Griffiths and Sebestyen 2016, Hanson et al. 2016, McFarlane et al. 2016, Griffiths et al. 2017; Hobbie et al. 2017; Iversen et al. 2017).

- Anthony Walker published a paper on *Sphagnum* species net and gross photosynthetic capacity (Walker et al. 2017) that represents the empirical basis for modeling *Sphagnum* vegetation layers within the land surface component of ecosystem and Earth System models.
- SPRUCE-MIP activity first results: 11 modeling groups are performing pre-treatment simulations, and several groups have submitted results. Datasets are being prepared to enable treatment simulations in each of the 10 enclosures.
- Jiafu Mao published a paper in *Nature Climate Change* that attributes long-term trends in leaf area index in the northern extratropical latitudes to human activity using satellite data and coupled Earth system models.
- A new framework for model sensitivity analysis is improving understanding about which parameters and processes most influence carbon cycling, and is being used both at SPRUCE (Griffiths et al, in press) and in Task 4.
- Colleen Iversen initiated the Fine Root Ecology Database (FRED; <https://roots.ornl.gov>; Iversen et al. 2017), which has been downloaded more than 100 times across five continents, for use by modelers and empiricists alike.
- Task 4c on root function found that newer, younger roots have greater uptake capacity per unit surface area, but that total water uptake depended on the larger roots, with lower uptake rates, and strives to understand if the roots themselves cause substantial changes in soil hydraulic properties, such that the commonly used soil hydraulic properties used by models are not correct in models.
- Task 5 research showed that the future trajectory of soil organic carbon stocks may be more responsive to changes in soil moisture than to temperature, particularly in tropical and subtropical environments (Wang et al, submitted).
- Fluorescence Automated Measurement Equipment (FAME) was developed and deployed at MOFLUX. This instrumentation is being tested as an independent means of assessing forest gross primary production that will be critical for the interpretation of long-term eddy flux changes through time.
- At the MOFLUX eddy covariance site, and over the 2005–2015 time period, growing season net ecosystem productivity (NEP) and ( $R_s$ ) were largely controlled by plant water stress, and correlated to a significant linear relationships with community predawn leaf water potential integrals.
- Task 7 is adapting and advancing existing models of plant and ecosystem  $^{13}\text{C}/^{14}\text{C}$  discrimination within the context of understanding fossil fuel  $^{13}\text{C}/^{14}\text{C}$  as a terrestrial biosphere tracer.
- The LeafWeb data portal has been redone and redeployed on a user friendly server to enable its use by a wider researcher group.
- The plant physiology group has leveraged an ORNL-funded LDRD on Extreme Events with both the solar induced fluorescence measurement developments from MOFLUX, and new modeling efforts, to facilitate representation of plant stress responses to short-term extreme events in ALM.

#### 4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff produced 59 publications or completed manuscripts since our last summary report. This total includes 46 published/in press/accepted journal articles, 4 technical reports and book chapters, and 9 completed manuscripts that are working through the review process. This level of productivity over 1 years at 59 per year; remains an increase over the average paper production rate from January 2012 through February 2015 (42 per year). A TES SFA cumulative publication summary is provided in Appendix A with the most recent publications from the current reporting period listed first. This listing duplicates the Task-specific summaries already provided. Total number so report publications is down this year reflecting the departure of Robert Andres from the group.

The TES SFA group published in 31 different peer-reviewed publications in this reporting period include one paper in *Nature Communications* (Wilson et al. 2017), four papers in *Nature Climate Change* (Li et al. 2017; Mao et al. 2017; Zeng et al. 2017; Zhu et al. 2016) and one paper in *Nature Geoscience* (Wang et al. 2017). Other journals with 3 or more TES SFA papers in the current reporting period include: *Biogeosciences* (x7), *New Phytologist* (x5) and *Agricultural and Forest Meteorology* (x3).

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

We also continue to place significant and sustained effort on the production of archived data sets based on TES SFA work. A complete and cumulative summary of TES SFA data sets is provided in Appendix B.

#### **4B. FUTURE SCIENCE GOALS AND PLANS**

We are not anticipating near term redirection of process-level research beyond the plans described in the 2015 TES SFA renewal. As a part of the 2015 renewal we are working towards extending eddy covariance efforts under Task 6 to include similar measurements at the S1-Bog. These observations will help us translate mechanistic work within the manipulations to landscape and regional areas, and ultimately help test models of temperate peatland function in a global context.

