FY2018 PROGRESS REPORT
OAK RIDGE NATIONAL LABORATORY'S
TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA
(TES SFA)

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ABSTRACT

Understanding fundamental responses of ecosystem carbon (C) cycles to climatic and atmospheric change is the aim of the Terrestrial Ecosystem Science Scientific Focus Area (TES SFA). Improved predictive understanding of terrestrial ecosystems is the long-term motivation guiding our research. Overarching science questions are:

(1) How will atmospheric and environmental changes 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_2 and other greenhouse gases?

(3) What are the environmental change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of climate change impacts on ecosystem services and society?

The proposed science includes large manipulations, C-Cycle observations, database compilation, and fundamental process studies integrated and iterated with modeling activities. The centerpiece of our climate change manipulations is the SPRUCE experiment testing multiple levels of warming at ambient and elevated CO_2 on the C feedbacks from a black spruce *Sphagnum* ecosystem. Other TES SFA efforts aim to improve mechanistic representation of processes within terrestrial biosphere models by furthering our understanding of fundamental ecosystem functions, and their response to environmental change. The TES SFA aims to integrate experimental and observational studies with model building, parameter estimation, and evaluation to yield reliable model projections. This integrated model-experiment approach fosters an enhanced, interactive, and mutually beneficial engagement between models and experiments to further our predictive understanding of the terrestrial biosphere in the context of earth system functions.

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1.0 PROGRAM OVERVIEW

Oak Ridge National Laboratory's (ORNL) Terrestrial Ecosystem Science Science Focus Area (TES SFA) provides fundamental research in support of the DOE BER Climate and Environmental Science Division Strategic Plan (US DOE 2018) specifically addressing all five CESD grand challenges to various degrees. 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 2017 BERAC Grand Challenges Report (BERAC 2017). For example, the TES SFA contributes to understanding biological systems science, earth and environmental systems science, and aspects of microbial pathways important to earth systems. The TES SFA places 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 practices 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.
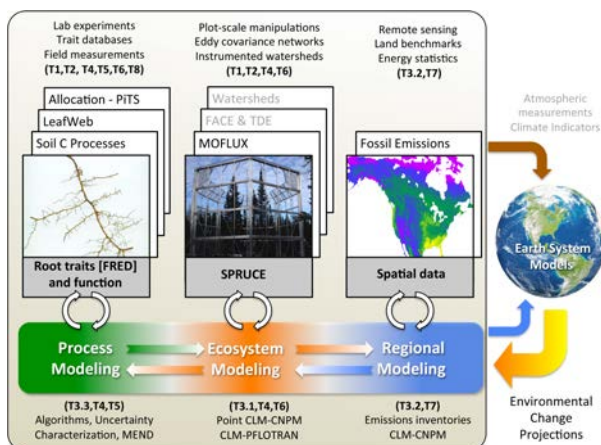
Fig. 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

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_2 levels in a *Picea mariana–Sphagnum* peat bog in northern Minnesota. The experiment provides a platform for testing mechanisms controlling vulnerability of organisms and ecosystem processes to important climate change variables providing data for model development.

The TES SFA also supports smaller-scale, process-level manipulations to quantify 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 changes 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_2 and other greenhouse gases?
3. What are the environmental change-induced shifts in terrestrial hydrologic and ecosystem processes that inform assessment of climate change impacts on ecosystem services and society?

Goals and Milestones

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

Goal 1: Resolve uncertainty in the sign and magnitude of global environment-terrestrial C-Cycle feedbacks under warming and rising CO_2 conditions.
- Long-term milestone: Provide an operational system to analyze C sources and sinks that integrate global C measurements, data assimilation and experimental results to quantify the sign (net uptake or loss of C from terrestrial ecosystems) and more tightly constrain the magnitude of the global climate-terrestrial C-Cycle feedbacks.

Goal 2: Understand and quantify organismal and ecosystem vulnerabilities to the interactive effects of atmospheric and environmental change using new experimental manipulations that employ multi-level warming with appropriate CO_2 exposures and measurements 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).

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.

Goal 4: Incorporate new findings on interannual and seasonal C and water dynamics and episodic and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and ESMs that emphasize the importance of the decadal time scale.

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

Goal 5: Search for 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 DOE's Climate and Environmental Sciences Directorate and is aligned with associated and related activities of the Climate Change Science Institute (CCSI) at ORNL. 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.
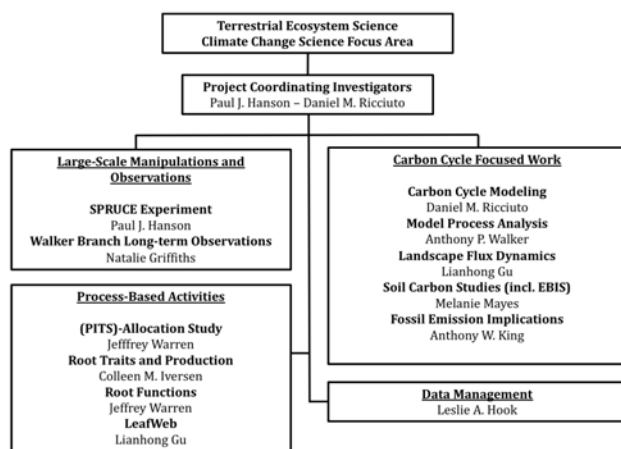
Fig. 2. Organizational chart for the TES SFA effective June 2018.

The TES SFA is supported by 36 dedicated scientific and technical staff at ORNL. Over 70 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, Net Primary Productivity (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 (Northern Arizona University).

Community composition – Community compositional changes are being led by Brian Palik of the USFS with the participation of Rebecca Montgomery (Univ. of Minnesota). 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_2 –Daniel Ricciuto coordinates efforts to utilize and incorporate experimental results into improved modeling frameworks for understanding the peatland C-Cycle and its feedbacks to climate together with Xiaoying Shi and Jiafu Mao.

A coordinating panel is made up of the Response SFA research manager (Hanson), the local USFS contact (Kolka), the Technical Task leaders listed above, and an external SPRUCE advisory committee. 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. This task is essentially complete.

Task 3abc – 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 3d – A newly extracted Multi-Assumption Systems Modeling task is being led by Anthony Walker to develop the Multi-Assumption Architecture Testbed (MAAT) for analyzing model process representations and to apply MAAT to specific TES-SFA science questions.

Task 4a – Jeff Warren led 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. This Task is complete.

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 (University of Missouri) operates the MOFLUX on-site activities. Other contributing staff include Colleen Iversen, Melanie Mayes, Anthony Walker, and Joanne Childs.

Task 7 – Anthony King was responsible for the task on implications of fossil emissions for terrestrial ecosystem science. This task will be discontinued in FY2019.

Task 8 –Lianhong Gu, Anthony Walker and Dali Wang supported LeafWeb in 2018.

The TES SFA benefits from a SPRUCE advisory panel that is dedicated to providing guidance on the science and operation of our flagship experiment. In FY2018 the active membership of the SPRUCE Advisory Panel included: Molly Cavaleri (Michigan Technological University); Caitlin Hicks Pries (Dartmouth); Tim Moore (McGill University); Pat Megonigal (Smithsonian Environmental Research Center) and Ted Schuur (Northern Arizona University).

4. PERFORMANCE MILESTONES AND METRICS

This section represents a summary of TES SFA activities accomplished since our last written document submitted in June 2017. 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 3d: Multi-Assumption Systems Modeling (Goals 2, 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.

4AI. REVIEW OF SCIENTIFIC PROGRESS BY TASK

Task 1: SPRUCE Infrastructure

SPRUCE warming treatments are running full time with limited interruptions other than those associated with scheduled maintenance. Warming treatments are being maintained day and night throughout the year. Elevated CO_2 exposures are applied only during daytime hours during the active growing season (April through November). The table shows the achieved whole-ecosystem warming treatments and elevated CO_2 treatments for the 2017 calendar year (Table 1). Treatment data are archived in Hanson et al. (2016).

Table 1. Mean annual air and soil temperatures and CO2 concentrations by SPRUCE plot for 2017.

Plot #s	Target Temperature Differential	Mean Air Temperature at +2 m	Mean Soil Temperature at -2 m	Ambient Daylight Mean Growing Season [CO2]	Elevated Daylight Mean Growing Season [CO2]
	(Delta °C)	(°C)	(°C)	ppm	ppm
Plots 7 & 21	Ambient	5.6, 5.0	5.9, 6.4	401.7, 401.0	-----
Plots 6 & 19	+0	7.2, 6.8	5.0, 6.5	402.5	874.2
Plots 11 & 20	+2.25	9.5, 9.1	7.5, 7.6	403.2	867.6
Plots 4 & 13	+4.5	11.8, 11.6	9.6, 9.8	407.3	856.7
Plots 8 & 16	+6.75	13.8, 13,7	11.8, 11.8	409.5	892.5
Plots 10 and 17	+9.0	15.8, 15.9	13.9, 13.8	410.9	893.3

In 2017, the unique isotopic signatures of the added CO_2 treatments were in the range of -27 ∂ ‰ for ^{13}C and -520 Δ ‰ for ^{14}C (Fig. 3). Through 2 full active seasons of eCO_2 exposures new tissue growth under eCO_2 continues to show isotopic changes suggesting that the combined current and storage reserves contributing to new tissue development have not yet achieved a new equilibrium (Fig. 4).
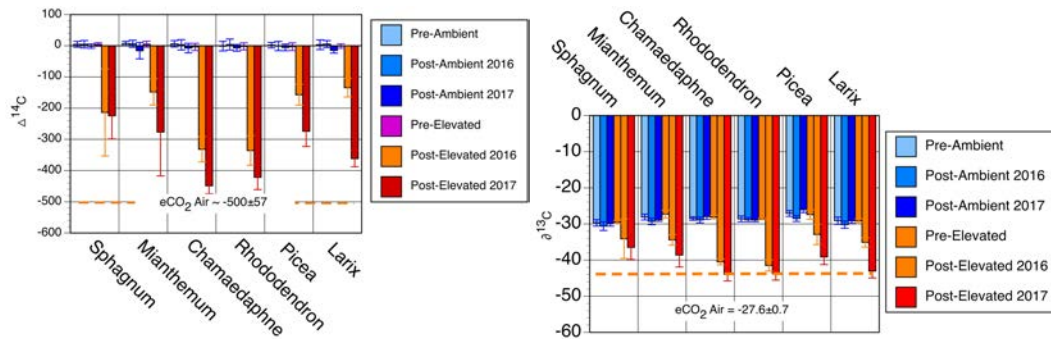
Fig. 3. Isotopic signatures for new aboveground foliar tissue growth across plots and eCO2 treatments.

Task 1: SPRUCE Response Data

Aboveground production for woody vegetation and forbs – After two years of warming, a significant pattern of reduced tree growth is evident (Fig. 4 left graph) driven primarily by changes in *Picea*. Opposite the patterns for trees, the shrub-layer NPP indicated an increasing trend with warming (Fig. 4 right). No apparent growth changes driven by eCO_2 treatments for trees or shrubs have yet developed. Within the shrub layer some species show either increases, decreases or no change with warming.
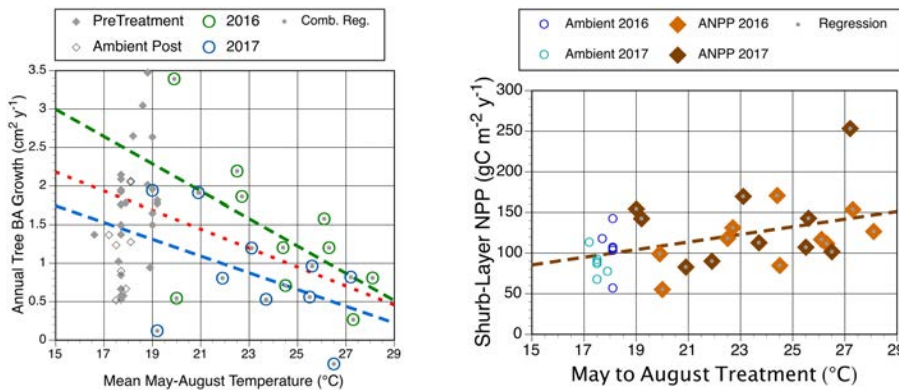
Fig. 4. Combined tree growth for *Picea* and *Larix* (left) and net primary production for non-tree, shrub-layer vegetation (right) in 2016 and 2017 under whole-ecosystem warming.

Phenology – A summary publication of phenology responses of the SPRUCE experiment is being published in *Nature* (Richardson et al. 2018). It documents 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.

Sphagnum production and Nitrogen Content - We measured the growth, community composition, and plot-level NPP of the *Sphagnum* community and documented significant responses to the warming treatments. NPP declined linearly with increasing temperature, amounting to a loss of 10 g C m-2 per degree temperature increase (Fig. 5); there was no effect of elevated CO_2. This important change in the C economy of the bog in the second year of treatment was caused by a negative effect of growth at the higher temperatures and a significant loss of *Sphagnum* cover. *Sphagnum* cover had been close to 100%, but in 2017 the ground area that was no longer covered by live *Sphagnum* increased to 40% in the warmer enclosures. The effect of temperature was manifested primarily through the altered hydrology of the enclosures: there was a significant linear effect of minimum water table elevation on *Sphagnum* NPP.
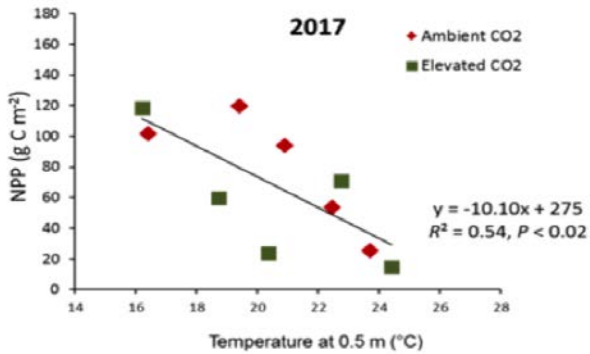
Fig. 5. Production of the *Sphagnum* community in response to warming treatments.

Root ingrowth cores - We used root ingrowth cores to evaluate the fine-root growth response of peatland plants to warming. In addition to response at the ecosystem scale, we also evaluated differences between hummocks and hollows and among plant functional groups. Between 2014 and 2016, warming significantly increased fine-root growth on the ecosystem scale (Fig. 6), but a mixed-effects model including soil moisture and temperature suggested that the increase in root growth was driven by drying rather than warming. Shoulder sampling periods (October to June) had negligible growth before whole-ecosystem warming was initiated. However, starting October 2016, this sampling period shows a significant warming response of fine-root growth. Across all sampling periods, contrary to our
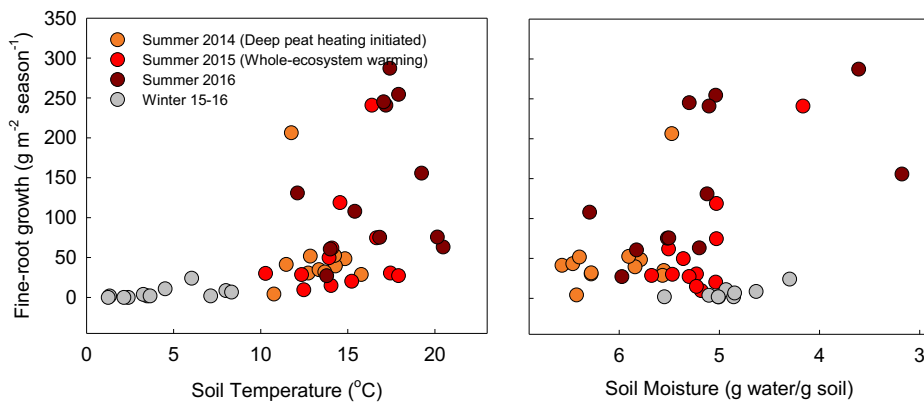
Fig. 6. Fine-root growth response to warming and drying (left to right on the x-axes) on an ecosystem scale (plant type and microtopography have been pooled). A mixed-model with fixed effects: soil moisture, temperature and CO_2 treatment, suggests that drying ($P = 0.0002$) is a stronger driver of fine-root growth than warming ($P = 0.66$). A random effect, season (shown as colors in the graphs), explains 74% of the restricted maximum likelihood variance of our mixed model. Overall model fit R^2 was 0.70 ($n = 40$).

expectation, fine roots growing in hollows had a greater treatment response than hummocks. Furthermore, the hollow response was driven by moisture, while the hummock response was driven by temperature.

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Lastly, as expected, faster-growing shrub and larch fine roots showed a greater treatment response than spruce. Our results suggest that warming will continue to increase fine-root growth until there is a moisture or nutrient limitation, but that this response will differ across microtopographic positions and among species. This response will be especially large in the previously water-saturated hollows that are now aerobic due to drying.

   Plant Available nutrients - We used ion-exchange resins to assess whether a gradient of warming in an ombrotrophic bog increases plant-available nutrients across hummock-hollow microtopography and throughout the peat profile. We compared the response with nutrient concentrations in porewater. Plant-available nutrients were assessed using ion-exchange resin capsules incubated serially beginning in 2013 (data citation: Iversen *et al.*, 2017); collections are on-going. Warming increased resin-available nutrients in the SPRUCE experimental plots. In 2017, after 2 full years of whole-ecosystem warming, the average available NH_4-N was five times greater in surface peat and 20 times greater in deeper peat in the +9 °C treatment compared with the unheated enclosure (Fig. 7). The greater magnitude of the increase below the rooting zone was likely because of increased nutrient uptake by the vegetation or microbes from surface peat layers (i.e., greater competition for nutrients). Additional nutrients taken up by the plant community are detectable as increased nutrient concentrations in *Sphagnum* mosses and vascular plant tissues. Interestingly, the same warming response was not apparent in porewater at a comparable depth increment in the hollows. Thus, ion-exchange resins can be conceptualized as a 'plant root', competing for nutrients with plants and microbes, while porewater represents a pool of residual nutrients that have not been immobilized by plants or microbes. The relative balance of peat carbon storage depends in part on whether vegetation growth increases in response to warming and increased nutrient availability, or whether this response is limited by increased drying.
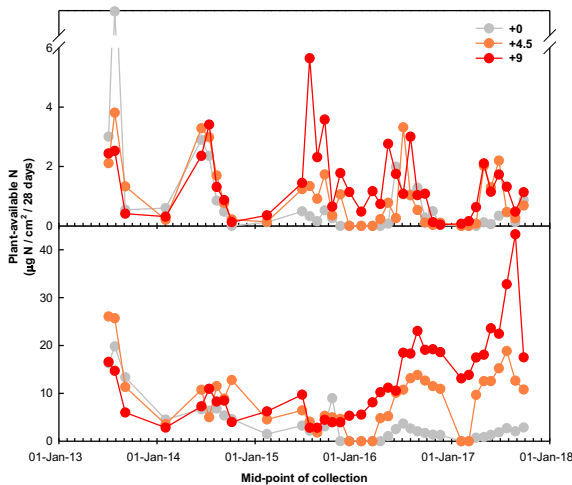
Fig. 7. Changes in the resin-availability of NH_4-N over time from 2013 to 2017 in the hummocks, at a 10-cm depth from the surface of the peat (a) or 60-cm depth from the surface (b). At each depth, each data point is averaged over the two resin arrays in each experimental plot, and also averaged across the two experimental plots per experimental treatment shown (i.e., averaged across ambient and elevated [CO₂]; there is thus far no obvious effect of elevated [CO₂] on nutrient availability.).