The TES SFA plans to enhance efforts to leverage knowledge gained from past and ongoing process studies, manipulative experiments and ecosystem observations (e.g., SPRUCE, PiTS, belowground fundamentals, landscape fluxes, EBIS, and TDE) to improve ecosystem models. Future, highly focused experimental studies will be used to test key mechanistic processes in the ACME land model (ALM).

To improve the modeling of gross primary production, we are applying new understanding of mesophyll diffusion, fluorescence, nitrogen and phosphorous limitations and thermal thresholds for photosynthesis and respiration to improve the modeling of gross primary production in CLM and ALM.

Improved *Sphagnum* modeling – Within the ALM frameworks we are developing a mechanistic model of sphagnum photosynthesis based on in situ assessment of GPP, *Sphagnum* production, capitula water content and environmental conditions. The data and modeling results will also provide critical information for latent heat and energy balance calculations.

#### **4C. NEW SCIENCE FOCUS AND IDENTIFIED KNOWLEDGE GAPS**

Early results from the SPRUCE study have suggested that further investment in the biogeochemical cycling of phosphorus and the biological fixation of N<sub>2</sub> are needed to adequately capture long-term nutrient feedbacks within the bog with warming. Models will be used to evaluate the potential feedback magnitudes from P limitations and N<sub>2</sub> fixation inputs to better define the need for future measurements.

We have clearly seen warming induced changes in the phenology of the bog vegetation with the expected acceleration of spring growth activities, but also a clear extension of the autumn growing season. In many current ecosystem models including ALM, the predominant driver for fall senescence based on the interpretation of observational interannual variation is day length. The SPRUCE data show that algorithms will need to be modified to include warming influences on fall phenology changes. We have added new phenology cameras to better capture dynamics of ground layer vegetation.

Identified knowledge gaps also drive model developments within the ACME, NGEE-Tropics and NGEE-Arctic projects that are complementary to efforts within the TES SFA. The TES SFA will continue to contribute new science to the ACME code base, including new algorithms for phenology and responses to extremes, and *Sphagnum* processes described above. Our modeling efforts will also benefit from developments in the other projects, such as improved hydrology through the ALM-PFLOTTRAN coupling in NGEE-Arctic and the inclusion of a global phosphorus cycling model in ACME.

#### **4D. COLLABORATIVE RESEARCH**

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

- Dr. Joel Kostka, Jeff Chanton and colleagues have continued to receive support from DOE BER for their ongoing studies of microbial ecology at SPRUCE.
- Drs. Scott Bridgman and Jason Keller and colleagues are also supported to conduct a DOE BER funded study of mechanisms underlying heterotrophic CO<sub>2</sub> and CH<sub>4</sub> fluxes in a peatland.
- Drs. Kirsten Hofmockel and Eric Hobbie are supported by DOE BER to address the question – Can microbial ecology inform ecosystem level C-N cycling response to climate change?
- Drs. Brandy Toner, Ed Nater and colleagues from the University of Minnesota, are conducting the Mercury and Sulfur Dynamics in the SPRUCE experiment using funding provided through the USDA Forest Service.
- Dr. Andrew Richardson leads the task on phenology with his funding for the Phenocam network. This may become a funded task with SPRUCE support in the future.
- Dr. Bruce McCune (Oregon State University) and Sarah Jovan (USDA Forest Service) have their own support to study lichen responses to warming and elevated CO<sub>2</sub> within the SPRUCE experimental infrastructure.
- Dr. Adrian Finzi obtained DOE BER support to add high temporal resolution measures of CO<sub>2</sub> and CH<sub>4</sub> flux from the experimental plots that will include <sup>13</sup>C isotopic capabilities. This work continues with new on site staff
- Dr. Karis McFarlane, Tom Guilderson, Jennifer Pett-Ridge and colleagues have completed a LLNL-CAMS internal laboratory directed funds to work with SPRUCE to characterize the <sup>14</sup>C isotopic composition of gases emanating from the S1-Bog surface. Such data help interpret the relative balance between old and new C sources impacted by the SPRUCE warming and CO<sub>2</sub> treatments.
- Dr. Nancy Glenn is now contracted through SPRUCE to provide ground-level LIDAR observations as a supplement to our destructive woody harvests and *Sphagnum* production estimates. Jake Graham is executing the onsite work.
- Dr. Yiqi Luo's group is utilizing new high-temporal-resolution, model-data iterative analyses to better define measured ecosystem responses with the intention of helping the research group apply measurement efforts to critical processes.
- Dr. Xiaofeng Xu continues work with the modeling group on improved biogeochemical cycling models for methane flux.
- Dr. Danielle Way (University of Western Ontario) is an unfunded collaborator who has been providing expertise and two PhD students to assist with seasonal assessment of *Picea* and *Larix* photosynthetic and respiratory thermal and CO<sub>2</sub> acclimation.

#### **CITED REFERENCES**

- BERAC (2010) *Grand Challenges for Biological and Environmental Research: A Long-Term Vision; A Report from the Biological and Environmental Research Advisory Committee March 2010 Workshop*, DOE/SC-0135, BERAC Steering Committee on Grand Research Challenges for Biological and Environmental Research ([www.science.doe.gov/ober/berac/BER\\_LTVreport.pdf](http://www.science.doe.gov/ober/berac/BER_LTVreport.pdf))
- US DOE (2012) *Biological and Environmental Research Climate and Environmental Sciences Division Strategic Plan*, U.S. Department of Energy, Office of Science, July 2012, DOE/SC-0151, <http://science.energy.gov/~media/ber/pdf/CESD-StratPlan-2012.pdf>.

## **5. STAFFING AND BUDGET SUMMARY**

### **5A. FY2017 FUNDING ALLOCATION BY PROGRAM ELEMENT**

FY2017 spending is summarized in the following table. The listed amounts represent costs and commitments incurred through 13 June 2017. Total expected available funding for ORNL's TES SFA includes \$2,464K carryover from FY2015 and \$8,255K of new budget authorization. As of 13 June 2017 we have not yet received \$2,578K of the expected annual FY2017 allocation.

**FY2017 Budget expenditures by TES SFA Program Element through 13 June 2017.**

Task	Cost Through 13 June 2017 (\$K)	Commitments Through 13 June 2017 (\$K)	Remaining Funds 13 June 2017 (\$K)	Expected Additional Allocation (\$K)
T1: SPRUCE Science	2044	170	240	765
T3: Carbon Cycle Modeling	975	153	6	560
T6: MOFLUX	411	67	-13	261
T4b: Process Study - Root traits	100	96	94	99
T4c: Process Study - Root Func.	139	3	106	78
T5: Soil C Studies	325	45	0	197
T7: C Emissions	142	0	58	69
T8: LeafWeb	90	8	71	24
T1: SPRUCE – Operations	649	151	551	394
T1: SPRUCE – Materials	80	19	91	0*
T1: SPRUCE – Reserve	0	0	153	92
ORNL Reserves	32	0	210	39
<b>SFA Totals</b>	<b>\$4,987</b>	<b>\$712</b>	<b>\$1,567</b>	<b>\$2,578</b>

\* FY2017 funds are already fully allocated.

We are currently spending at rates consistent with the spending plans outlined in the February 2015 TES SFA renewal proposal budgets for FY2017. We anticipate unspent carry over funds to be approximately \$1,500K across all TES SFA tasks.

Small amounts of new budget authorization provide to the TES SFA for closely related activities are managed as independent efforts and not included in this analysis (\$50K).

**5B. FUNDING ALLOCATION TO EXTERNAL COLLABORATORS**

A variety of collaborations are maintained and funded by the TES SFA to provide necessary commodities, and disciplinary expertise and effort in areas critical to the completion of research tasks. In FY2016 we directly funded the following individuals or groups.

**The University of Missouri (\$170K)** is subcontracted to provide MOFLUX on site execution of the following measurements: stand-level eddy covariance, soil CO<sub>2</sub> efflux, belowground production via repeated minirhizotron image collections, stem allometric increment data, and litter basket net primary production. Since 1 June 2016, In June 2016, **J.D. Wood** was hired into a research position at MU to serve as Missouri site-PI of the MOFLUX site due to the departure of J. Hubbart.