   Woody Plant Physiology – In FY17-18 we continued our long-term automated measurements of sap flow and stem diameter in trees and soil water content within the hummock hollow complex in the 12 SPRUCE measurement plots. The sap flow measurements, in particular and complementary gas exchange and water potential data have indicated significant, species specific increases in water use by the trees, with no apparent temperature or CO_2 treatment effect on black spruce water use, but significant increases in tamarack water use with temperature (Fig. 8). The spruce strategy is conservative, maintaining hydraulic safety at the expense of C uptake, even as C losses through temperature dependent respiration increase. In contrast, the larch increased C uptake yet push the bounds of hydraulic safety. Future work will assess the trade-offs between growth and defense, and consequences of each strategy. The sap flow system has also indicated a strong temperature effect (but not CO_2) on spring phenology by increasing initiation of sap flow by 1-3+ days per degree and extending sap flow into the fall by ~1 day per degree (larch) or up to 3+ days per degree for spruce, depending on timing of the first hard freeze event. Results complement and support the PhenoCam image-based analysis. The sap flow systems have been installed for several years now with significant loss of performance and sensor failures. In FY19, we will perform a

full reassessment and reinstallation of the sapflow system, including deployment to additional trees to maximize our future ability to track and measure this critical response.
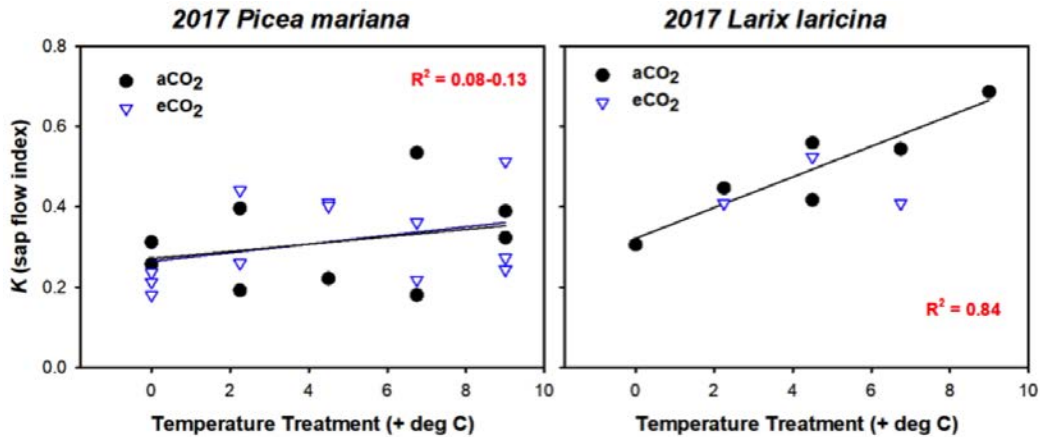

Fig. 8. Differential tree water use in response to temperature, but not CO_2 at the SPRUCE site illustrates different hydraulic strategies by spruce and larch. The spruce reduced stomatal aperture, maintained safe leaf water potentials above the turgor loss point and maintained stable water use. In contrast, the larch kept stomata open, increased water stress beyond the turgor loss point, and increased water use.

Foliar gas exchange (photosynthesis and respiration) and its response to temperature and CO_2 was also a major focus of FY17. We conducted two intensive, 2-week long field/lab campaigns in June and August 2017 in collaboration with our physiology PhD student's lab at Western Ontario University, staff, post-docs and PhD students at University of Minnesota, and our ORNL ecophysiology team of staff, modelers, post-docs, technicians and interns. The goals were to assess thermal or CO_2 acclimation of key photosynthetic and respiratory parameters that are essential to process-based modeling. This work included collecting clippings from each of the four primary woody species, *Picea, Larix*, Rhododendron and *Chamaedaphne* at dawn from each chambered plot, recutting underwater, transporting to the growth-chamber facilities at the University of Minnesota for gas exchange assessments, then repeating the next day. The campaign involved more than 15 people, 13 gas exchange machines, 6-8 growth chambers and, somewhat regrettably, thousands of miles of driving. Yet it yielded 1000+ photosynthesis- CO_2 temperature response (A-Ci) and foliar (dark) respiration temperature response curves ranging from ~10 to 45+ °C. Data are still being organized and analyzed, then we will leverage LeafWeb to generate the required *Vcmax* and *Jmax* photosynthetic parameters.

In addition to the FY17 foliar respiration temperature response curves, in spring FY18, we collected some initial stem respiration temperature response curve data for the four primary woody species using a custom gas exchange chamber (0-60 °C). Those results indicated that woody respiration increases up to 55 °C but fails between 55-60 °C. Additional work with woody respiration in stems and roots (outside plots initially) is planned for summer FY18. Data from the foliar, stem and root respiration results will be used to explore theoretical and novel respiratory-temperature response equation frameworks that will be later incorporated into the Earth Land Model (ELM).

Foliar and branch tip morphological and anatomical responses have also been a major focus. In response to the drier and warmer conditions we expected shifts in canopy structure and leaf area as new tissue developed under treatment conditions. In summer 2017, we assessed morphological characteristics of the four primary woody species using destructive samples collected during the intensive physiology campaigns. Traits studied include stem length and diameter, number and length of primary and secondary branches, leaf size and mass per area, the projected branch silhouette: projected area of individual leaves (silhouette to projected leaf area ratio, SPAR) and leaf nitrogen and carbohydrate content. Among *C. calyculata* samples, leaf mass per area (LMA) and chlorophyll increased with temperature. *L. laricina* showed a negative correlation between LMA or SPAR and temperature, but only in the ambient CO_2 chambers. New *P. mariana* shoot growth displayed SPAR values that increased with temperature, and

LMA values that decreased with temperature. Anatomical stem xylem analysis is ongoing that will reveal potential changes in theoretical hydraulic conductivity and resistance to cavitation, as well as to direct new more involved stem hydraulic experiments. Results will be used as possible to test and improve foliar, shoot or hydraulic traits acclimation in the model.

Plant- Soil Water Dynamics - We have 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. Building on initial results that indicated differential species-specific water stress, we plan to collect some comprehensive diurnal patterns of foliar water potential in July. These samples will be subsequently assessed for non-structural carbohydrates and foliar N content to further explore the ecophysiological implications of the treatments, and the balance between hydraulic stress and carbon uptake. The sap flow system has proven very useful for assessing diurnal patterns of water stress and midday stomatal depression, but the sensors have now been installed for several years, pushing their lifespan. As such, in late summer 2018, we will assess 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 2020.

Due to poor soil moisture sensor performance and from extensive discussion at the SPRUCE meetings, we have developed a comprehensive new plan to improve our measurements of soil water content vertically through the profile from the top of the *Sphagnum* to the catotelm. This is a MODEX effort that will use existing as well as new or improved measurements, and more detailed modeling. In June 2018 the soil moisture sensors were removed, inserted into porous measurement vessels full of peat with a standardized bulk density and reinserted into the hummocks or hollows. We expect the peat within the core to come to equilibrium with the surrounding hummock, thus giving a better measure of soil water that is comparable across plots. In addition, we expect that during drying cycles, the uniform bulk density around each sensor will allow sensor response that reflects treatment. New surface wetness sensors are also being tested to assess potential quantification of dew, throughfall or *Sphagnum* surface moisture. Some limited destructive samples of soil moisture will be collected. Using these various new measurements, water table depth, to be collected LIDAR data, and older published soil hydraulic parameter data, we plan to validate and improve the ELM-SPRUCE modeled soil moisture content through the profile. This will provide a much-needed co-variate for response variable measurements across the disciplines.

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). Continued study of experimental warming plots is however necessary to assess if the deep peat carbon bank is susceptible to increased temperatures over the decadal course of the SPRUCE field-based experiment and what processes may limit microbial responses in these systems. Since 2014 we have been conducting annual sampling and characterization of peat microbial communities to facilitate this. QPCR (to measure overall population sizes of bacteria, fungi and archaea) and rRNA gene sequence-based analyses (to measure community composition changes) are conducted on samples from all experimental plots as well as ambient controls at 11 depth increments (132 total samples). Additionally, metagenomic data are collected 4 depth increments and sequenced in collaboration with JGI. These data are made available upon completion of initial assembly and QC (Kluber et al 2016a, 2018) along with other environmental data on the peat samples (Kluber et al. 2016b, Gutknecht et al. 2017). To date, the metagenomics based effort alone has resulted in over 8.31E+10 base pairs of DNA sequence information.
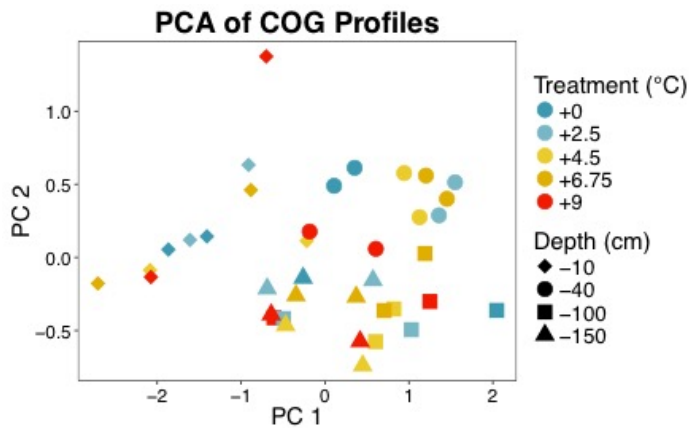
Fig. 9. Principal coordinate analysis of the abundance of functional gene types (COG-based gene classes) from SPRUCE metagenome sequencing shows strong grouping by depth, but not temperature after one year of belowground warming.

Results from the 2015 Deep Peat Heating (DPH) phase show that similar to rRNA gene and QPCR examinations, the metagenomes show striking changes in phylogenetic and functional composition with depth, however responses to treatments were not yet evident (Figure 9). Analyses of the remaining year metagenomes is ongoing and will be the primary task of a new postdoctoral associate arriving in July 2018.

Hydrology and Water Chemistry – After two years of whole-ecosystem warming, lateral water fluxes (i.e., stream flow) decreased with warming likely due to increased evapotranspiration (Fig. 10). Solute concentrations in outflow were variable across treatments, but there was a general pattern of higher total organic carbon (TOC) and cation (i.e., calcium, potassium, sodium) concentrations in outflow from the warmer plots likely due to increased mineralization and leaching of recently produced organic matter. Despite the higher TOC concentrations in outflow from warmer enclosures, TOC fluxes were lower because of lateral water flow is the predominant driver of TOC fluxes. A manuscript describing the performance of the subsurface corral and lateral outflow system is in progress with submission planned for August 2018.
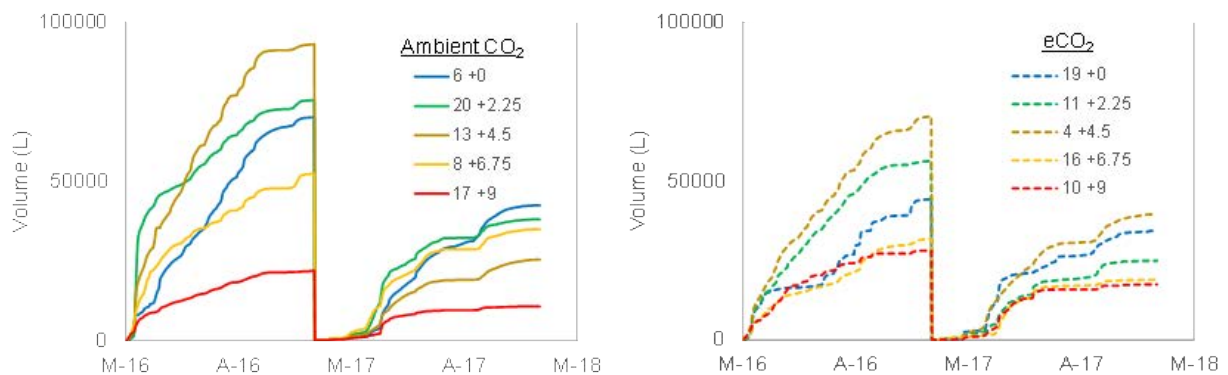
Fig. 10. Cumulative lateral outflow (i.e., stream flow) from SPRUCE enclosures and responses to warming over two years (2016, 2017). Lateral outflow was lower with warming likely due to increased evapotranspiration. There was no clear effect of elevated CO_2. Outflow from enclosures in 2016 was complicated by residual effects of installation and leaks (plots 8, 13, & 20). Leaks were fixed in summer 2016.

Porewater – Total organic carbon (TOC) and cation concentrations increased in shallow porewater (0-10 cm, 30-40 cm depths) with warming, consistent with the observations in outflow (described above). No changes in chemistry were observed in deeper porewater (50 cm depth and below). Further, nutrient concentrations (i.e., nitrate, ammonium, soluble reactive phosphorus) have not changed in shallow or deeper porewater with warming. As described above, increased TOC concentrations may reflect increased mineralization in response to warming. However, we hypothesize that a similar increase in nutrient

concentrations was not observed because any mineralized nutrients were rapidly taken up by biota in this nutrient-limited ecosystem.

Analyses of porewater warming responses are ongoing, and a manuscript detailing pre-treatment variation in porewater is being drafted. This manuscript is describing variation in porewater chemistry among peatlands (bogs to fens) in the Marcell Experimental Forest and is in progress with submission planned for December 2018.

Decomposition - Multiple decomposition studies are being conducted at SPRUCE. To date, we have measured mass loss on litterbags retrieved after being deployed in the enclosures for 1 year and are currently processing litterbags collected after 2 years (retrieved October 2017).

In the main experiment examining the decomposition of 6 common litter types (i.e., spruce needles, shrub leaves, fine roots, *Sphagnum*), we found no clear effect of warming on the decomposition of aboveground litter types after 1 year. However, decomposition rates of fine roots (both spruce and Labrador tea fine roots) increased with warming after 1 year. There may be several explanations for the differences in above vs belowground litter decomposition, including differences in chemistry, biology (i.e., different decomposers), and methodology (i.e., different mesh sizes, deployment depths).

A second decomposition experiment with mixed species bags found that after 1 year, spruce needles and Labrador tea leaves broke down at a faster rate when mixed with *Sphagnum* and slower when mixed with polyester (a control used to represent the structure of *Sphagnum* but without the chemistry). This finding is opposite our hypothesis of a slower breakdown rate due to the known inhibitory effect of *Sphagnum* (and its chemistry) on decomposition rates. Preliminary analyses suggest that the faster decomposition may be due to differences in the ability of *Sphagnum* vs. polyester to hold moisture. Given that mixed species bags were deployed only in hummocks, this suggests that water is limiting decomposition in these environments.

The third experiment revealed that labile C decomposition (cotton strips = 99% cellulose) increased with temperature, but there was no clear pattern with depth. Given that labile C decomposition responded to warming, but aboveground litter types did not, this suggests that litter chemistry may be limiting decomposition more so than temperature at least in the initial stages of litter breakdown (i.e., first year).

Lastly, a study was initiated in October 2017 to measure the decomposition of peat at different depths (0-10, 10-20, 20-30, and 30-40 cm) in the SPRUCE enclosures using decomposition ladders. Analysis of the peat decomposition samples is led by the USFS.

Net CO_2/CH_4 efflux – After two full growing seasons under experimental warming and elevated CO_2 responses we have observed limited effects of eCO_2, and differential responses to the flux of CO_2 and CH_4. CO_2 efflux appears to increase with warming with a slight "acclimation" for higher temperature treatments (perhaps a drying effect). CH_4 Fluxes also increase with warming and may be enhanced for the higher temperature treatments. When you combine these treatment trends with *in situ* temperatures throughout an annual cycle we estimate that the +9 °C treatments show a 19 and 194 % increase in flux for CO_2 and CH_4, respectively (Fig. 11).
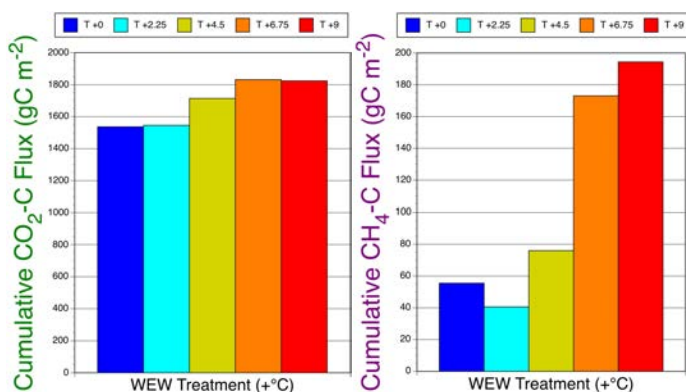
Fig. 11. Estimated annual CO_2 (left) and CH_4 (right) flux for the SPRUCE study site for 2017.

Carbon Cycle Assessments for the S1-Bog – Data from vegetation NPP assessments and large collar flux data were combined to produce initial estimates of the response of the SPRUCE peatland to the temperature treatments (Fig. 12).
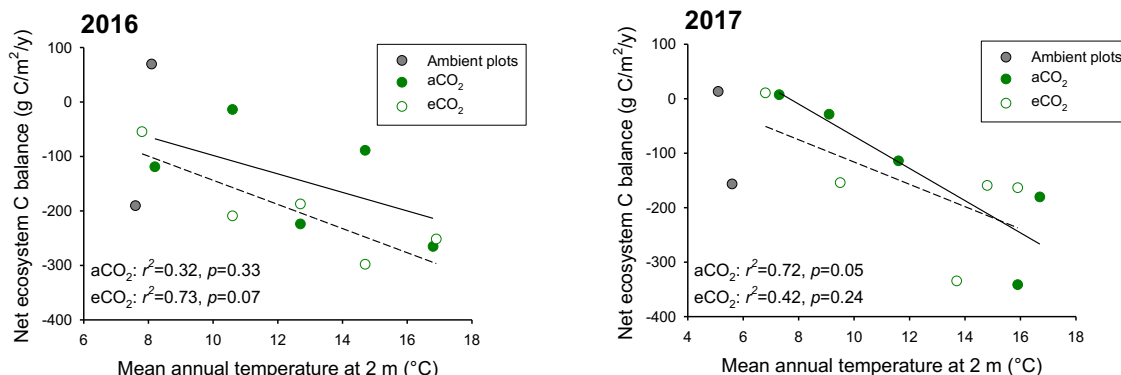
Fig. 12. Change in peatland C balance for 2016 and 2017 as a function of treatment temperatures.

The bog appears to be an increasing C source with warming, with the effect being stronger in 2017 than in 2016. No clear effect of elevated CO_2 is yet evident. Slopes vary somewhat across CO_2 treatments and years, but when all data are combined we estimate C loss per °C of warming to be 20 g C m^{-2} y^{-1}. Bog elevation data assessments confirm a pattern of C loss with warming (data not shown).

Within-Enclosure Integrated Eddy Covariance and Sun-Induced Chlorophyll Fluorescence (SPIECS) Studies – The objectives of SPIECS are to 1) understand processes controlling gross primary production, ecosystem respiration, CH_4 emissions, evaporation, transpiration, and sensible heat fluxes as well as relationships among them in wetland ecosystems, 2) provide continuous ecosystem-level datasets to validate and improve wetland ecosystem models, and 3) to scale SPRUCE science beyond the S1-Bog. To achieve these objectives, a permanent shrub-level outside-enclosure eddy covariance (EC) system was installed in Ring 2, August 2015. We have also developed a roving integrated EC/Sun-Induced Chlorophyll Fluorescence System (SIF) system.
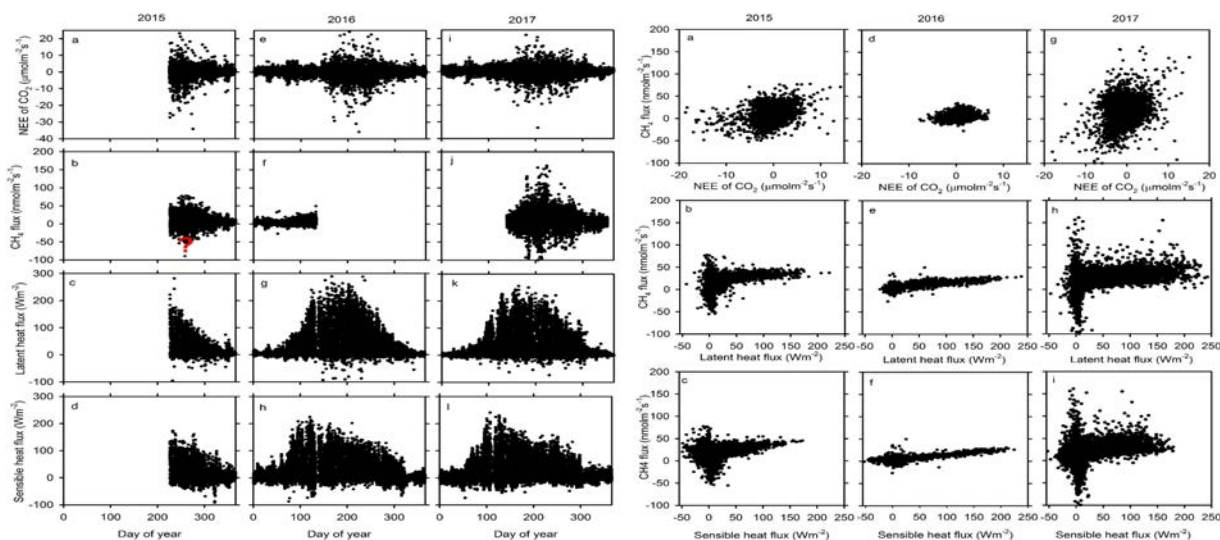
Fig. 13. LEFT: Seasonal dynamics in the eddy covariance fluxes of carbon dioxide, methane, latent heat and sensible heat observed in Ring 2. RIGHT: Correlation of methane fluxes with fluxes of carbon dioxide, latent heat and sensible heat in different years as observed by the EC system in Ring 2.

The integrated EC/SIF system is scheduled for its first installation inside a SPRUCE enclosure in July 2018 and will be rotated in different SPRUCE enclosures periodically and also potentially to nearby wetlands in the following years. Analysis of EC data obtained by the shrub-level EC system results in the following findings (Fig. 13): there are clear seasonal and diurnal variations in CH_4 fluxes which are strongly correlated with sensible and latent fluxes, and strong net uptake of CH_4 is observed when sensible heat and latent heat fluxes are weak. These two findings suggest mechanisms for CH_4 emission and consumption in wetlands. Correlations between CO_2 and CH_4 fluxes are weak or non-existent.

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
FY 2017 Deliverables		
Aug 2017	Submission of baseline SPRUCE water relations manuscript. Submit sap flow and water potential data to TES SFA data archive.	Paper in progress for 2018
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.	Paper under internal revision for new submission
Sept 2017	Submission of SPRUCE manuscript describing initial response of photosynthesis and respiration of *Picea mariana* and *Larix laricina* under whole ecosystem warming and elevated [CO_2], and TES SFA data archive.	Paper in progress for 2018
FY 2018 Deliverables		
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 *Chamaedaphne calyculata* and *Rhododendron groenlandicum* under whole ecosystem warming and elevated [CO_2], and TES SFA data archive.	Paper in progress for 2018
Summer 2018	Complete draft manuscript on the moss decomposition study.	Litterbag retrieval in 2018. Manuscript in 2019.
Sep 2017	Draft manuscript comparing porewater chemistry across peatlands (S1 bog, S2-bog, Bog Lake Fen).	Paper is in progress for 2018.
FY 2019 Deliverables		
Feb 2019	Manuscript on nutrient availability responses to warming	Planned
March 2019	Manuscript on tree and shrub-level Growth.	Planned
Oct 2019	Manuscript on root-fungal interactions using AMR technology.	Planned
Oct 2019	Dataset of initial morphological responses to SPRUCE treatments in the four main woody plant species.	Underway
Dec 2019	Dataset and Leafweb analysis of photosynthetic and respiration x temperature response curves from intensive 2017 campaign.	Underway
Dec 2019	Manuscript on stream flow responses to warming, Planned.	Planned
May 2020	Submission of SPRUCE manuscript describing initial morphological and xylem anatomical responses to treatments.	Planned

Task 1 SPRUCE Publications

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. *Soil Science Society of America Journal* 81:1668-1688, doi:10.2136/sssaj2016.12.0422.

Gill AL, Giasson M-A, Yu R, Finzi AC (2017) Deep peat warming increases surface methane and carbon dioxide emissions in a black spruce-dominated ombrotrophic bog. *Global Change Biology* 23:5398–5411, DOI: https://doi.org/10.1111/gcb.13806

Haynes KM, Kane ES, Potvin L, Lilleskov EA, Kolka RK, Mitchell CPJ (2017) Gaseous mercury fluxes in peatlands and the potential influence of climate change. *Atmospheric Environment* 154:247-259.

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* 14:2481-2494, doi:10.5194/bg-14-2481-2017.

Huang Y, Jiang J, Ma S, Ricciuto DM, 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 – Biogeosciences* 122: 2046-2063, doi:10.1002/2016JG003725.

Iversen CM, Childs C, Norby RJ, Ontl TA, Kolka RK, Brice DJ, McFarlane KJ, Hanson PJ (2018) Fine-root growth in a forested bog is seasonally dynamic, but shallowly distributed in a nutrient-poor peat. *Plant and Soil* 424:123-143, doi:10.1007s11104-017-3231-z.

Jiang J, Huang Y, Ma S, Stacy M, Shi Z, Ricciuto DM, Hanson PJ, Luo Y (2018) Forecasting responses of a northern peatland carbon cycle to elevated CO2 and a gradient of experimental warming. *Journal of Geophysical Research – Biogeosciences* 123:1057-1071, https://doi.org/10.1002/2017JG004040.

Ma S, Jiang J, Huang Y, Shi Z, Wilson RM, Ricciuto D, Hanson PJ, Luo Y (2017) Data-constrained projections of methane fluxes in a northern Minnesota peatland in response to elevated CO2 and warming. *Journal of Geophysical Research – Biogeosciences* 122:2841-2861, doi: 10.1002/2017JG003932.

McFarlane KJ, Hanson PJ, Iversen CM, Phillips JR, Brice DJ (2018) Local spatial heterogeneity of Holocene carbon accumulation throughout the peat profile of an ombrotrophic Northern Minnesota bog. *Radiocarbon* 60:941-962, doi:10.1017/RDC.2018.37.

Richardson AD, Hufkens K, Milliman T, Aubrecht DM, Furze ME, Seyednasrollah B, Krassovski MB, Latimer JM, Nettles WR, Heiderman RR, Warren JM, Hanson PJ (2017) Ecosystem warming extends vegetation activity but heightens cold temperature vulnerability. *Nature* (in press).

Smith RJ, Nelson PR, Jovan S, Hanson PJ, McCune B (2018) Novel climates reverse carbon uptake of atmospherically-dependent epiphytes: climatic constraints on the iconic boreal forest lichen Evernia mesomorpha. *American Journal of Botany* 105:266-274, doi: 10.1002/ajb2.1022.

Steinweg JM, Kostka JE, Hanson PJ, Schadt CW (2018) Temperature sensitivity of extracellular enzymes differs with peat depth but not with season in an ombrotrophic bog. *Soil Biology and Biochemistry* (accepted).

Tfaily MM, Wilson RM, Cooper WT, Kostka JE, Hanson P, Chanton JP (2018) Vertical stratification of peat pore water dissolved organic matter composition in a peat bog in Northern Minnesota. *Journal of Geophysical Research – Biogeosciences* 123:479-494. https://doi.org/10.1002/2017JG004007, **Highlighted by EOS in May 2018.**

Warren MJ, Lin X, Gaby JC, Kretz CB, Kolton M, Morton PL, Pett-Ridge J, Weston D.J., Schadt CW, Kostka JE et al. 2017. Molybdenum-Based Diazotrophy in a *Sphagnum* Peatland in Northern Minnesota. [collaborator contribution]. *Applied and Environmental Microbiology* 83:e01174-17.

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 (2017) Hydrogenation of organic matter as a terminal electron sink sustains high CO_2:CH_4 production ratios during anaerobic decomposition. *Organic Geochemistry* 112:22-32, doi: 10.1016/j.orggeochem.2017.06.011.

Walker AP, Carter KR, Gu L, Hanson PJ, Malhotra A, Norby RJ, Sebestyen SD, Wullschleger SD, Weston DJ (2017) Biophysical drivers of seasonal variability in *Sphagnum* gross primary

production in a northern temperate bog. *Journal of Geophysical Research - Biogeosciences* 122:1078-1097, doi:10.1002/2016JG003711.

Zalman CA, Meade N, Chanton JP, Kostka JE, Bridgham SD, Keller JK (2018) Methylotrophic methanogenesis in *Sphagnum* -dominated peatland soils. *Soil Biology and Biochemistry* 118:156-160.

Task 1 Data Sets

Fourteen 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)

Work on the Walker Branch Watershed task is limited to finalizing publications from previous field and laboratory experiments. A study that examined coupled biogeochemical cycling (N and P) using a novel dual nutrient addition approach in the headwaters of Walker Branch Watershed is currently in revision:

Griffiths NA, Johnson LT (2018) Influence of dual nitrogen and phosphorus additions on nutrient uptake and saturation kinetics in a forested headwater stream. *Freshwater Science* (being revised).

Two papers that synthesized patterns in N cycling in streams across the globe, including data from Walker Branch Watershed, were published in the past year:

Norman BC, Whiles MR, Collins SM, Flecker AS, Hamilton SK, Johnson SL, Rosi EJ, Ashkenas LR, Bowden WB, Crenshaw CL, Crowl T, Dodds WK, Hall RO Jr., El-Sabaawi R, Griffiths NA, Martí E, McDowell WH, Peterson SD, Rantala HM, Riis T, Simon KS, Tank JL, Thomas SA, von Schiller D, Webster JR (2017) Drivers of nitrogen transfer in stream food webs across continents. *Ecology* 98:3044-3055.

Tank JL, Martí E, Riis T, von Schiller D, Reisinger AJ, Dodds WK, Whiles MR, Ashkenas LR, Bowden WB, Collins SM, Crenshaw CL, Crowl TA, Griffiths NA, Grimm NB, Hamilton SK, Johnson SL, McDowell WH, Norman BM, Rosi EJ, Simon KS, Thomas SA, Webster JR (2018) Partitioning assimilatory nitrogen uptake in streams: an analysis of stable isotope tracer additions across continents. *Ecological Monographs* 88:120-138.

Task 3abc: Mechanistic Carbon Cycle modeling

This task incorporates model development and MODEX activities at the point scales (task 3a), regional to global scales (task 3b), and at the level of mechanistic functional units (task 3c) to identify process contributions to the global climate C cycle forcing from terrestrial ecosystems. Development on the Multi-Assumption Architecture and Testbed has branched off to a higher level subtask (task 3b; see below). Brief summaries of progress are presented along with tabular summaries of progress on proposed deliverables.

Task 3a – Improving ecosystem models with site-level observations and experiments

<u>SPRUCE modeling -</u> In April 2018, E3SM version 1 (including the land model ELM) was released to the public. ELMv1 contains developments initiated or co-funded by the ORNL TES SFA, including carbon and nutrient storage (Metcalfe et al., 2017) and phosphorus cycling (Yang et al., 2017). We have created a SPRUCE-specific branch of ELMv1 (ELMv1-SPRUCE), which includes the representation of hummock-hollow microtopography and *Sphagnum* plant functional type. This model has more realistic nutrient cycling but does not yet include the Microbe model developed by subcontractor Xiaofeng Xu (San Diego State University). Porting Microbe to ELMv1 is a difficult technical challenge which we expect to resolve using the PFLOTRAN framework in 2019. We are continuing to maintain the previous version ELMv0-SPRUCE (formerly known as ALM-SPRUCE) for the purposes of predicting methane cycling and for comparison with v1. The *Sphagnum* photosynthesis submodel has been successfully implemented in ELMv1-SPRUCE and a publication is in preparation. This submodel predicts the reduction of moss net primary productivity with warming similar to what is currently being observed. Following the high-profile publication by Richardson et al. (in press), we are developing an improved phenology submodel for SPRUCE which we expect to be relevant for other ecosystems. ELM-SPRUCE

improvements, along with other wetland modeling tasks, are on the ACME version 2 roadmap for integration in 2018 and 2019 with joint TES SFA and E3SM support. EcoPAD, an ecological forecasting framework for the SPRUCE site has been completed using the terrestrial Ecosystem (TECO) model (University of Northern Arizona). EcoPAD has been demonstrated in three publications (Ma et al., 2017, Jiang et al., 2018, Huang et al., 2017), and was successfully integrated with the SPRUCE Vista Data Vision software to provide continuously updated hind casts of selected variables (http://sprucedata.ornl.gov/). In January 2018, we contributed results from ELM-SPRUCE to workshops on hydrology and nutrient cycling, which helped to identify specific measurement and model shortcomings that are being addressed this year. Following guidance from the SPRUCE advisory panel, we are organizing a MODEX workshop and SPRUCE model intercomparison workshop in the fall of 2018.
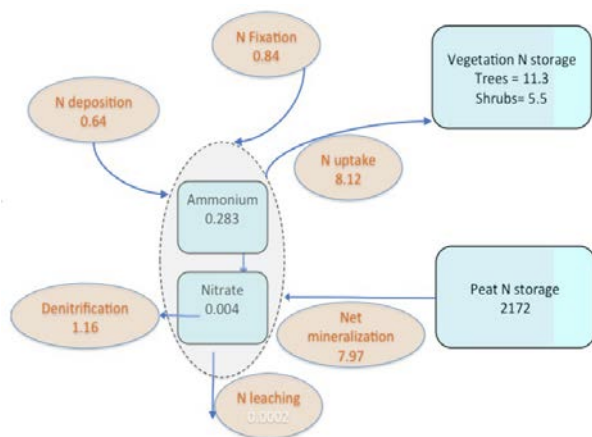
Fig. 14. Pre-treatment nitrogen budget as simulated by ELMv1-SPRUCE (yellow: fluxes in gN m^{-2} yr^{-1}; blue: pools in gN/m^2). At a nutrient cycling workshop held in January 2018, we compared the model and observed budgets and used this to prioritize model development tasks – e.g. the need for a better representation of organic N leaching, long-term peat accumulation, denitrification and N fixation

Modeling at other sites - Beyond SPRUCE, we are also using the point version of ELM (version 1) at MoFlux and additional AmeriFlux sites relevant for the TES SFA. We are currently developing a site-level benchmarking package focused on model-data comparison with AmeriFlux data, which will complement the International Land Model Benchmarking Project (ILAMB) package and serve as a useful tool for SFA model development tasks. These model development tasks at SPRUCE to improve model physiology, nutrient cycling, phenology, and root function are being evaluated across sites covering a wide range of environmental conditions using this framework. An uncertainty quantification (UQ) framework jointly developed by E3SM and the ORNL TES SFA provides critical information about model parameter sensitivity (Ricciuto et al., 2018), and can be used to improve model performance through calibration of model parameters with observations. Lu et al. (2018) demonstrated that calibrating ELM using a surrogate modeling approach combined with a parameter optimization method significantly improves predictions of leaf area index (LAI) and carbon fluxes at the Missouri Flux eddy covariance site (Fig. 15).
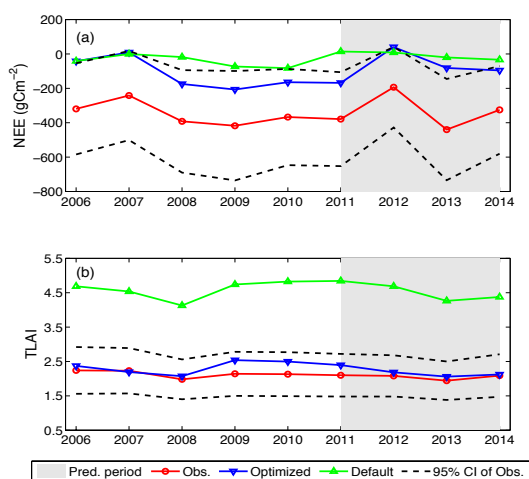
Fig. 15. 3000 ELM simulations were performed, randomly varying 8 sensitive model parameters. These simulations were used to build a surrogate model of net ecosystem exchange (NEE) and leaf area index (TLAI) at the Missouri Ozark Flux site. This surrogate model was then calibrated using an efficient global optimization algorithm, and the optimized parameters were fed into ELM to perform new simulations. The optimized version of ELM performs much better than the default, especially for TLAI. For NEE, the interannual variability is represented better, although a significant bias remains. This is an indication that model structure (i.e., missing or incorrect process representation), rather than parametric uncertainty drives model error.