Dr. Jeff Wood assumed the role of the University of Missouri on-site investigator for ORNL.

**Yiqi Luo- The University of Oklahoma (\$75K)** – Dr. Luo;s research group at OU is developing an ecological forecasting capability at SPRUCE. Using the TECO model as a demonstration, data assimilation capabilities are being developed and applied using SPRUCE observations, and forecasts were made for the 10 experimental plots using a range of future scenarios. A methane model was also added to TECO. 1 manuscript has been submitted with two additional manuscripts in preparation. This subcontract is planned to end in FY17. A new subcontract will be established with Northern Arizona University, where Dr. Luo will join in August 2017, to finish extending the work to ALM-SPRUCE modeling efforts.

**Xiaofeng Xu - San Diego State University (\$38K)** - In a joint subcontract with NGEE-Arctic, Dr. Xu is developing and testing a CH<sub>4</sub> modeling capability for the CLM and ALM SPRUCE modeling efforts. This work has contributed to two manuscripts. Work to refine and optimize the model with SPRUCE observations is continuing.

**Mingzhou Jin – University of Tennessee: (\$31K)** - Dr. Jin and graduate student Whitney Forbes are developing techniques for detection and attribution of terrestrial ecosystem responses to anthropogenic forcings. Dr. Jin has contributed to a manuscript in Nature Climate Change on the detection and attribution of northern hemisphere greening, and a second manuscript is underway.

**Chengen Yang – University of Tennessee (\$13K)** - Chengen Yang is a graduate student working with Dr. Joshua Fu. Jointly with the BGC feedbacks SFA, Chengen is subcontracted to evaluate and improve model predictions of biomass. A manuscript on this effort is complete.

**John Latimer (\$58K)** – We have subcontracted John part-time through Xcel Engineering since 2014 to collect weekly minirhizotron images from the SPRUCE experimental plots, and to collect and exchange ion-exchange resin capsules every 28 days from the SPRUCE experimental plots. John also hosts a weekly phenology show on the local NPR station in Grand Rapids, MN (<http://www.kaxe.org/programs/phenology.aspx>) and has been assisting with phenological observations in the SPRUCE experimental plots.

**M. Luke McCormack (\$50K)** – Dr. McCormack, a research associate at the University of Minnesota, has been subcontracted to analyze global patterns in root traits compiled in the Fine-Root Ecology Database (*FRED*) and develop a manuscript on this topic. In addition, Luke is working with an interdisciplinary team of empiricists, modelers, and database managers to improve the conceptual representation of root traits and their associated functions in terrestrial biosphere models.

**A. Shafer Powell (\$65K)** – Shafer, a post-Baccalaureate intern at ORNL, has been subcontracted to add data from published literature to *FRED*, maintain and quality-assure the *FRED* database, and maintain the associated data dictionary and user guidance document. To date, Shafer has filled more than one million data cells with root-trait related data.

**RhizoSystems, LLC (\$28K)** – The company who designed and built the automated minirhizotrons (AMRs) is being subcontracted for support and maintenance of these systems. This includes off-site repair and maintenance of all AMR and RhizoSystems-installed equipment and remote assistance with field repair on-site. It also includes assistance with and support of the RV3n software as well as AMR-related software updates to and routine maintenance of RhizoSystems-installed computers.

**Interagency Agreement with the USDA Forest Service (\$40K)** – This agreement allows Forest Service employees to help with the operation, planning and execution of the SPRUCE experimental infrastructure and science tasks. It also provides some coverage for the use of the USDA FS bunk house on the Marcell Experimental Forest.

**Keith Oleheiser (\$97K)** - The hydrology and porewater chemistry task greatly benefited from the subcontract for XCEL Engineering technician Keith Oleheiser. Keith Oleheiser is based in Minnesota, and collects water samples (porewater, outflow, precipitation) and hydrology measurements, and assists with other field tasks. He also analyses all SPRUCE water samples at the USFS research lab in Grand Rapids, MN for pH, specific conductivity, alkalinity, anions, cations, nutrients, and total organic carbon.

**Ryan Heiderman (\$100K)** – A technical contract was established for Ryan to help W. Robert Nettles with the day-to-day operation of SPRUCE treatments and the calibration and upkeep of automated data collections systems.