Task 3a Deliverable status

2018	- Document ecological forecasting system	*Complete*
	- Deliver model to E3SM	*In progress*

Task 3b - Regional and global land ecosystem modeling

Contribution of environmental forcings to US runoff changes for the period 1950-2010 - Runoff in the United States is changing, and this study finds that the measured change is dependent on the geographic region and varies seasonally. Specifically, observed annual total runoff had an insignificant increasing trend in the US between 1950 and 2010, but this insignificance is due to regional heterogeneity with both significant and insignificant increases in the eastern, northern, and southern US, and a greater significant decrease in the western US. Trends for seasonal mean runoff also differs across regions. By region, the season with the largest observed trend is autumn for the east (positive), spring for the north (positive), winter for the south (positive), winter for the west (negative), and autumn for the US as a whole (positive). Based on the detection and attribution analysis (Fig. 16) using gridded WaterWatch runoff observations along with semi-factorial land surface model simulations from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP), we find that while the roles of CO_2 concentration, nitrogen deposition, and land use and land cover appear inconsistent regionally and seasonally, the effect of climatic variations is detected for all regions and seasons, and the change in runoff can be attributed to climate change in summer and autumn in the south and in autumn in the west. We also find that the climate-only and historical transient simulations consistently underestimated the runoff trends, possibly due to precipitation bias in the MsTMIP driver or within the models themselves. This work was mainly supported by the TES SFA project and recently published in *Environmental Research Letters* (Forbes et al., 2018).
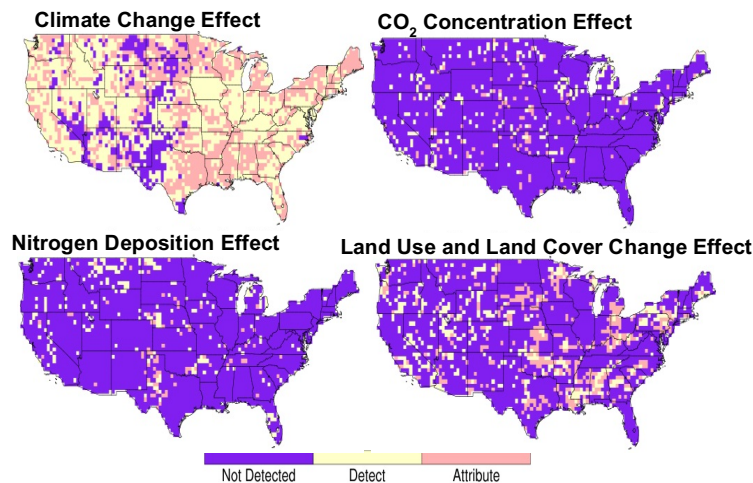
Fig. 16. Spatial patterns of D&A scaling factors. Not detected (purple) denotes a scaling factor whose corresponding 95% confidence interval was less than zero or included zero. If the 95% confidence interval was greater than zero but did not include one, the forcing was detected (yellow). A positive confidence interval was labeled as attributed (pink) if it included one.

Modeling tree stem-water dynamics - A novel tree stem-water model was developed to capture the dynamics of stem-water storage and its contribution to daily transpiration. The module was incorporated into the Community Land Model (CLM), where it was used to test model sensitivity to stem-water content for an evergreen rainforest site in Amazonia, i.e., the BR-Sa3 eddy covariance site. With the inclusion of the stem-water storage, CLM produced greater dry-season latent heat flux that was closer to observations, facilitated by easier canopy access to a nearby stem-water source, rather than solely dependent on soil water (Fig. 17). The simulated stem-water content also showed seasonal variations in magnitude, along with the seasonal variations in sap flow rate. Stored stem water of a single mature tree was estimated to contribute 20-80 kg/day of water to transpiration during the wet season and 90-110 kg/day during the dry season, thereby partially replacing soil water and maintaining plant transpiration during the dry season. Diurnally, stem-water content declined as water was extracted for transpiration in

the morning and then was refilled from soil water beginning in the afternoon and through the night. The dynamic discharge and recharge of stem storage was also shown to be regulated by multiple environmental drivers. Our study indicates that the inclusion of stem capacitance in CLM significantly improves model simulations of dry-season water and heat fluxes, in terms of both magnitude and timing. This work was partially supported by the TES SFA project and recently submitted to *Agricultural and Forest Meteorology* (Yan et al., 2018).
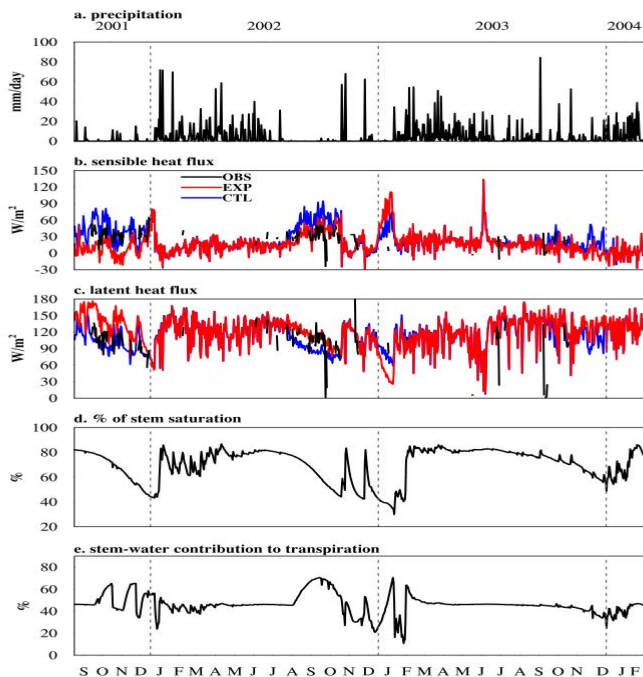
Fig. 17. Daily averaged model simulations and observations at the BR-Sa3 site during September 2001 to February 2004: (a) observed precipitation (mm); (b) a comparison of sensible heat flux among model simulations with stem-water storage (EXP) and one without (CTL), and observations; (c) the same as (b) but for latent heat flux; (d) the percentage of stem saturation; and (e) stem-water-contribution to transpiration.

Task 3b Deliverable status

2018	- Finish global optimization framework with GPP reanalysis time series	Underway
	- D&A of global GPP	Underway

Task 3c – Functional testing

Sensitivity analysis of ELM-SPRUCE consistently demonstrates that photosynthesis and autotrophic respiration parameter uncertainty dominates uncertainty in the treatment response of NEE (Griffiths et al., 2017). Using our functional testing framework, we continue to explore the functional representation of photosynthesis and dark respiration (R_d) in ELM. The functional unit testing of the temperature response of black spruce foliar dark respiration was expanded to include alternative temperature functions and is being integrated with observations from SPRUCE physiology field campaigns using parameter calibration techniques. Results show that non-exponential formulations better represent the SPRUCE pre-treatment observations. These functions are currently being implemented in the full version of ELM-SPRUCE to investigate the impact of functional uncertainty on carbon and nutrient cycling.

The functional testing framework is being used to evaluate the ELM decomposition submodel using long-term intersite decomposition experiment team (LIDET) data at 20 sites. The LIDET experiments are better suited to modeling as a functional unit, in which the environmental data is fed into the decomposition model directory, because performing the experiment in the full ELM introduces unrealistic nutrient and phenology feedbacks due to a misrepresentation of the scale of the experiment. Performing the LIDET experiment in the functional unit gives results that are more consistent with observed behavior (Fig. 18). A similar litter decomposition experiment is underway at SPRUCE, and we intend to use this framework to improve the decomposition model in peat environments.

In conjunction with the Optimization of Sensor networks for Climate Models (OSCM), we have extended a python-based functional testing framework to include the carbon cycle submodel of ELM (including phenology, growth, allocation and mortality). Using this simplified ELM (sELM), we can perform uncertainty quantification and model calibration much more efficiently. sELM is being used as a testbed for rapid model development of phenology and allocation algorithms, which can then be integrated and tested in the full ELM. We are also exploring machine learning and artificial intelligence (AI) approaches to build surrogate models of functional units, which may substantially improve model performance and allow scaling of ELM to pre-exascale architectures.
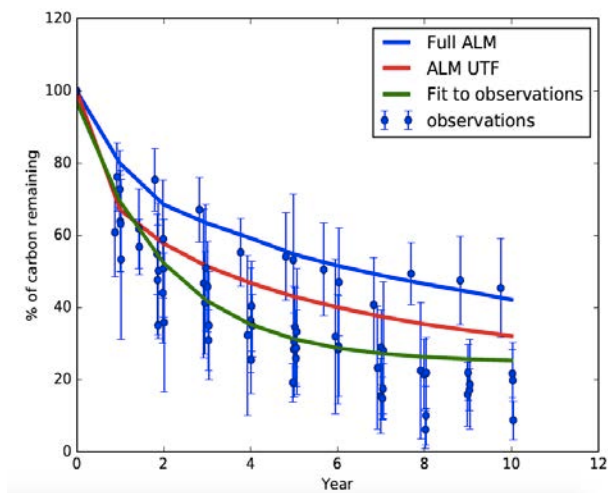
Fig. 18. Comparison of the functional testing and the full model approach to predicting loss of carbon in litter bags in the LIDET experiment. This figure summarizes the results for evergreen conifer forests over the 10-year period of the experiment. The unit test framework (UTF) outperforms the full version of the model because of unrealistic feedbacks described above.

Task 3c Deliverable status

2018	Regional CLM functional testing and multiscale UQ with observational datasets	Underway

Task 3 Publications

Duarte HF, Raczka BM, Ricciuto DM, Lin JC, Koven CD, Thornton PE, Bowling DR, Lai CT, Bible KJ, Ehleringer JR (2017) Evaluating the Community Land Model (CLM4.5) at a coniferous forest site in northwestern United States using flux and carbon-isotope measurements. *Biogeosciences* 14(18):4315-4340.

Forbes WL, Mao JF, Jin MZ, Kao SC, Fu WT, Shi XY, Ricciuto DM, Thornton PE, Ribes A, Wang YT, Piao SL, Zhao TB, Schwalm CR, Hoffman FM, Fisher JB, Ito A, Poulter B, Fang YY, Tian HQ, Jain AK, Hayes DJ (2018) Contribution of environmental forcings to US runoff changes for the period 1950-2010. *Environmental Research Letters* 13(5):054023.

Huang YY, Jiang J, Ma S, Ricciuto D, Hanson PJ, Luo YQ (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-Biogeosciences* 122(8):2046-2063.

Jiang J, Huang YY, Ma S, Stacy M, Shi Z, Ricciuto DM, Hanson PJ, Luo YQ (2018) Forecasting Responses of a Northern Peatland Carbon Cycle to Elevated CO_2 and a Gradient of Experimental Warming. *Journal of Geophysical Research-Biogeosciences* 123(3):1057-1071.

Lu D, Ricciuto D, Gu L, Stoyanov M (2018) Calibration of a land model using surrogate based global optimization. *Journal of Advances in Modeling Earth System* (accepted)

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* 14(18):4295-4314.

Ma S, Jiang J, Huang YY, Shi Z, Wilson RM, Ricciuto D, Sebestyen SD, Hanson PJ, Luo YQ (2017) Data-Constrained Projections of Methane Fluxes in a Northern Minnesota Peatland in Response to Elevated CO2 and Warming. *Journal of Geophysical Research-Biogeosciences* 122(11):2841-2861.

Ricciuto, D, Sargsyan K, Thornton P (2018) The Impact of Parametric Uncertainties on Biogeochemistry in the E3SM Land Model. *Journal of Advances in Modeling Earth Systems* 10(2): 297-319.

Wu, D, Ciais P, Viovy N, Knapp A, Wilcox K, Bahn M, Smith M, Vicca S, Fatichi S, Zscheischler J, He Y, Li X, Ito A, Arneth A, Harper A, Ukkola A, Paschalis P, Poulter B, Peng C, Ricciuto D, Reinthaler D, Chen G, Tian H, Genet H, Mao J, Ingrisch J, Nabel J, Pongratz J, Boysen L, Kautz M, Schmitt M, Meir P, Zhu Q, Hasibeder R, Sippel S, Dangal S, Shi X, Wang YP, Luo Y, Liu YW, Piao SL (2018) Asymmetric Responses of Primary Productivity to Altered Precipitation Simulated by Ecosystem Models across Three Long-term Grassland Sites. *Biogeosciences* (accepted).

Zhou S, Yu BF, Schwalm CR, Ciais P, Zhang Y, Fisher JB, Michalak AM, Wang WL, Poulter B, Huntzinger DN, Niu SL, Mao JF, Jain A, Ricciuto DM, Shi XY, Ito A, Wei YX, Huang YF, Wang GQ (2017) Response of water use efficiency to global environmental change based on output from terrestrial biosphere models. *Global Biogeochemical Cycles* 31(11):1639-1655.

Task 3d: Multi-Assumption Systems Modeling – New Effort

Given the potential and uniqueness in the approach to formalising model structural uncertainty in the *Formal Model Structural Uncertainty Analysis: Tools and Methods* sub-task of Task3a, this work has been elevated to the position of a task. The goal of the Multi-Assumption Systems Modeling task is to develop methods that formally assess model structural uncertainty, i.e. the uncertainty that arises in modelling a system when multiple competing hypotheses and assumptions exist to represent the mechanics of a process. Hypotheses can be evaluated in a systems context and the influence on model output of each of the processes of a given system, and their multiple representations, can be ranked.

This task is achieving this goal by developing agile software and novel algorithms to formalise model structural uncertainty analysis. The Multi-Assumption Architecture and Testbed (MAAT) is the novel software framework designed specifically for formal model structural (i.e. process representation) uncertainty analysis (Fig. 19). The MAAT software system, written in R, is a flexible object-oriented software package comprising a model agnostic ensemble builder that can automatically manipulate modularised code to simply and efficiently generate models that vary in process representation, sometimes referred to as multi-physics, parameter values, and boundary conditions. The MAAT allows full global process-representation and parameter uncertainty analysis based on Sobol's method and that of Dai et al., (2017).
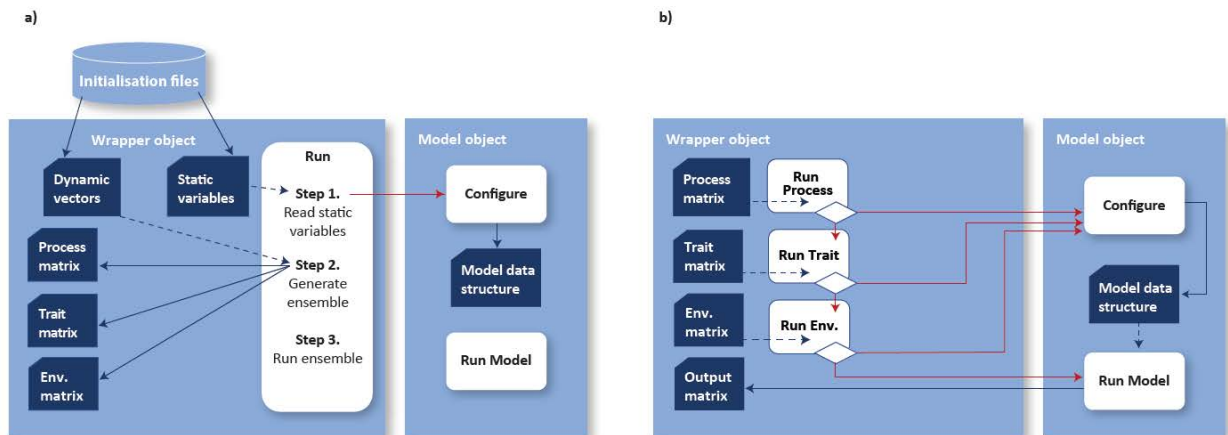
Fig.19. Schematic representing the basic structure and execution process of the model agnostic model ensemble builder of MAAT. Panel a) represents the first two steps of a MAAT execution: 1) reading user input data from initialization files; and 2) generating ensemble matrices from dynamic variables. Panel b) represents a single iteration of the 'run cascade' which forms the third step of a MAAT execution. 'Proto' objects (light blue boxes) contain data structures (dark blue shapes) and functions (white rectangles). Blue arrows represent the transfer of data via a read (dashed) or write (solid), and red arrows represent function call. During the execution of the run cascade, each run function associated with a particular variable type (process representation, parameter, environment) reads a line of the variable type matrix and calls the model object configure function with the line from the matrix as an argument. The configure function writes the variable values to the model object data structure, then the run function calls the next run function in the run cascade. The final run function in the cascade is the model run function which executes the model and writes output to the output data structure in the wrapper object.

A goal of this task is to promote robust modeling practice using multi-assumption methods. In pursuit of this goal, Anthony Walker convened a session on Multi-Hypothesis Modeling co-organized across hydrology and biogeoscience themes at the AGU Fall Meeting 2017. Leaders in the field came to talk at the session and despite being at 4pm on the last day of the meeting, the session was well attended with ~100 conference goers. The promotion of these methods within the DOE and wider scientific communities has been successful in influencing E3SM related model development activities, in particular FATES model development of the PARTEH code to isolate allocation and nutrients code to facilitate evaluation and rapid implementation of alternative assumptions. Dr. Walker Walker was also invited to present the multi-asumption approach to research groups at the University of Oxford and the University of Reading in the UK.

Future plans are to develop Markov Chain Monte Carlo (MCMC) parameter estimation algorithms within MAAT to support model analysis of *Sphagnum* carbon fluxes at the SPRUCE experiment. Code for the DREAM algorithm developed by Dan Lu and invented by Jasper Vrugt will form the basis of the algorithm. In FY19 we intend to hire a post-doc to code the MEND soil decomposition model within MAAT. This activity will strengthen links across tasks and further support model development within the SFA.

Task 3b Deliverables

Date	Deliverable	Status
2017	Promote multi-hypothesis methods to the wider community by organizing a session at the AGU Fall Meeting.	Completed
2018	Publish MAAT v1.0 model description paper.	In review and posted as a discussion paper in GMDD
2018	Publish MAAT code open source on GitHub website.	Completed
2018	Contribute to TRENDY model ensemble and GCP.	Completed

Task 3b Publications/Manuscripts

Walker AP, Ye M, Lu D, DeKauwe MG, Gu L, Medlyn, BE, Rogers A, Serbin SP (2018) The Multi-Assumption Architecture and Testbed (MAAT v1.0): Code for ensembles with dynamic model structure including a unified model of leaf-scale C3 photosynthesis. *Geoscience. Model Development Discussion*, 1–39. https://doi.org/10.5194/gmd-2018-71 (in review)

Le Quéré C, Andrew RM, Friedlingstein P, Sitch S, Pongratz J, Manning AC, Korsbakken JI, Peters GP, Canadell JG, Jackson RB, Boden TA, Tans PP, Andrews OD, Arora VK, Bakker DCE, Barbero L, Becker M, Betts RA, Bopp L, Chevallier F, Chini LP, Ciais P, Cosca CE, Cross J, Currie K, Gasser T, Harris I, Hauck J, Haverd V, Houghton RA, Hunt CW, Hurtt G, Ilyina T, Jain AK, Kato E, Kautz M, Keeling RF, Klein Goldewijk K, Körtzinger A, Landschützer P, Lefèvre N, Lenton A, Lienert S, Lima I, Lombardozzi D, Metzl N, Millero F, Monteiro PMS, Munro DR, Nabel JEMS, Nakaoka S, Nojiri Y, Padin XA, Peregon A, Pfeil B, Pierrot D, Poulter B, Rehder G, Reimer J, Rödenbeck C, Schwinger J, Séférian R, Skjelvan I, Stocker BD, Tian H, Tilbrook B, Tubiello FN, Laan-Luijkx IT van der, Werf GR van der, Heuven S van, Viovy N, Vuichard N, **Walker AP**, Watson AJ, Wiltshire AJ, Zaehle S, Zhu D (2018) Global Carbon Budget 2017. *Earth System Science Data* 10, 405–448. https://doi.org/10.5194/essd-10-405-2018.

Software

The Multi-Assumption Architecture and Testbed (MAAT v1.0) is now open source, available at https://github.com/walkeranthonyp/MAAT.

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

The $^{13}CO_2$ PiTS carbon partitioning project ended several years ago after an enormous amount of data was collected. Seasonal patterns of root and stem growth, sap flow, soil respiration, soil water content, and comprehensive meteorological measurements were collected prior to, during and after the spring, summer and fall $^{13}CO_2$ dogwood labeling experiments. Following each labeling event, the isotopic signal was tracked through foliage and into fruit, phloem, roots and mycorrhizal hyphae, then measured as it

exited the soil surface. The signal was isolated in soil without any roots or fungal hyphae, soil with both roots and fungal hyphae (Combined), and soil with fungal hyphae alone (Fungal). In the fall we cut (trenched) around two of the fungal chambers just before labeling, severing the hyphae and thus severing the path for the ^{13}C label as sugar/exudate transfer into the fungal chamber (Fig. 20 below). These chambers subsequently showed much lower $^{13}CO_2$ efflux from the surface, indicating that the label was traveling through the fungal hyphae, not through the subsurface soil air (i.e., following respiration from fine roots or microbes outside the chamber). Results indicate that in all seasons the fungal hyphae are receiving and respiring much if not the majority of the ^{13}C label that moves belowground and subsequently respired. The rapid transfer of C from the plant to the fungi and subsequent release is a missing link in process-based earth system models. During the PiTS sampling, we collected all the necessary components to run a point version of ELM, including full allometric harvesting of the trees, both below and aboveground.
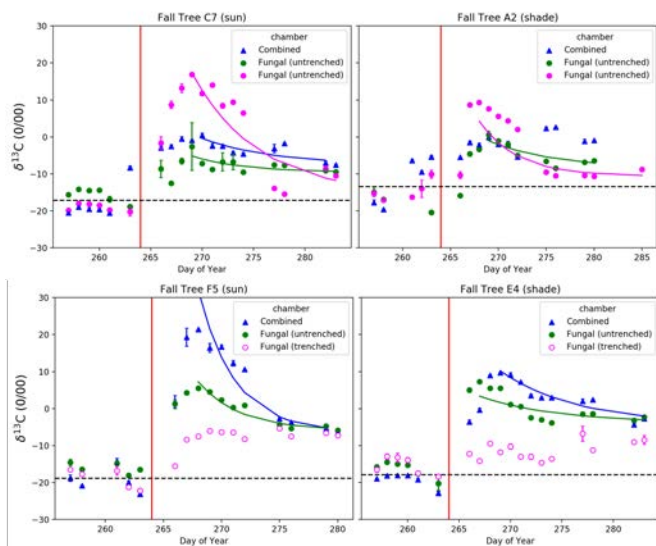
Fig. 20. Soil efflux of $^{13}CO_2$ following whole-tree labeling of shaded or full sun-exposed dogwood trees. Efflux is measured above soil collars that 1) contain bulk soil with roots and mycorrhizal hyphae (Combined) or 2) fungal hyphae only using a 61 µm root exclusion mesh that was connected to the surrounding soil (Fungal (untrenched)), or whose hyphal connections with the surrounding soil were severed (Fungal (trenched)).

Task 4a. Deliverable status

Date	Deliverable	Status
Oct 2017	Submission of final PITS dogwood $^{13}CO_2$ labeling and shading data manuscript. Submit data to TES SFA data archive.	In progress, but pushed back
Jan 2018	Submission of final PITS dogwood $^{13}CO_2$ labeling and shading modeling manuscript.	In progress, but pushed back

Task 4b: Leveraging root traits to inform terrestrial biosphere models (aka FRED)

The first version of FRED (FRED 1.0) was released to the broader public in February 2017 (data citation: Iversen *et al*., 2016; Iversen *et al*., 2017). FRED has been popular; over the course of 1 year, FRED 1.0 was downloaded more than 200 times from http://roots.ornl.gov to address a number of questions related to modeling, local site or species measurements, and broad trait relationships across species or sites. A pre-release of FRED (FRED 0.0) that was incorporated into the fourth version of the TRY database (TRY 4.0; https://www.try-db.org) has also been quite popular; the FRED-TRY synergy increases the representation of belowground plant traits in TRY and facilitates above- and belowground trait linkages. Over the time period from July 2017 to February 2018, observations from FRED 0.0 were requested from TRY 175 times; half of these queries were focused on root traits, while the rest were for ancillary data only. Downloads of FRED 0.0 and FRED 1.0 span the world, including 42 countries across six continents, but were mainly focused in the United States, Europe, and China (http://roots.ornl.gov/overview).

A new version of FRED was released on June 8, 2018. FRED 2.0 is an improved version of his older brother (data citation: Iversen *et al*., 2018), with 50% more root trait observations, particularly in the

categories of root anatomy, architecture, chemistry, and morphology (Fig. 21). FRED 2.0 has more than 105,000 observations of more than 300 root traits, with data collected from more than 1200 data sources. The ancillary data available have increased concurrently with increased root trait observations. FRED 2.0 is now freely available to the broader community of root and rhizosphere ecologists at http://roots.ornl.gov/public-release. The observation numbers associated with individual root traits and ancillary data can be found on the website under the 'traits' tab.

   We have continued to solicit feedback from the broader community of FRED users. Based on community input, we now report the numbers of root trait observations associated with individual plant species (http://roots.ornl.gov/species) . Furthermore, the names of the more than 2000 species in FRED 2.0 have now been harmonized to The Plant List (http://www.theplantlist.org). FRED 2.0 has been submitted to TRY and will be a part of the next version (TRY 5.0) upon its release this fall.
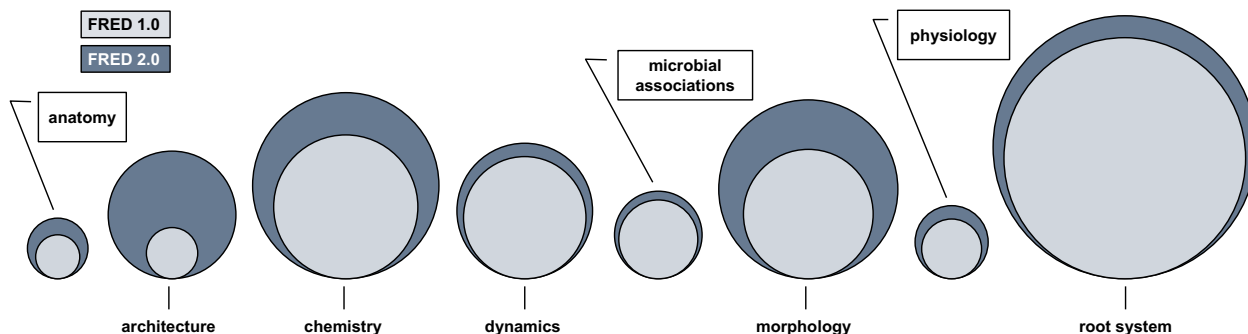
Fig. 21. Root trait observations included in FRED 2.0, grouped into broad trait categories according to McCormack *et al.* (2017); the area of each circle from FRED 1.0 and FRED 2.0 was scaled according to the observation numbers in each category. There was a 50% increase in root trait observations between FRED 1.0 and FRED 2.0, with the greatest increases in the categories of anatomy (88% increase), architecture (519%), chemistry (67%), and morphology (91%). However, the root traits included in FRED 2.0 are unequally distributed across these broad trait categories. More details on the observation numbers for other traits can be found at https://roots.ornl.gov/data-inventory.

Task 4b. Deliverable status

Date	Deliverable	Status
August 2017	Synthesize and highlight global patterns and trends in root traits, and root trait variation within and among model-defined plant functional types.	Paper Completed
June 2018	Second version of Fine-root ecology database (FRED 2.0) – Accessible through TES SFA and TRY.	Completed (Released in June 2018) (http://roots.ornl.gov)
Sep 2018	Sensitivity analyses linking PFT root parameterizations with ecosystem function using *FRED* and ALM.	Underway
Sep 2018	Use FRED 2.0 to inform new paradigm of root-mycorrhizae interactions and the belowground economics spectrum.	Underway
Jan 2019	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.	Underway
April 2019	Break-out session hosted at annual DOE PI meeting to continue engagement of broader community and leverage above- and belowground trait linkages and data collected in other DOE-funded efforts (SPRUCE, NGEEs, PiTS, FACE, AmeriFlux)	Planned

Task 4b Publications/Manuscripts
McCormack ML, Powell AS, Iversen CM (2018) Letter: The Fine-Root Ecology 1 Database version 2 – bigger, better, and free. *EOS* (in press).

Data Sets
 Version 2 of the FRED data base has been posted (Iversen et al. 2018).

Task 4c. Linking Root Traits to Function
 The root function task was developed to improve understanding of root function and implications for modeling. We have been leveraging the neutron imaging facilities at ORNL to quantify root-specific water uptake, and link that to root traits, such as diameter or order. One detailed experiment used a poplar seedling exposed to extreme drought, followed by development of a new root system, then compared water uptake from the new versus older root system (Fig. 22). The smaller diameter newer roots had greater water uptake per unit surface area than the older larger diameter roots, ranging from 0.0027–0.0116 g/cm2 root surface area/h. We subsequently applied these data to a model of root water extraction and interlayer soil water movement using soil hydraulic parameters from root free soil. Model analysis based on those root-free soil hydraulic properties indicated unreasonably large water fluxes between the vertical soil layers during the first 16 hours after wetting – suggesting problems with common soil hydraulic or root surface area modeling approaches, and the need to further research and understand the impacts of roots on soil hydraulic properties. This resulted in a publication that has gained significant interest (Dhiman et al. 2018). Since ELM and other process-based models depend heavily on soil water release curves and texture/bulk density-based calculations of saturated hydraulic conductivity, we deemed this indirect root function an important enough issue to pursue further. In FY18 we recruited an MS student to test the hypothesis that plant roots and associated mycorrhizal hyphae will both significantly affect soil hydraulic properties. To address this hypothesis, we have begun new neutron imaging work using hanging water columns, and laboratory measurements of hydraulic conductivity through sterile soil, hyphal only soil, root only soil, and root+hyphae soil, using sand or a silty loam soil. This work will carry on through FY19. In addition, we are developing another neutron image-based manuscript that describes rhizosphere development, and how it is linked to root size, regardless of species. This work assessed multiple species and focused on near root water content for different size classes. A manuscript has been written and is under internal review and revision. Based on these studies, and new results from the PiTS analysis (below), we will reassess the direction of the root function task next FY.
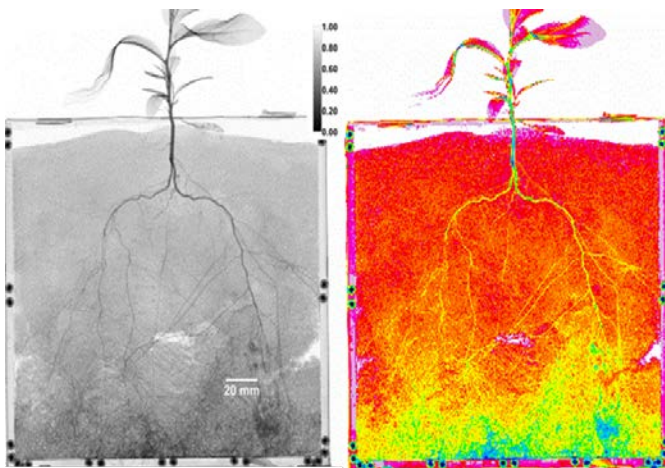
Fig. 22. Composite images of 16 radiographs of an 11-week old poplar plant growing in sand, intensity indicates water content. Tracking water uptake through time, we quantified greater uptake rates for newer, younger roots.

Task 4c. Deliverable status

Date	Deliverable	Status
Dec 2017	Submission of manuscript assessing drought and root size on water uptake.	Paper completed
Dec 2017	Data analysis and submission of manuscript focused on linking root morphology and age to water uptake across multiple species.	Pushed back for Sept 2018

| Dec 2017 | Begin deployment of Rhizosphere Ecology Laboratory for integrative assessment of belowground dynamics. | Still under consideration |
| Dec 2019 | Neutron imaging and laboratory analysis of root and hyphal impacts on soil hydraulic properties. | Underway |

Task 4c Publication

Dhiman I, Bilheux HZ, DeCarlo KF, Painter SL, Santodonato LJ, Warren JM (2018) Quantifying root water extraction after drought recovery using sub-mm in situ empirical data. *Plant and Soil* 424:73-89; doi: 10.1007/s11104-017-3408-5.

Task 5: Microbial Processing of Soil C

We continued to focus on moisture sensitivity this year in both models and experiments. We used the E3SM Land Model (ELM, CLM-CN version) to simulate soil respiration at the MOFLUX site using observations from 2005-2013. We determined that the model default parameters using the uncalibrated Clapp & Hornberger moisture retention function significantly underestimated annual soil respiration (SR) and gross primary production (GPP), while underestimating soil water potential during growing seasons and overestimating it during non-growing seasons. A site-specific soil water retention curve was fit with the Hanson empirical model, and used to calibrate the Clapp & Hornberger model, and both representations dramatically enhanced representations of GPP and SR (Fig. 23). However, the model continued to underestimate soil respiration during peak growing seasons, and overestimate soil respiration during non-growing seasons and did not simulate the significant suppression of SR during an exceptional drought year. A number of parameter adjustments were made, which affected leaf area index (LAI) and GPP that improved representation of SR during peak growing seasons, but still did not improve representation of non-growing seasons (Fig. 24). One potential reason may be lack of representation of the seasonal cycle of microbial organisms and soil macroinvertebrates, which have high biomass and activity during peak growing seasons and tend to be dormant during non-growing seasons.
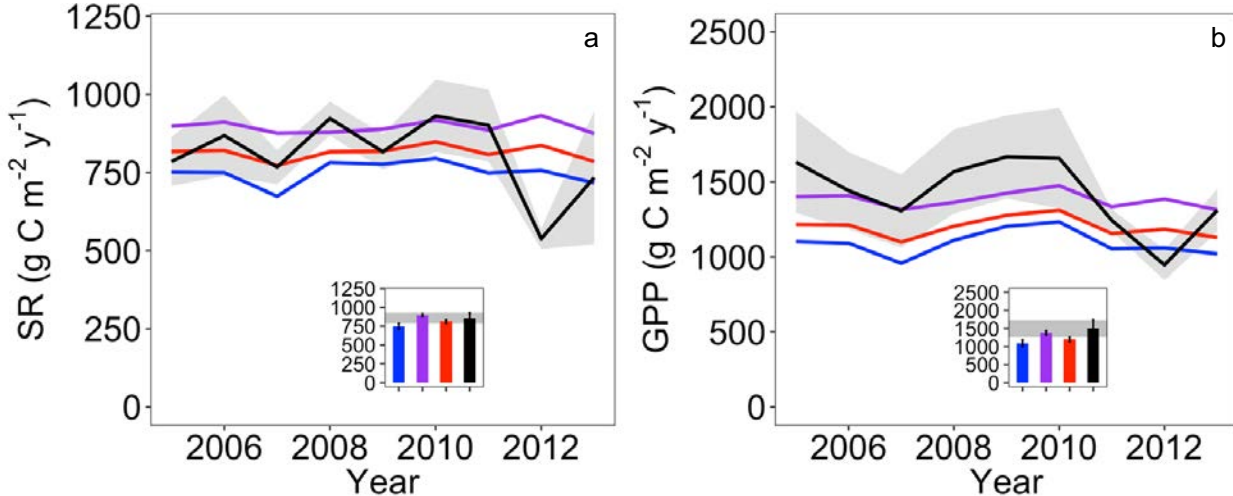
Fig. 23: Annual soil respiration (SR) and gross primary production (GPP). Blue lines are the ELMv0 simulations with default parameters (MOD$_{default}$), red lines with the soil water potential improved using the calibrated Clapp & Hornberger model (MOD$_{cCP}$), and purple lines with the soil water potential improved using the Hanson model (MOD$_{H}$). Black lines and grey area are the observed (OBS) mean and 1 sigma range, which were calculated from 8 field replications for SR, and from three different net ecosystem exchange partitioning methods for GPP. The inset bar plots are mean annual average ± 1 sigma across 2005-2011.

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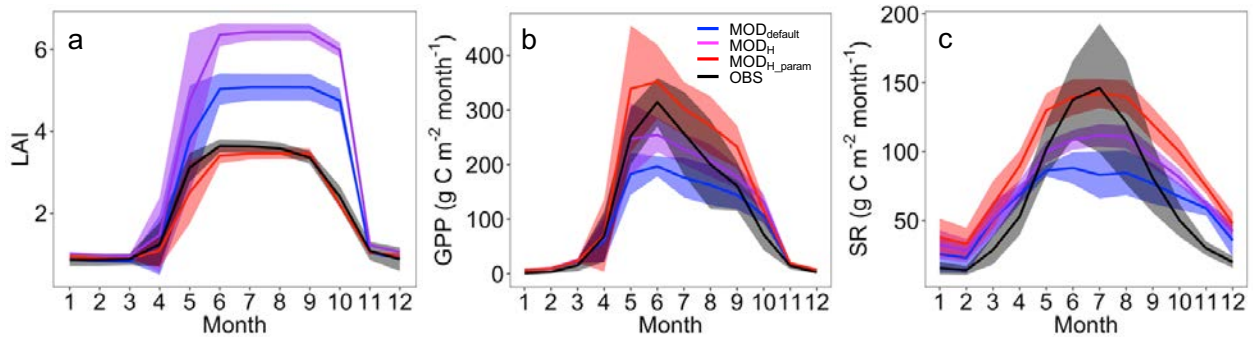
Fig. 24. The annual mean cycles of leaf area index (LAI), gross primary production (GPP) and soil respiration (SR). OBS: observation; MOD$_{default}$: model output before soil water potential improvement; MOD$_H$: model output after soil water potential improvement by the Hanson model; MOD$_{H\_param}$: model output after soil water potential improvement by the Hanson model and parameter adjustments.