**Infrastructure subcontracts** in support of the SPRUCE project in FY2016 include funds and funding for site maintenance (***Pokegama Electric \$77K***), electrical service (***Lake Country Power \$150K***), propane supply (***Lakes Gas Co. \$200K***), elevated CO<sub>2</sub> supply (***PRAXAIR Inc. \$200K***), satellite internet connections (***Hughes Net & Viasat \$10K***), and leased space in Minnesota (***\$45K***). The amounts required for each of these operational contracts will be reevaluated annually as actual usage rates and prices change.

## 5C. PERSONNEL ACTIONS AND PROCEDURES

***New Hires*** – One new staff hire and a technical support person were brought on in the past year. **Dr. Junyi Liang** was hired as a postdoctoral fellow to work with Melanie Mayes on Task 5. **Ryan Heiderman**, a graduate level technical support person, was hired to work full time with W. Robert Nettles to help maintain the operations and measurement capabilities of the SPRUCE project.

**David McLennan** – David was hired on May 16, 2016 into the Oak Ridge Associated Universities Laboratory Technology Program to support TES-SFA and related research, including plant ecophysiology and laboratory analyses such as non-structural carbohydrates. This year-long post-BS internship program is designed to identify and evaluate potential new technicians. David was extended for a second year.

Anticipated Future Hires – Looking ahead to FY2018, the TES SFA plans to pursue hiring additional postdoctoral fellows to supplement full time staff positions and as the budget allows.

Retirements and Releases – No staff have retired in FY2017. Laurel Kluber completed her postdoctoral position working with Chris Schadt and Melanie Mayes.

Procedures for advancing new and developing investigators - New TES SFA staff members are commonly first hired through postdoctoral research associate positions and their performance and contributions to task activities are tracked. Our postdocs are vetted for potential future roles as task leads, and are hired as staff into leadership roles as appropriate for our needs.

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

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

#### **5D. NATIONAL LABORATORY INVESTMENT IN THE PROGRAM IN FY2017**

In past years, ORNL has demonstrated its commitment to environmental change research through substantial investments in climate change modeling, the development of innovative large-scale experimental infrastructures through the Laboratory Directed Research and Development program (LDRD), the construction of a field support building (Building 1521), greenhouses, the Joint Institute for Biological Sciences, and renovations in support of molecular ecology. Concepts for the belowground warming technologies used for the SPRUCE Experiment (Task R1) were initiated with ORNL LDRD funds totaling \$480K in FY2008 and FY2009, and current LDRD projects are leveraging the SPRUCE experiment to advance various fields of study. In FY2014, ORNL provided the equivalent of \$1000K staff support from internal funds to allow completion of the SPRUCE warming aboveground infrastructure. No ORNL funds were requested or have been needed in FY2017.

The Climate Change Science Institute brings together all ORNL Climate Change staff including members of the TES SFA to foster 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. ORNL data centers (e.g., CDIAC and NASA Distributed Active Archive Center for Biogeochemical Dynamics (NASA-DAAC)) provide the infrastructure support for data and model integration, and information archival needs of the TES SFA. We will transition to work with the new DOE BER data center in the coming months.

We are also using other facilities at collaborating DOE National Laboratories. The Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (LLNL-CAMS) provides large volume, high precision <sup>14</sup>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.

#### **5E. CAPITAL EQUIPMENT**

Since the threshold amount of funds needed to define a capital expenditure has risen, no ORNL TES SFA funds were used to acquire capital equipment in FY2016. Funding for SPRUCE experimental infrastructure maintenance and development at the S1-Bog are not classified as capital expenditures, but represent an analogous investment for the decadal duration of the experiment.