We now have a year's worth of data from trenching around four autochamber plots at MOFLUX. We determined there is good agreement of the proportion of heterotrophic respiration (i.e., trenched plots) to total soil respiration with the calibrated ELM for the site (Fig. 25). We found the $\delta^{13/12}C$ signature was mostly similar for soil and root respiration, so it could not be used for discrimination of respiration sources. Monitoring continues for total CO_2 fluxes at the site.
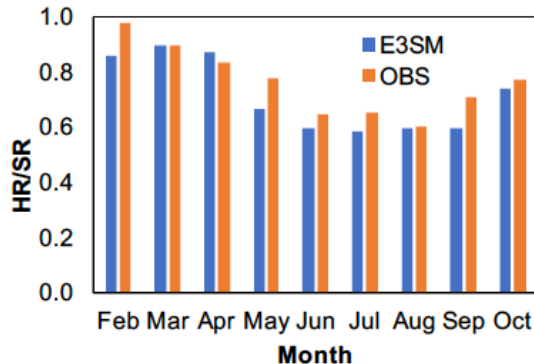
Fig. 25. Heterotrophic (HR) over total soil respiration (SR) from the trenched plots at MOFLUX and represented with the E3SM mode.

A set of incubation experiments simultaneously investigating soil texture and moisture is ongoing, using the loamy soils from MOFLUX, a sandy soil from GA, and a clayey soil from TX. We expected the soils would have different moisture optima for highest CO_2 efflux, and the information will be used to improve the representation of moisture sensitivity in the MEND and ELM models. The sandy soils are the most sensitive to dry conditions, showing strong decreases in CO_2 fluxes as compared to wet conditions (Fig. 26). The clayey soils emitted the most CO_2 under wet conditions, and the loamy soils were intermediate.

Using ELM and MEND on the MOFLUX site, we are testing the sensitivity of soil carbon loss to moisture extremes (+5%, -5%, +10%, -10% soil water content), and frequencies of 10 and 20 drought/wetting events per 100 years. We find that microbial respiration is much more sensitive to drought than to wetting (which is similar to what we observe in the incubation experiment discussed above), exhibiting as much as a 10% decrease in microbial respiration with the most severe drought conditions, and as much as a 5% increase in microbial respiration with the most severe wetting conditions. Analysis with MEND demonstrates that large decreases in active microbial biomass are responsible for the drop in respiration under drought conditions, with concomitant effects decreasing the supply rates of dissolved, particulate, and mineral-associated organic carbon. Consequently, intensified drought/wetting conditions are inferred to decrease carbon losses through microbial respiration. These findings are significant since most of the modelling studies involving microbial soil carbon cycling are focused on temperature effects. Drought can also influence input rates of organic materials such as litter, roots, and coarse woody debris, but those effects are not yet included in our improved model.
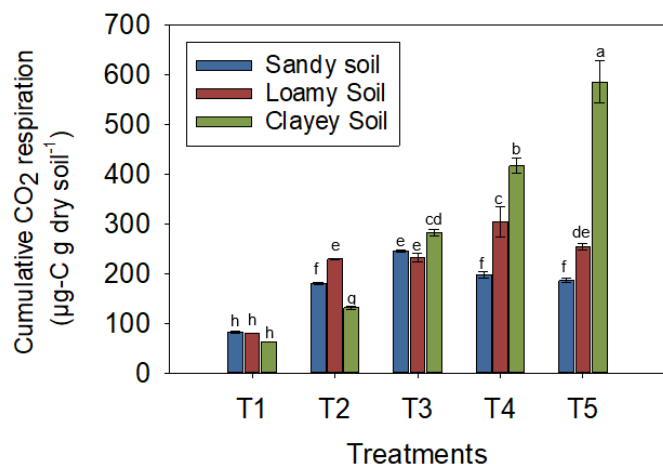
Fig. 26. Cumulative respiration at 90 days for the sandy, loamy, and clayey soils, where T1 = air-dried, T2 = 25% water-holding capacity (WHC), T3 = 50% WHC, T4 = field WHC, and T5 = complete saturation.

Another set of incubation experiments involving four paired temperate forest and grassland sites, ^{13}C labeled glucose for the short-term (144 hours) experiments and ^{13}C labeled cellulose for the long-term (729 days) study, were completed and the data was prepared for publication (as reported in FY17 report). In FY18, we are using MEND to model the data (Fig. 27). This study is helping to identify which parameters are the most sensitive under short- and long-term conditions, and in particular, the to calibrate short-term versus long-term microbial parameters.
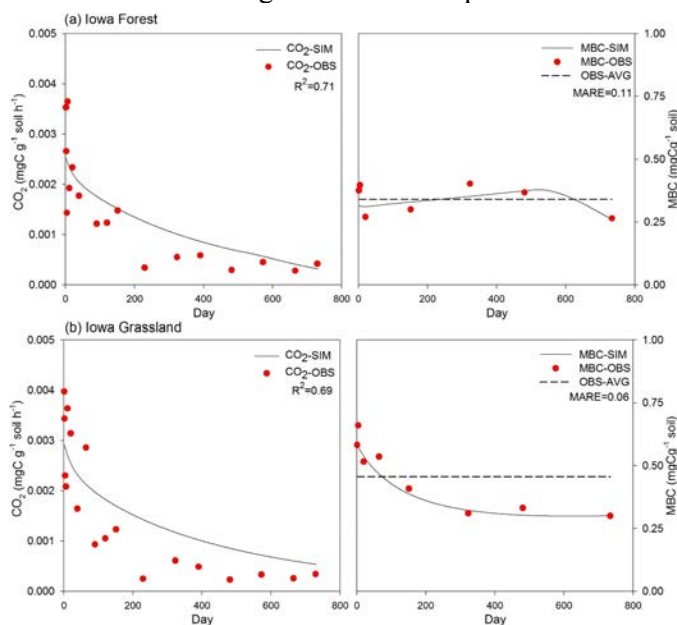
Fig. 27. Simulation (SIM) and observation (OBS) of respiration rate (CO_2) and microbial biomass carbon (MBC) in the control treatments from the Iowa study sites. R^2: coefficient of determination, higher R^2-values ($R^2 \leq 1$) indicate better model performance; MARE: mean absolute relative error, lower MRE values (MARE ≥ 0) are preferred. Different objective functions were used for CO_2 and MBC because there were more observations for CO_2 (n=18) than for MBC (n=8).

Future Plans - We intend to develop a whole-ecosystem modeling strategy for the MOFLUX and SPRUCE sites using ELM, PFLOTRAN, and MEND.

Task 5. Deliverable Status

Date	Deliverable	Status
05/17	Complete temperate grassland v forest, short-term, long-term isotope study.	Complete
03/17	Incorporate soil moisture effects and test against MOFLUX field scale experimental data in ELM and MEND model.	01/18
12/17	Model temperate grassland v forest short-term, long-term isotope study using MEND.	09/18
5/18	Complete lab-scale moisture – texture sensitivity experiments.	11/18
9/18	Incorporate flexible C:N ratio into MEND.	Complete
new	Modeling soil carbon loss in response to intensified soil moisture extremes using MEND and ELM.	02/19

new	Whole ecosystem modelling strategy using ELM-PFLOTRAN-MEND for MOFLUX & SPRUCE sites.	01/20

Task 5 Publications/Manuscripts

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. *Global Change Biology* (in revision).

Li, J, Jian, S, de Joff, JP, Lane, CS, Wang, G, Mayes, MA, Hui, D (2018) Differential effects of warming and nitrogen fertilization on soil respiration and microbial dynamics in switchgrass croplands. *Global Change Biology Bioenergy* http://dx.doi.org/10.1111/gcbb.12515.

Liang, J, Wang, G., Riccuito, DM, Gu, L, Hanson, PJ, Wood, JD, Mayes, MA (2018) Evaluating the E3SM Land Model at a temperate forest site using flux and soil water measurements. Geoscientific Model Development Discussion. https://www.geosci-model-dev-discuss.net/gmd-2018-34/.

Wang G, Huang W, Mayes MA et al. (2017) Soil moisture drives microbial controls on carbon decomposition in subtropical forests. *Soil Biology and Biochemistry* (submitted).

Wang, K, Peng, C, Zhu, Q, Zhou, X, Wang, M, Zhang, K, Wang, G (2017) Modelling global soil carbon and soil microbial carbon by integrating microbial processes into the ecosystem process model of TRIPLEX-GHG. *Journal of Advances in Modeling Earth Systems* 9:2368–2384, doi: 10.1002/2017MS000920.

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

Solar-induced chlorophyll fluorescence - There has been a continued focus on the observation and interpretation of canopy solar-induced chlorophyll fluorescence (SIF). This has been accomplished through emphasizing: (i) continued optimization of hardware/software of the Fluorescence Automated Measurement Equipment (FAME) system as well as post processing routines for retrieving SIF, (ii) enhancing ecosystem observations of the canopy radiation environment, and (iii) leaf-level observations of photosynthesis parameters, water relations and optical properties. A critical aspect of this work has been a continuous, rigorous assessment directed towards understanding and characterizing the performance of the system. We believe that this is a key deficiency in the growing body of literature regarding ground-based SIF observations, and that this has hampered the development of SIF measurement techniques.

At the height of the growing season FAME acquires approximately 1000–1400 paired samples from which SIF can be retrieved, thus providing a dense dataset to explore diurnal to seasonal SIF dynamics. The 2017 growing season was the first real field test of the system's ability to maintain the spectrometer detector at a constant -10 °C (to maintain high sensitivity), which was found to be the case despite experiencing ambient atmospheric temperatures in excess of 30 °C. The ratio of outgoing to incoming integration times increased approximately linearly as a function of incoming PAR, until the ratio saturated at ~5 at incoming PAR of ~1250 μmol m-2 s-1, demonstrating consistent and predictable behavior of the dynamic optimization of integration time, which is key for acquiring high fidelity spectra for retrieving SIF. This robust system has yielded new science results regarding the temporal patterns of SIF in temperate deciduous forests.

The seasonal pattern of mid-day SIF revealed a rapid increase during spring, peaking in late-May to early-June and a gradual decline through to the end of the growing season, and showed general agreement with variations in plant water stress (Fig. 28). This seasonal pattern is broadly consistent with those of carbon (C) and vegetation dynamics such as net C uptake, leaf area index (LAI) and canopy greenness. A more in depth probing of SIF dynamics at shorter timescales revealed consistent (i) saturation of SIF at high incident PAR, and (ii) diurnal hysteresis in the light response. Saturation of SIF at high light is similar to what is expected for leaf-level net photosynthesis and ecosystem carbon fluxes for C3 vegetation. These key findings highlight the crucial need to better understand the factors controlling temporal SIF dynamics in order to unlock its full potential for independently monitoring ecosystem gross primary production (GPP).
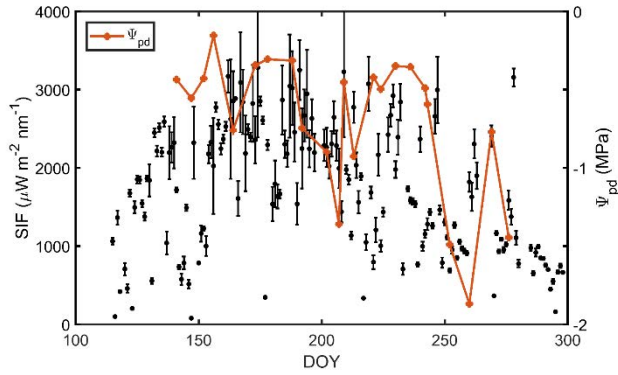
Fig. 28. Time series of mean mid-day SIF s (left y-axis) and predawn leaf water potential (Ψpd, right y-axis) during the 2017 growing season. Error bars represent 1 standard error, for which the magnitude was largely dependent on the degree of variable cloudiness, which increases the noise in SIF retrievals.

To support the interpretation of observed SIF and aid in future modeling efforts, we have increased our capacity to observe ecosystem absorbed PAR (APAR) through the deployment (May 2018) of a new data acquisition system that includes line quantum sensors deployed above and below the canopy. All line quantum sensors are monitored by the same datalogger, thus allowing for high frequency (1 Hz), synchronized measurement of the canopy light environment. We also conducted extensive leaf-level measurements during 2017, which have been expanded in scope during 2018. Leaf-level Pulsed Amplitude Modulation (PAM) measurements reveal important temperature dependencies of the non-photosynthetic quenching (NPQ) light response (Fig. 29). Upregulation of NPQ at elevated temperatures and slow relaxation kinetics may partially explain the hysteresis in the canopy SIF light response.
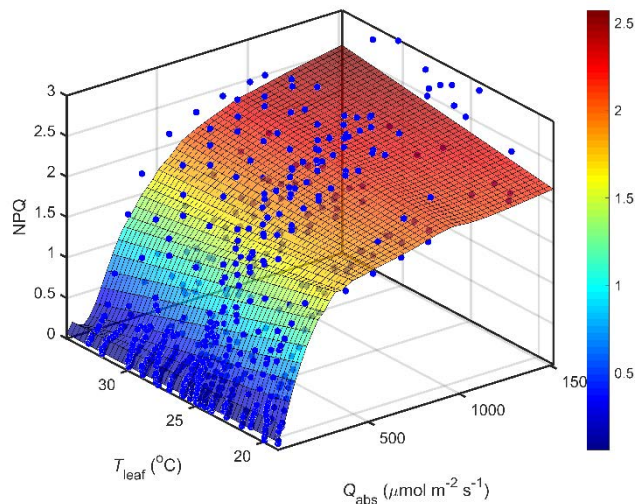
Fig. 29. Response of the nonphotochemical quenching parameter, NPQ, to leaf temperature (T_{leaf}) and absorbed PAR (Q_{abs}) for sunlit *Quercus alba* L. leaves. The blue dots represent observations from PAM fluorimetry and the response surface was generated using a local regression technique. The color also scheme represents the magnitude of NPQ.

We are also examining how leaf optical properties and leaf water status may affect SIF. Diurnal cycles of leaf water potential (ΨL) and leaf transmissivity (τL) were made over three days in early June 2018 for four important tree species in the MOFLUX forest. The diurnal cycles of ΨL differed among species, and in general displayed rapid changes in the morning with more muted variation during the afternoon. Afternoon SIF may be inhibited by the elevated water stress that persists from mid-day through the afternoon. We have also initiated simple measurements of τL using a single quantum sensor. Preliminary observations reveal diurnal patterns in τL with differences among species. In general, we found that τL was lowest in early morning, increased through mid-day and may decline later in the afternoon. These changes in optical properties could potentially be due to the repositioning of chloroplasts to avoid absorbing PAR, which has consequences for the supply of photons for driving the light reactions of photosynthesis, and thus SIF emission. Taken together, a comprehensive suite of leaf-level observations is underway to help disentangle the complicated mechanism(s) driving the temporal dynamics of SIF. Our comprehensive ecophysiological observations are essential to establish a thorough

understanding of processes that drive variations in SIF, which is needed to support the development of models of SIF that are compatible with existing photosynthesis models.

Bridging SIF and GPP via NPQ modeling - The precise relations of SIF with GPP or ecosystem stress responses are currently uncertain. A key factor in this uncertainty is the dynamics of NPQ which competes with photochemical quenching for carbon dioxide (CO_2) reduction and strongly influences SIF-GPP relationships. For this reason, our modeling efforts have focused on developing a simple, mechanistically-sound NPQ model to facilitate understanding of SIF-GPP relationships. We developed a dynamic NPQ model that takes into consideration the leaf irradiance history. The model simulates the induction and relaxation of NPQ on minute time scales. As a result, it is well suited to model NPQ and its effect on SIF-GPP relationships under fluctuating light conditions caused by rapidly developing and evolving cloud fields, which are a frequent phenomenon in nearly all vegetated climate zones. Initial tests show that the model can accurately capture the transient processes of both light induction and dark relaxation of NPQ (Fig. 30). The model has the potential to be implemented in large-scale models such as E3SM for simulating terrestrial SIF emission and photosynthesis.
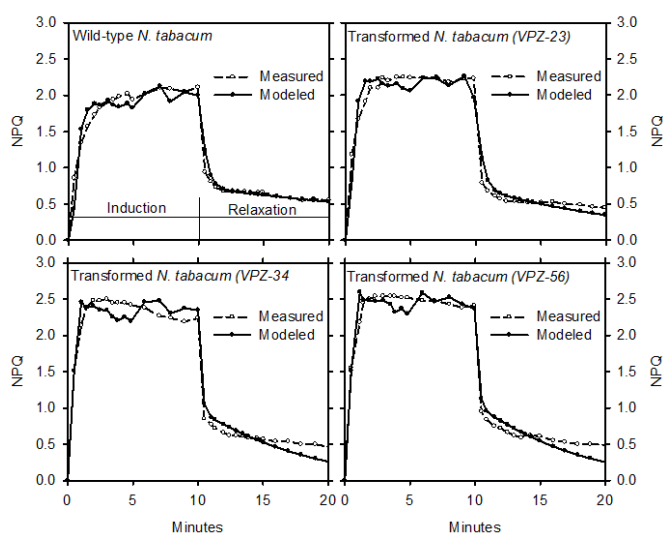
Fig. 30. Test results on the light induction and dark relaxation of NPQ simulated by the dynamic model. Light is turned on during the induction phase (photosynthetically action radiation = 1000 μmol m^{-2} s^{-1}) and turned off during the relaxation phase. Each phase lasts 10 minutes. The measurements are from Kromdijk et al. (2016), Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. Science, 354 (857-861).

Belowground carbon cycling - Ongoing work aimed at better understanding and modeling below ground carbon cycling, and its links with above ground processes continues. We analyzed the photosynthetic and precipitation regulation of soil respiration and tested the generality of this regulation across growing seasons. This effort used decade-long continuous measurements of soil respiration and eddy covariance records of net ecosystem exchange of CO_2 and examined the intrinsic linkage between photosynthesis, precipitation and soil respiration. Results showed that the response of soil respiration to precipitation events depended on the antecedent soil moisture level. Precipitation resulted in a rapid increase, insensitive response, and sharp decrease of soil respiration for low (<30%), intermediate (30–35%), and high (>35%) initial soil moisture levels, respectively. Photosynthesis regulated soil respiration at the diurnal scale, with a time lag of four to nine hours. The variations in this time lag were affected by past trajectories of moisture and temperature. Photosynthesis exerted a prolonged modulation on soil respiration during dry versus wet seasons. We found that models of soil respiration were improved by incorporating photosynthesis as an input along with soil temperature and moisture (Liang et al. 2018). This suggests that physiological and environmental processes jointly control soil respiration and are important for modeling soil respiration. We continue collaboration with Task 5 (see Task 5).