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## APPENDIX A: COMPLETE PUBLICATION LIST – ORNL TES SFA

### Published, accepted and in review papers for the ORNL TES SFA since the 2016 Annual Report

1. Abramoff R, Xu X, Hartman M, O'Brien S, Feng W, Davidson E, Finzi A, Moorhead D, Schimel J, Torn M, Mayes M (2017) The Millennial Model: in search of measurable pools and exchanges in soil carbon cycling for the new century. *The Journal of Advances in Modeling Earth Systems* (in review).
2. Andres RJ, Boden TA, Higon DM (2016) Gridded uncertainty in fossil fuel carbon dioxide emission maps, a CDIAC example. *Atmospheric Chemistry and Physics* doi:10.5194/acp-2016-258.
3. Brooks SC, Brandt CC, Griffiths NA (2017) Estimating uncertainty in ambient and saturation nutrient uptake metrics from nutrient pulse releases in stream ecosystems. In Revision at *Limnology and Oceanography: Methods* 15:22-37. doi: 10.1002/lom3.10139.
4. Dai H, Ye M, Walker AP, Chen X (2017) A new process sensitivity index to identify important system processes under process model and parametric uncertainty. *Water Resources. Research* 53:2577-3522, doi:10.1002/2016WR019715
5. Dhiman I, Bilheux HZ, DeCarlo KF, Painter SL, Santodonato LJ, Warren JM (2017) Quantifying root water extraction after drought recovery using sub-mm in situ empirical data. *Plant and Soil* (under review).
6. Fang Y, Michalak AM, Schwalm C, Huntzinger D, Berry JA, Ciais P, Piao S, Poulter B, Fisher JB, Cook RB, Hayes D, Huang M, Ito A, Lei H, Mao J, Parazoo N, Shi X, Tao B, Wang W, Wei Y, Yang J (2017) Global land carbon sink response to temperature and precipitation varies with ENSO phase. *Environmental Research Letters*. (accepted in press).
7. Ficken C, Warren JM (2017) Sensitivity and recovery of soil respiration to extreme drought in AM and ECM mesocosms. *Global Change Biology* (under review)
8. Freschet GT, Valverde-Barrantes OJ, Tucker CM, Craine JM, McCormack ML, Violle C, Fort F, Blackwood CB, Urban-Mead KRU, Iversen CM, Bonis A, Comas LH, Cornelissen JHC, Dong M, Guo D, Hobbie SE, Holdaway RJ, Kembel SW, Makita N, Onipchenko VG, Picon-Cochard C, Reich PB, De la Riva EG, Smith SW, Soudzilovskaia NA, Tjoelker M, Wardle DA, Roumet C. 2017. Climate, soil and plant functional types as drivers of global fine-root trait variation. *Journal of Ecology*, DOI: 10.1111/1365-2745.12769.
9. Follstad Shah JJ, Kominoski JS, Ardón M, Dodds WK, Gessner MO, Griffiths NA, Hawkins CP, Lecerf A, LeRoy CJ, Manning DWP, Johnson SL, Rosemond AD, Sinsabaugh RL, Swan CM, Webster JR, Zeglin LH (2017) Global synthesis of the temperature sensitivity of leaf litter breakdown in streams and rivers. *Global Change Biology* (in press).
10. Furze M, Jensen A, Warren J, Richardson A (2017) Seasonal patterns of nonstructural carbohydrate reserves in four woody boreal species. *Botany* (being revised)
11. Geron C, Daly R, Harley P, Rasmussen R, Seco R, Guenther A, Karl T, Gu L (2016) Large drought-induced variations in oak leaf volatile organic compound emissions during PINOT NOIR 2012. *Chemosphere* 146:8-21.
12. Griffiths NA, Hanson PJ, Ricciuto DM, Iversen CM, Jensen AM, Malhotra A, McFarlane KJ, Norby RJ, Sargsyan K, Sebestyen SD, Shi X, Walker AP, Ward EJ, Warren JM, Weston DJ (2017) Temporal and spatial variation in peatland carbon cycling and implications for interpreting responses of an ecosystem-scale warming experiment. In Revision at *Soil Science Society of America Journal* (in press)
13. Griffiths NA, Sebestyen SD (2016) Dynamic vertical profiles of peat porewater chemistry in a northern peatland. *Wetlands* 36:1119-1130.
14. Gu L, Norby RJ, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Winter K (2016) Photosynthetic parameters and nutrient content of trees at the Panama crane sites. OSTI Identifier:1255260.
15. Gu L, Pallardy SG, Hosman KP, Y Sun (2016) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. *Agricultural and Forest Meteorology* 217: 120-136.