Collaborative research activities and outreach - MOFLUX personnel have continued external research collaborations that have fostered improved understanding surface-atmosphere gas and energy exchanges, carbon allocation in forests, the remote sensing of plant water status/stress and drought-pathogen interactions as related to tree mortality. Tours of the MOFLUX site are given periodically to educate visitors about MOFLUX-specific, and wider ORNL TES-SFA research activities. Groups have

included classes from the University of Missouri (MU) and Westminster College, the Missouri Chapter of the Nature Conservancy and the Missouri Chapter of the Society of American Foresters. MOFLUX personnel have also been invited to present MOFLUX-related science at a local high school and in classes at MU.

Task 6. Deliverable status

Date	Deliverable	Status
Oct 2017	Extra deliverable: Collaborate with OCO-2 Science team to evaluate performance of OCO-2 SIF product.	Published Science
Mar 2018	Submit 2017 MOFLUX data to AmeriFlux Changes in revised AmeriFlux official data format requirements disrupted the highly automated MOFLUX data post-processing pipeline.	Delayed to June 2018
Apr 2018	Extra deliverable: Technical paper on the performance of the Fluorescence Auto-Measurement Equipment (FAME).	Manuscript submitted
May 2018	Extra deliverable: Paper on the dynamics of Sun-induced Chlorophyll Fluorescence measured by FAME.	Manuscript submitted
Summer 2018	Report on the potential EC application in large open-top enclosures.	In progress
Sep 2018	Report on spatial heterogeneity of soil moisture, root growth and soil efflux.	Manuscript submitted
Dec 2018	Development of a dynamic non-photochemical quenching model to facilitate the study of SIF-GPP relations.	Planned
May 2019	Submit 2018 MOFLUX data to AmeriFlux.	Planned
Aug 2019	MOFLUX SIF system operational.	In progress

Task 6 Publications/Manuscripts

Barba J, Cueva A, Bahn M, Barron-Gafford GA, Bond-Lamberty B, Hanson PJ, Jaimes A, Kulmala L, Pumpanen J, Scott RL, Wohlfahrt G, Vargas R (2018) Comparing ecosystem and soil respiration: a review of tower-based and soil measurements challenges. *Agricultural and Forest Meteorology* 249:434-443, doi: 10.1016/j.agrformet.2017.10.028.

Chen M, Griffis TJ, Baker JM, Wood JD, Meyers T, Suyker A (2018) Simulating the long-term carbon budget across agricultural sites using CLM4-Crop, *Agricultural and Forest Meteorology* 256–257:315–333, doi: 10.1016/j.agrformet.2018.03.012.

Chen, Z., Griffis TJ, Baker JM, Millet D, Wood JD, Dlugokencky E, Andrews A, Sweeney C, Hu C, Kolka R (2018) Source partitioning of methane emissions and its seasonality in the U.S. Midwest. *Journal of Geophysical Research: Biogeosciences* 123:646–659, doi: 10.1002/2017JG004356.

Filella I, Zhang C, Seco R, Potosnak M, Guenther A, Karl T, Gamon J, Pallardy S, Gu L, Kim S, Balzarolo M, Fernandez-Martinez M, Peñuelas J (2018) A MODIS Photochemical Reflectance Index (PRI) as an estimator of isoprene emissions in a temperate deciduous forest. *Remote Sensing* 10, 557, doi:10.3390/rs10040557.

Griffis TJ, Chen ZC, Baker JM, Wood JD, Millet DB, Lee X, Venterea RT, Turner PA (2017) Nitrous oxide emissions are enhanced in a warmer and wetter world. *Proceedings of the National Academy of Sciences* 114:12081–12085, doi: 10.1073/pnas.1704552114.

Jiang X, Guenther A, Potosnak, M, Geron C, Seco R, Karl T, Kim S, Gu L, Pallardy S (2018). Isoprene emission response to drought and the impact on global atmospheric chemistry. *Atmospheric Environment* 183:69-83.

Liang, J, Wang, G., Riccuito, DM, Gu, L, Hanson, PJ, Wood, JD, Mayes, MA (2018) Representation of site-specific soil water potentials improves modeling of soil respiration. *Geoscientific Model Development Discussion* https://www.geosci-model-dev-discuss.net/gmd-2018-34/.

Momen M, Wood JD, Novick KA, Pangle R, Pockman WT, MacDowell NG, Konings, AG (2017) Interacting effects of leaf water potential and biomass on vegetation optical depth. *Journal of Geophysical Research: Biogeosciences* 122:3031–3046, doi 10.1002/2017JG004145. Article selected by the editorial board for highlighting in the American Geophysical Union's Eos publication

(Witman, S. (2018), Scientists probe water inside leaves via satellite, *Eos*, 99, https://doi.org/10.1029/2018EO089975).

Montane F, Fox AM, Arellano AF, MacBean N, Alexander MR, Dye A, Bishop DA, Trouet V, Babst F, Hessl AE, Pederson N, Blanken PD, Bohrer G, Gough CM, Litvak ME, Novick KA, Phillips RP, Wood JD, Moore DJP (2017) Evaluating the effect of alternative carbon allocation schemes in a land surface model (CLM4.5) on carbon fluxes, pools and turnover in temperate forests. *Geoscientific Model Development* 10:3499-3517, doi: 10.5194/gmd-10-3499-2017.

Sun Y, Frankenberg C, Wood JD, Schimel DS, Jung M, Guanter L, Drewry DT, Verma M, Porcar-Castell A, Griffis TJ, Gu LH, Magney TS, Köhler P, Evans B, Yuen K (2017) OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. *Science* 358:189, doi: 10.1126/science.aam5747.

Wood, JD, Knapp BO, Muzika R-M, Stambaugh, MC, Gu L (2018) The importance of drought-pathogen interactions in driving oak mortality events in the Ozark Border Region. *Environmental Research Letters* 13:015004, doi: 10.1088/1748-9326/aa94fa.

Xiao K, Griffis TJ, Baker JM, Bolstad PV, Erickson MD, Lee X, Wood JD, Hu C (2018) Evaporation from a temperature closed-basin lake and its impact on present, past and future water level. *Journal of Hydrology* 561:59–75, doi: 10.1016/j.jhydrol.2018.03.059.

Zheng YQ, Unger N, Tadić JM, Seco R, Guenther AB, Barkley MP, Potosnak MJ, Murray L, Michalak AM, Qiu XM, Kim S, Karl T, Gu LH, Pallardy SG (2017) Drought impacts on photosynthesis, isoprene emission and atmospheric formaldehyde in a mid-latitude forest. *Atmospheric Environment* 167: 190-201.

Data Sets

Pallardy, SG, Gu, L, Wood, JD, Hosman, KP, Sun, Y, Hook, L. Predawn Leaf Water Potential of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2017. United States: N. p., 2018. Web. doi:10.3334/CDIAC/ORNLSFA.004.

Task 7: Implications of Fossil Emissions for Terrestrial Ecosystem Science

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, moving away from estimates of fossil fuel emissions themselves. 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.

Task 7b. Development of high precision ^{13}C and ^{14}C modeling in ELM-SPRUCE and ELM for application to isotopic tracer studies at the SPRUCE site and in connecting observed variations in $^{13}C/^{14}C$ in fossil fuel emissions with observations of $^{13}C/^{14}C$ 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 CO_2, estimates of anthropogenic CO_2 emissions and models of oceanic CO_2 uptake (Le Quéré et al., 2017), one can estimate net global CO_2 exchange between the atmosphere and terrestrial ecosystems as the residual of the balanced global carbon budget (Fig. 31). By this estimate, the terrestrial biosphere not influenced by land-use change is a growing sink for atmospheric CO_2, averaging 2.29 ± 0.15 Pg C y-1 (mean ± 1 standard error) for the period 1959-2016 with a growth rate of 0.03 Pg C y-1, but with considerable year-to-year variability (Fig. 31). Within the uncertainty in observations of atmospheric CO_2, anthropogenic emissions and oceanic uptake, this residual calculation is a sound estimate of the global behavior of terrestrial ecosystems over the past 60 years. A task of terrestrial ecosystem science is to explain the trend and variability in this estimate. This "residual land sink" is a benchmark against which the performance of global terrestrial biosphere models, including the land models of Earth System Models, should and has been evaluated (e.g., Huntzinger et al., 2017).
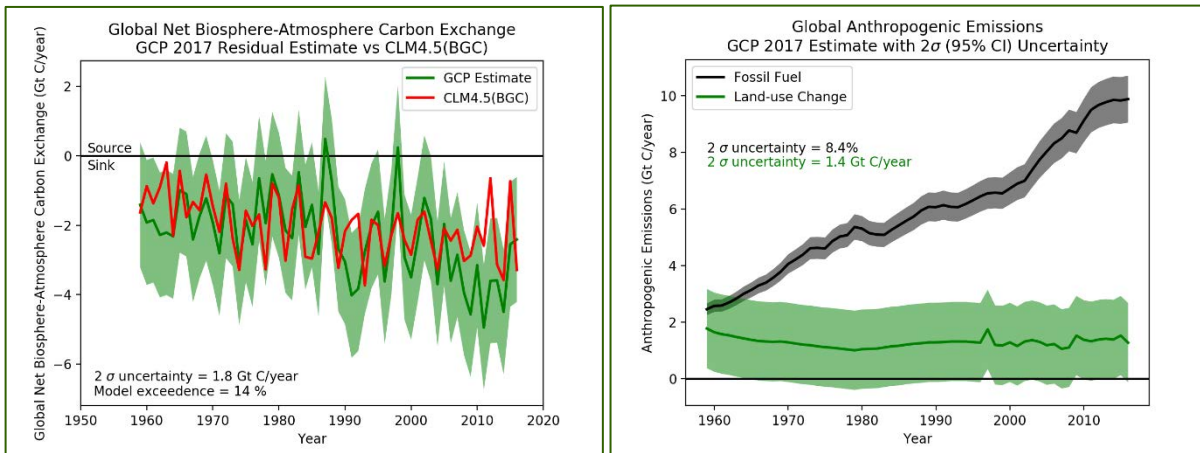
Fig. 31. Comparison of model simulated biospheric sink with estimates from balancing the global carbon budget and its uncertainty. 31b. Uncertainty (± 2σ) in fossil fuel and land-use change emissions contributing to uncertainty in global carbon budget and the residual terrestrial biosphere sink.

However, the "within the uncertainty" above is an important caveat. Based on earlier work of Task 7, the uncertainty (2σ; 95% confidence interval) in fossil fuel emissions is 8.4% (Andres et al., 2014) (Fig. 31b). Combined with uncertainty in other carbon budget components (Le Quéré et al., 2017), for example the 2σ uncertainty in land-use change emissions of 1.4 Pg C y-1 (Fig. 32), the 2σ uncertainty surrounding the global net terrestrial ecosystem CO_2 exchange is ±1.8 Pg C y-1 (Fig. 31). Ignoring the uncertainty, the estimate of a general terrestrial sink includes 2 years (1987 and 1998) in which terrestrial ecosystems undisturbed by land-use change are a small source of CO_2 to the atmosphere (Fig. 31). However, with 2σ uncertainty, these terrestrial ecosystems may have been a source in as many as 17 years (Fig. 31). At the 2σ uncertainty bounds, terrestrial ecosystems may have been a cumulative sink as large as -237.15 Pg C (averaging 4.09 ± 0.15 Pg C y-1) or as small as 28.35 Pg C (averaging 0.49 ± 0.15 Pg C y-1). In short, the uncertainty surrounding the residual land sink, a consequence of uncertainty in fossil fuel emissions and other components of the global carbon budget, diffuses the benchmark and clouds what terrestrial ecosystem science and terrestrial biosphere models are attempting to understand.
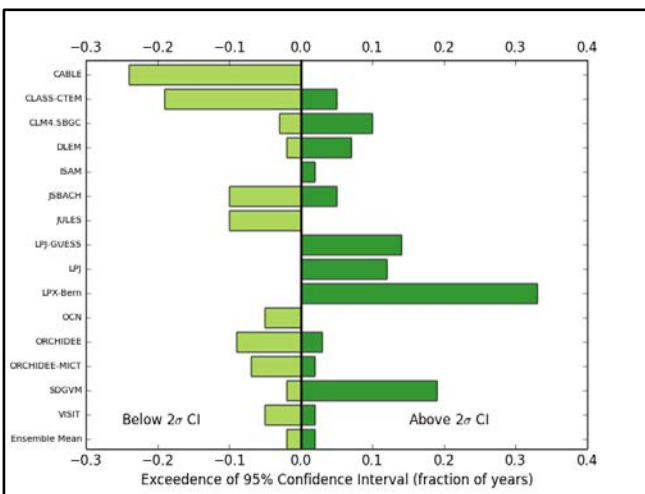
Fig. 32. Model exceedance of 2σ uncertainty surrounding the estimate of terrestrial biosphere sink obtained by balancing the global carbon budget. Model results from Le Quéré et al. (2017).

As Lovenduski and Bonan (2017) have noted: "Constraining models to an uncertain observation may not increase their predictive skill." Nonetheless, if we take the uncertainty surrounding the residual land sink seriously, and we should, this is the nature of the benchmark we have, one with considerable uncertainty. Model evaluations against this benchmark should explicitly take this uncertainty into account. However, most available metrics of model skill (e.g., root mean square error and related indices of skill) do not explicitly account for uncertainty in the benchmark.

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We are preparing a manuscript examining how well global terrestrial biosphere models simulate the trend and interannual variability of the global-budget estimate of the terrestrial sink within the context of this uncertainty (e.g., which models fall outside the 2σ uncertainty and in what years; Fig. 32). As part of this manuscript we are introducing a revised skill scores methodology which explicitly accounts for the uncertainty surrounding the global-budget estimate of the terrestrial sink (e.g., Table 2).

In addition, if one adds land-use change emissions to the residual land-sink, one obtains a 60 year history of global Net Biosphere Production (NBP), the global extension of Net Biome Production [Chapin et al., 2006]. We are preparing a manuscript which analyzes the time-series properties of this history.

Model	Conventional RMSE	RMSE Spread[a]	"Uncertain" RMSE[b]	"Corrected" RMSE[c]
	Gt C/year	Gt C/year	Gt C/year	Gt C/year
CABLE-POP	1.47	3.13-1.01	$1.47_{3.13}^{1.01}$	0.27
CLASS-CTEM	1.44	2.67-1.87	$1.44_{2.67}^{1.87}$	0.37
CLM4.5BGC	1.08	1.85-2.32	$1.08_{1.85}^{2.32}$	0.18
DLEM	1.03	1.70-2.39	$1.03_{1.70}^{2.39}$	0.05
ISAM	0.84	1.79-2.16	$0.84_{1.79}^{2.16}$	0.03
JSBACH	1.26	2.54-1.78	$1.26_{2.54}^{1.78}$	0.35
JULES	1.21	2.41-1.90	$1.21_{2.41}^{1.90}$	0.25
LPJ-GUESS	1.35	1.79-2.63	$1.35_{1.79}^{2.63}$	0.36
LPJ	1.28	1.44-2.77	$1.28_{1.44}^{2.77}$	0.30
LPX-Bern	1.68	1.36-3.21	$1.68_{1.36}^{3.21}$	0.50
OCN	0.98	2.39-1.63	$0.98_{2.39}^{1.63}$	0.08
ORCHIDEE	1.19	2.29-2.01	$1.19_{2.29}^{2.01}$	0.13
ORCHIDEE-MICT	1.06	2.46-1.63	$1.06_{2.46}^{1.63}$	0.25
SDGVM	1.31	1.64-2.68	$1.31_{1.64}^{2.68}$	0.19
VISIT	1.01	2.40-1.67	$1.01_{2.40}^{1.67}$	0.15
Ensemble Mean	0.85	1.99-1.99	$0.85_{1.99}^{1.99}$	0.02

Table 2. Conventional model skill scores and skill scores modified to explicitly account for uncertainty in model benchmark. Model results from *Le Quéré et al.* (2017)
a) Root Mean Square Error (RMSE) calculated on upper and lower uncertainty bounds.
b) RMSE is given as 〚score〛_lower^upper where score is the RMSE evaluated against the nominal value and upper and lower are RMSE evaluated against the upper and lower 2σ uncertainty.
c) Only values outside 2σ uncertainty are scored in RMSE

Towards Task 7b: The stable isotope ^{13}C is frequently used as a tracer in site-scale studies (e.g., the dogwood PiTS activity of Task 4a and the SPRUCE experiment of Task 1). But can variations in global fossil-fuel ^{13}C, as earlier identified under Task 7, be used as a tracer of global terrestrial biosphere activity? To answer that question, we are investigating the robustness and precision of simulated ^{13}C discrimination and fate in ELM-SPRUCE at the SPRUCE site. The SPRUCE ^{13}C observations are an ideal platform for evaluating model performance, and the linkage between ELM-SPRUCE and ELM facilitates transfer of understanding and modeling from the site-scale to the global terrestrial biosphere. These observations are being complemented with observations and simulation from the dogwood PiTS activity of Task 4a. As part of this activity an initial implementation of the Gu and Sun (2014) photosynthesis model with mesophyll conductance and isotope discrimination has been completed and further development is in process for potential incorporation into ELM-SPRUCE.

Towards Task 7c: From a terrestrial ecosystem perspective, the uncertainty surrounding the residual terrestrial biosphere sink and the associated global NBP can only be reduced by reducing the uncertainty in emissions from land-use land-cover change. The remaining uncertainty is irreducible from the perspective of terrestrial ecosystem science, resulting from uncertainty in anthropogenic emissions and ocean uptake outside the purview of terrestrial ecosystem science. Reducing the uncertainty in the biosphere flux is needed to enhance the value of the estimate as a model benchmark. Accordingly, we are in the initial stages of a reevaluation of the terrestrial biosphere contributions to uncertainty in land-use change emissions. This activity does not consider the uncertainty in socioeconomic drivers of uncertainty, as important as they are, but rather focuses on those contributions which are addressable by terrestrial ecosystem science such as estimates of biomass impacted by land-use change and the fate of carbon following disturbance. Particular attention is given to these components as simulated in ELM.