16. Gu L, Pallardy SG, Yang B, Hosman KP, Mao J, Ricciuto D, Shi X, Sun Y (2016) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a central USA forest. *Journal of Geophysical Research - Biogeosciences* 121, 1884-1902.
17. Hanson PJ, Riggs JS, Nettles WR, Phillips JR, Krassovski MB, Hook LA, Richardson AD, Aubrecht DM, Ricciuto DM, Warren JM, Barbier C (2017) Attaining whole-ecosystem warming using air and deep soil heating methods with an elevated CO<sub>2</sub> atmosphere. *Biogeosciences* 14: 861–883, doi: 10.5194/bg-14-861-2017
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19. Hill WR, Griffiths NA (2017) Nitrogen processing by grazers in a headwater stream: riparian connections. *Freshwater Biology* 62:17-29.
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25. Iversen CM, Norby RJ (2014) Terrestrial plant productivity and carbon allocation in a changing climate. In *Handbook of Global Environmental Pollution: Global Environmental Change*, [Freedman B, ed.] New York, NY: Springer, pp. 297-316.
26. Jian S, Li J, Chen J, Wang G, Mayes MA, Dzantor KE, Hui D, Luo Y (2016) Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. *Soil Biology and Biochemistry* 101: 32-43. DOI:10.1016/j.soilbio.2016.07.003
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30. Kueppers LM, Iversen CM, Koven CD (2016) Expanding the use of plant trait observations in Earth system models. *Eos* 97 (DOI:10.1029/2016EO049947).
31. Li J, Wang G, Mayes MA, Allison SD, Frey SD, Shi Z, Hu XM, Luo Y, Mellilo JM (2017) Reduced carbon use efficiency and increased microbial turnover with soil warming. *Nature Climate Change* (submitted).

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37. Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016) Evaluating the Community Land Model in a pine stand with shading manipulations and <sup>13</sup>C labeling, *Biogeosciences*, 13, 641-657, doi:10.5194/bg-13-641-2016
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41. McFarlane KJ, Iversen CM, Phillips JR, Brice DJ, Hanson PJ (2016) Temporal and spatial heterogeneity of carbon accumulation in an ombrotrophic bog in northern Minnesota over the Holocene. (*Being revised for a new journal*).
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47. Shaw AJ, Schmutz J, Devos N, Shu S, Carrell AA, Weston DJ (2016) Chapter Five-The *Sphagnum* Genome Project: A New Model for Ecological and Evolutionary Genomics. *Advances in botanical research*, 78, pp.167-187.
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## APPENDIX B: COMPLETE LIST OF 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](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](http://tes-sfa.ornl.gov/sites/default/files/TES_SFA_Data_Policy_20130510_Ver_1_approved.pdf)

Data sets marked with a triple asterisk (\*\*\*) have been added since June 2016.

### SPRUCE Public Data Sets:

1. Griffiths NA, Hook LA, Hanson PJ (2016) **SPRUCE S1 Bog and SPRUCE Experiment Location Survey Results, (2015)** 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.015>
2. \*\*\* Griffiths NA, Sebestyen SD (2016) **SPRUCE S1 Bog Porewater, Groundwater, and Stream Chemistry Data: 2011-2013.** 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.018>
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<http://dx.doi.org/10.3334/CDIAC/spruce.028>
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8. \*\*\* 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>.
9. \*\*\* Hanson PJ, Phillips JR, Riggs JS, Nettles WR, Todd DE (2014) **SPRUCE Large-Collar In Situ CO<sub>2</sub> and CH<sub>4</sub> 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>.
  10. 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.)
  11. \*\*\* 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>.
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  13. \*\*\* Hanson PJ, Riggs JS, Nettles WR, Krassovski MB, Hook LA (2016) **SPRUCE Whole Ecosystems Warming (WEW) Environmental Data Beginning August 2015**. 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.032>
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  15. 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>.
  16. \*\*\* Iversen CM, Childs J, Norby RJ, Garrett A, Martin A, Spence J, Ontl TA, Burnham A, Latimer J. (2017) SPRUCE S1 bog fine-root production and standing crop assessed using with minirhizotrons in the Southern and Northern ends of the S1 bog. 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.019>.
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  18. \*\*\* Iversen CM, Ontl TA, Brice DJ, Childs J (2017) SPRUCE S1 Bog plant-available nutrients assessed with ion-exchange resins from 2011-2012 in the Southern end of the S1 bog. 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.022>.
  19. \*\*\* Iversen CM, Latimer J, Burnham A, Brice DJ, Childs J, Vander Stel HM (2017) SPRUCE plant-available nutrients assessed with ion-exchange resins in experimental plots, beginning in 2013. 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.036>.
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21. \*\*\* Kluber LA, Phillips JR, Hanson PJ, Schadt CW (2016) **SPRUCE Deep Peat Heating (DPH) Peat Water Content and Temperature Profiles for Experimental Plot Cores, June 2014 through June 2015**. 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.029>
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23. 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](http://dx.doi.org/10.3334/CDIAC/spruce.029)) ]
24. \*\*\* Ontl TA, Iversen CM (2016) **SPRUCE S1 Bog areal coverage of hummock and hollow microtopography assessed along three transects in the S1 bog**. 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.023>.
25. \*\*\* Phillips JR, Brice DJ, Hanson PJ, Childs J, Iversen CM, Norby RJ, Warren JM (2017) **SPRUCE Pretreatment Plant Tissue Analyses, 2009 through 2013**. 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.038>
26. \*\*\* Shi X, Thornton PE, Ricciuto DM, Hanson PJ, Mao J, Sebestyen SD, Griffiths NA, Bisht G (2016) **SPRUCE Representing Northern Peatland Microtopography and Hydrology within the Community Land Model: Modeling Archive**. 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.031>
27. 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>.
28. \*\*\* Walker AP, Carter KR, Hanson PJ, Nettles WR, Philips JR, Sebestyen SD, Weston DJ (2017) **SPRUCE S1 Bog Sphagnum CO<sub>2</sub> Flux Measurements and Partitioning into Re and GPP**. 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.039>
29. \*\*\* Wilson RM, Hopple AM, Tfaily MM, Sebestyen SD, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane KJ, Kostka JE, Kolton M, Kolka R, Kluber LA, Keller JK, Guilderson TP, Griffiths NA, Chanton JP, Bridgham SD, Hanson PJ (2016) **SPRUCE Stability of Peatland Carbon to Rising Temperatures: Supporting Data**. 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.026>

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

1. Finzi AF, Giasson MA, Gill AL (2016) **SPRUCE Autochamber CO<sub>2</sub> and CH<sub>4</sub> 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.016>
2. \*\*\* Kluber LA, Allen SA, Hendershot JN, Hanson PJ, Schadt CW (2017) **SPRUCE Deep Peat Microbial Diversity, CO<sub>2</sub> and CH<sub>4</sub> Production in Response to Nutrient, Temperature, and pH Treatments during Incubation Studies**. 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.040>

#### Other TES SFA Public Data Sets and Tools:

1. Griffiths NA, Tieggs SD (2016) **Walker Branch Watershed: Temperature Response of Organic-Matter Decomposition in a Headwater Stream**. 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.003>
2. Iversen CM, Powell AS, McCormack ML, Blackwood CB, Freschet GT, Kattge J, Roumet C, Stover DB, Soudzilovskaia NA, Valverde-Barrantes OJ, van Bodegom PM, Violle C (2016) **Fine-Root Ecology Database (FRED): A Global Collection of Root Trait Data with Coincident Site, Vegetation, Edaphic, and Climatic Data, Version 1**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. Access on-line at: <http://dx.doi.org/10.3334/CDIAC/ornlsfa.005>.
3. 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>.
4. \*\*\* Kluber LA, Phillips JR, Wang G, Schadt CW, Mayes MA (2017) **Soil Respiration and Microbial Biomass from Soil Incubations with <sup>13</sup>C Labeled Additions**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. <http://dx.doi.org/10.3334/CDIAC/ornlsfa.010>
5. **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/>.
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. Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Hourly, Daily, and Annual Precipitation**. 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.006>
8. Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: 15-minute and Daily Stream Discharge and Annual Runoff**. 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.007>
9. Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Daily Climate and Soil Temperature Data**. 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.008>
10. Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Weekly Stream Water Chemistry**. 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.009>
11. Pallardy SG, Gu L, Hosman KP, Sun Y (2015) **Predawn Leaf Water Potential of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2014**. 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.004>
12. 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).
13. **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<sub>2</sub> 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<sub>2</sub> fertilization. *Proceedings of the National*

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