Task 7. Deliverable status

Date	Deliverables	Status
FY 2018	Manuscript synthesizing consequences of fossil-fuel and carbon-cycle uncertainty for understanding of the terrestrial biosphere C sink.	Posters presented; manuscript in preparation
FY 2018-19	Evaluation of ^{13}C representation in ELM-SPRUCE.	Early code development and assessment

FY 2018-19	Assessment of current science on terrestrial biosphere contributions to uncertainty in land-use emissions.	In process

Task 7 Publications/Manuscripts

Huntzinger DN, Michalak AM, Schwalm C, Ciais P, King AW, Fang Y, Schaefer K, 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) Uncertainty in the response of terrestrial carbon sink to environmental drivers undermines carbon-climate feedback predictions. *Scientific Reports* 7:4765, doi: 10.1038/s41598-017-03818-2.

Task 8: LeafWeb

LeafWeb is an automated online tool (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. A new focus has been placed on data support on understanding and modeling the relationship between the emission of sun-induced chlorophyll fluorescence and gross primary productivity.

Progress for FY2017 – For FY2018, we have made the following progresses:
- We successfully implemented a LeafWeb algorithm to estimate C4 photosynthesis model parameters. This new functionality to LeafWeb was requested by LeafWeb users.
- We also implemented algorithms for joint analysis of A/Ci/PAR/Temperature/PAM curves.
- About 2000 photosynthetic response curves were analyzed by LeafWeb in FY2018.
- We collected a substantial amount of data to support the development of dynamic non-photochemical quenching models needed to understand and modeling SIF-GPP relations.
- We upgraded the security settings of www.leafweb.org to meet the standard required by the Department of Homeland Security.

On-going activities –
- Evaluate the performance of the C4 and joint A/Ci/PAR/Temperature/PAM curve analysis modules.
- Improve LeafWeb graphic functionalities to allow independent charting of different variables to help users visualize and understand their data.
- Add graphic functionalities for the outputs of the new C4 model
- Add new functionalities to help users detect errors in their input data to LeafWeb.

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_2 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 June 2017 with some TES SFA support.

Asbjornsen H, Campbell JL, Jennings KA, Vadeboncoeur MA, McIntire C, Templer PH, Phillips RP, Bauerle TL, Dietze MC, Frey SD, Groffman PM, Guerrieri R, Hanson PJ, Kelsey EP, Knapp AK, McDowell NG, Meir P, Novick KA, Ollinger SV, Pockman WT, Schaberg G, Wullschleger SD, Smith MD, Rustad L (2017) Guidelines and considerations for designing precipitation manipulation experiments in forest ecosystems. *Methods in Ecology and Evolution* (in press).

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* 133:333-345, doi:10.1007/s10533-017-0337-6.

McDowell N, Allen CD, Anderson-Teixeira K, Brando P, Brienen R, Chambers J, Christoffersen B, Davies S, Doughty C, Espirito-Santo ADF, Fisher R, Fontes CG, Galbraith D, Goodsman D, Grossiord C, Hartmann H, Holm J, Johnson DJ, Kassim AR, Michael M, Koven C, Kueppers L, Kumagai T, Malhi Y, McMahon SM, Mencuccini M, Meir P, Moorcroft P, Muller-Landau HC, Phillips OL, Powell T, Sierra CA, Sperry J, Warren J, Xu C, Xu X(2018) Drivers and mechanisms of tree mortality in moist tropical forests. *Tansley Review - New Phytologist*, https://doi.org/10.1111/nph.15027.

Yip DZ, Veach AM, Yang ZK, Cregger MA, Schadt CW. 2018. Methanogenic Archaea dominate mature heartwood habitats of Eastern Cottonwood (*Populus deltoides*). *New Phytologist* (in press)

4AII. SCIENCE HIGHLIGHTS SINCE JUNE 2017

- ORNL TES SFA staff completed 58 articles including publications in *Science*, *Nature,* and the *Proceedings of the National Academy of Sciences* June of 2017.
- SPRUCE – We sustained SPRUCE whole ecosystem warming (WEW) treatments throughout 2017 and 2018-to-date with very minor interruptions for maintenance or system error.
- SPRUCE – A high-impact paper in *Nature* is in press describing phenology response of SPRUCE vegetation to the first two years of warming. Notable and surprising is the warming induced extension of the fall growing season normally considered to be under day length control.
- SPRUCE – After two years of whole-ecosystem warming, lateral water fluxes (i.e., stream flow) decreased with warming likely due to increased evapotranspiration. Total organic carbon and cation (i.e., potassium, calcium) concentrations in stream water and porewater are higher in warmer enclosures, possibly reflecting increased mineralization. However, there were no

measurable changes in nutrient (N and P) concentrations in porewater, likely because any nutrients that are mineralized are rapidly taken up by biota in this nutrient-poor ecosystem.

- SPRUCE – A manuscript that describes coupled biogeochemical cycling (N and P) using a novel dual nutrient addition approach in the headwaters of Walker Branch Watershed is currently in revision in *Freshwater Science*. Further, two papers that synthesized global patterns in stream N cycling dynamics, including data collected from Walker Branch, were published in the past year.
- SPRUCE – Plant physiology work reveals divergent responses in the two dominant tree species which has widespread implications across the boreal north – a high impact publication is expected.
- SPRUCE – Warming has increased the amount of plant-available nutrients, especially in deeper peat.
- CC Modeling – A series of publications have been produced following active MODEX activities involving SPRUCE empirical data sets and ecosystem models (Huang et al. 1017; Jiang et al. 2018; Ma et al. 2017).
- CC Modeling – Successfully implemented a calibration approach using surrogate modeling to improve E3SM land model predictions as the Missouri flux site using observations.
- CC Modeling – Developed and applied a new detection and attribution capability for offline land model simulations for determining the causes of changes in runoff in the continental US.
- CC Modeling – Integrated ELM-SPRUCE into E3SM version 1, improving predictions of nutrient cycling at the site.
- Multi-Assumption Architecture and Testbed (MAAT) v1.0 code is published open source on GitHub https://github.com/walkeranthonyp/MAAT.
- Soil C – Task 5 focused on how soil moisture affected soil carbon decomposition, because increased frequency of drought may be a consequence of global change but is generally neglected within the literature. A field study, a lab study, and a theoretical study all found that decreasing soil moisture usually tended to increase or stabilize soil carbon, which runs counter to the expectations of decreased soil carbon under increased temperature expected from future global change.
- FRED 1.0 was downloaded from http://roots.ornl.gov hundreds of times since its release last year. Version 2 of the Fine-Root Ecology Database was released to the public in early June 2018 from an updated web platform. There was considerable interest in this release from the broader community of root and rhizosphere ecologists; the project was liked or re-tweeted hundreds of times on Twitter.
- Root Function – Roots can have significant impacts on soil hydraulic properties, indicating need for new data and new modeling approaches.
- Fossil Emissions implications – We developed model skill scores which explicitly account for uncertainty in terrestrial land sink resulting from uncertainty in fossil fuel emissions.
- MOFLUX scientists contributed to the evaluation of NASA OCO-2 SIF products, resulting in a high-profile paper in *Science*. The Fluorescence Auto-Measurement Equipment developed by MOFLUX scientists has been in successful operation at MOFLUX since Sept 2016. Data obtained so far revealed highly asymmetrical seasonal and diurnal patterns of SIF emission. These patterns suggest strong dependence of SIF emission on long-term changes in canopy photosynthetic capacity and short-term variations in canopy microstructure, plant physiological stress and non-photochemical quenching.
- LeafWeb – Parameter estimation for C4 photosynthesis models has been enabled in LeafWeb.

4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff produced 58 publications or completed manuscripts since our last summary report. This total includes 51 published/in press/accepted journal articles, 1 technical report, 1 book chapter. Five papers are in press, 3 accepted and 5 are working through the review process. This level of productivity over 1 year exceeds our average paper production rate from January 2012 through February 2017 (44 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.

The TES SFA group published in 34 different peer-reviewed publications in this reporting period including one paper each in *Science* (Sun et al. 2017)*, Nature* (Richardson et al. 2018), and the *Proceedings of the National Academy of Sciences* (Griffis et al. 2017). We also published 7 papers in *Journal of Geophysical Research – Biogeosciences,* and 3 each in *Atmospheric Environment, Biogeosciences, Geoscientific Model Development, and the Journal of Advances in Modeling Earth Systems*. Publications in the past year covered a broader range of journals.

Journal selection for publication of TES SFA work is at the discretion of the senior author. Journals are 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

Future science plans for the TES SFA will be fully detailed in the forthcoming quadrennial review document due to DOE BER in February 2019. 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 E3SM land model (ELM). To improve the modeling of gross primary production, we will apply new understanding of canopy processes enabled through the development of the SIP instrument and use to improve the modeling of gross primary production in ELM.

Improved *Sphagnum* modeling – Within the ELM framework we are improving 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

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.

Early results from the SPRUCE study suggest further investment in the biogeochemical cycling of both nitrogen and phosphorus are needed to adequately capture long-term nutrient feedbacks within the bog with warming. Models are being used to evaluate the potential feedback magnitudes from P limitations and N_2 fixation inputs to better define the need for future measurements.

Identified knowledge gaps also drive model developments for land surface development of the E3SM model, and within NGEE project tasks that are complementary to efforts within the TES SFA. The TES SFA will continue to contribute new science to E3SM code base, including new algorithms for phenology and responses to extremes, and *Sphagnum* processes described above. TES SFA modeling efforts will

benefit from developments in the other projects, such as improved hydrology through the ALM-PFLOTRAN coupling in NGEE-Arctic and the inclusion of a global phosphorus cycling model in E3SM.

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 (Georgia Tech), Jeff Chanton (Florida State) and colleagues have received support from DOE BER for their ongoing studies of microbial ecology at SPRUCE, and the TES SFA has taken on the management of that funding via subcontract for FY2018, FY2019 and FY2020.
- Drs. Scott Bridgham (University of Oregon), Jason Keller (Chapman University) and colleagues are also supported to conduct a DOE BER funded study of mechanisms underlying heterotrophic CO_2 and CH_4 fluxes in a peatland.
- Dr. Andrew Richardson (Northern Arizona University) leads the task on phenology with his funding for the PhenoCam network, and we are working to make this a funded subtask in FY2018 and beyond.
- Drs. Kirsten Hofmockel (Pacific Northwest National Lab) and Eric Hobbie (University of New Hampshire) have been 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. Adrian Finzi's research group (Boston University) conducts high temporal resolution measures of CO_2 and CH_4 flux from the experimental plots that will include ^{13}C isotopic capabilities. This work continues with new on-site staff each year.
- Dr. Karis McFarlane and colleagues at LLNL-CAMS provide measurement support for ^{14}C isotopic composition of air, plant tissues and peat from the S1-Bog and SPRUCE experimental plots.
- Dr. Nancy Glenn (Boise State) 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 (Northern Arizona University) 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 (San Diego State University) 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_2 acclimation.
- Dr. Jalene M. LaMontagne (DePaul University) joined the SPRUCE group in 2017 to study mast seeding patterns in response to climate change.
- Dr. Bruce McCune (Oregon State University) and Sarah Jovan (USDA Forest Service) have their own support to study lichen responses to warming and elevated CO_2 within the SPRUCE experimental infrastructure.

CITED REFERENCES (NOT IN THE TES SFA APPENDIX LISTS)

Andres RJ, Boden TA, Higdon D (2014) A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission, *Tellus B: Chemical and Physical Meteorology* 66(1):23616.

BERAC (2017) Grand Challenges for Biological and Environmental Research: Progress and Future Vision; A Report from the Biological and Environmental Research Advisory Committee, DOE/SC–0190, BERAC Subcommittee on Grand Research Challenges for Biological and Environmental

Research (science.energy.gov/~/media/ber/berac/pdf/Reports/ BERAC-2017-Grand-Challenges-Report.pdf).

Chapin FS III, et al. (2006) Reconciling Carbon-cycle Concepts, Terminology, and Methods, *Ecosystems* 9(7):1041-1050.

Gu L, Sun Y (2014) Artefactual responses of mesophyll conductance to CO_2 and irradiance estimated with the variable J and online isotope discrimination methods. *Plant, Cell & Environment* 37(5):1231-1249.

Huntzinger DN et al. (2017) Uncertainty in the response of terrestrial carbon sink to environmental drivers undermines carbon-climate feedback predictions, *Scientific Reports* 7(1):4765.

Kromdijk et al. (2016) Improving photsynthesis and crop productivity by accelerating recovery from photoprotection. *Science* 354:857-861.

Le Quéré C, et al. (2017) Global Carbon Budget 2017. *Earth System Science. Data Discussion* 2017:1-79.

Lovenduski NS, Bonan GB (2017) Reducing uncertainty in projections of terrestrial carbon uptake. *Environmental Research Letters* 12(4):044020.

US DOE (2018) *Climate and Environmental Science Division Strategic Plan 2018-2023*, U.S. Department of Energy, Office of Science, DOE/SC-0151, https://science.energy.gov/~/media/ber/pdf/workshop%20reports/2018_CESD_Strategic_Plan.pdf

5. STAFFING AND BUDGET SUMMARY

5A. FY2018 FUNDING ALLOCATION BY PROGRAM ELEMENT

Total expected available funding for ORNL's TES SFA in FY2018 included $5,315K carryover from FY2017 (including $1,572K for external commitments) and $9,560K of new budget authorization. As of 15 June 2018, we have not yet received $2,390K of the expected annual FY2018 allocation. FY2018 spending is summarized in the following table.

FY2018 Budget expenditures by TES SFA Program Element through 12 June 2018. The data include prior year carryover amounts.

Task	Cost Through 12 June 2018 ($K)	Commitments Through 12 June 2018 ($K)	Remaining Funds 12 June 2018 ($K)	Expected Additional Allocation ($K)
T1: SPRUCE Science	2,212	143	710	632
T3: Carbon Cycle Modeling	927	68	330	244
T3b: Model Process Analysis	73	0	98	34
T6: MOFLUX	444	0	268	112
T4b: Process Study - Root traits	111	92	262	45
T4c: Process Study - Root Func.	127	78	97	45
T5: Soil C Studies	307	71	98	95
T7: C Emissions	57	0	77	21
T8: LeafWeb	105	0	65	33
T1: SPRUCE – Operations	920	528	912	65
T1: SPRUCE – Materials	91	29	147	150
T1: SPRUCE – Reserve	0	0	232	100
Georgia Tech SPRUCE Contract FY2018 to FY2020	44	348	0	857
SFA Contingency	1817	0	101	1607
SFA Totals	**$7,235**	**$1,357**	**$3,397**	**$4,040**

We are currently spending at rates consistent with the spending plans outlined in the February 2015 TES SFA renewal proposal budgets for FY2018. We anticipate unspent carry over funds to be approximately $3,000K across all TES SFA tasks and external commitments.

Some new budget authorization provide through the TES SFA for closely related activities are managed as independent efforts and not detailed in the analysis above.

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 FY2018 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_2 efflux, belowground production via repeated minirhizotron image collections, stem allometric increment data, and litter basket net primary production. Since June 2016, J.D. Wood serves as Missouri site-PI of the MOFLUX site.

Yiqi Luo- Northern Arizona University ($75K) – Dr. Luo's research group at NAU 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.

Xiaofeng Xu - San Diego State University ($38K) - In a joint subcontract with NGEE-Arctic, Dr. Xu is developing and testing a CH_4 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 ($63K) – 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.

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.

RhizoSystems, LLC ($32K) – 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 ($106K) – 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.

Nancy Glenn – Boise State University ($68K) – This contract provides twice annual terrestrial lidar scans of the SPRUCE experimental plots to help assess vegetation growth, elevation change, and to define water table depths.

Georgia Technological University ($392K) – The first year of a 3-year subcontract for a SPRUCE project titled *Toward the predictive understanding of greenhouse gas production in high latitude peatlands*.

Karis McFarlane – Lawrence Livermore National Laboratory ($57K) – We contract with LLNL to provide isotopic analyses (^{14}C and ^{13}C) for air (x5 events per year) and tissue analyses (x1 per year) to provide a record of the application and accumulation of unique isotopic tracers into the SPRUCE ecosystem.

Infrastructure subcontracts in support of the SPRUCE project in FY2018 include funds and funding for site maintenance *(Pokegama Electric $57K)*, electrical service *(Lake Country Power $148K)*, propane supply *(Lakes Gas Co. $216K)*, elevated CO_2 supply *(PRAXAIR Inc. $155K)*, satellite internet connections *(Hughes Net & Viasat $11K)*, 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 – No new hires through June 2018, but we are looking to add postdoctoral associates still.

Anticipated Future Hires – Looking ahead to FY2019, 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 FY2018. Eric Ward completed his postdoctoral appointment on the SPRUCE project to take a full-time position.

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 FY2018

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. 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 FY2018.

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., the 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 are transitioning to work with the new DOE BER data center ESS-DIVE in the coming months as a permanent repository.

We are also using other facilities at collaborating DOE National Laboratories. The Lawrence Livermore National Laboratory – Center for Accelerator Mass Spectrometry (LLNL-CAMS) provides large volume, high precision ^{14}C measurements for ecosystem tracer studies. Pacific Northwest National Laboratory's Environmental Molecular Science Laboratory combines advanced instrumentation such as high-throughput mass spectrometry, advanced microscopy instruments, and NMR instruments with high performance computing.

5E. CAPITAL EQUIPMENT

Since the threshold amount of funds needed to define a capital expenditure has risen, no ORNL TES SFA funds have been used to acquire capital equipment in FY2018. 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.

APPENDIX A: COMPLETE PUBLICATION LIST – ORNL TES SFA

<u>Published, accepted and in review papers since June 2017 (i.e., the past year)</u>

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. *Biogeochemistry* 137: 51-71, doi: 10.1007/s10533-017-0409-7.
2. Asbjornsen H, Campbell JL, Jennings KA, Vadeboncoeur MA, McIntire C, Templer PH, Phillips RP, Bauerle TL, Dietze MC, Frey SD, Groffman PM, Guerrieri R, Hanson PJ, Kelsey EP, Knapp AK, McDowell NG, Meir P, Novick KA, Ollinger SV, Pockman WT, Schaberg G, Wullschleger SD, Smith MD, Rustad L (2017) Guidelines and considerations for designing precipitation manipulation experiments in forest ecosystems. *Methods in Ecology and Evolution* (in press).
3. Barba J, Cueva A, Bahn M, Barron-Gafford GA, Bond-Lamberty B, Hanson PJ, Jaimes A, Kulmala L, Pumpanen J, Scott RL, Wohlfahrt G, Vargas R (2018) Comparing ecosystem and soil respiration: a review of tower-based and soil measurements challenges. *Agricultural and Forest Meteorology* 249:434-443, doi: 10.1016/j.agrformet.2017.10.028.
4. Chen M, Griffis TJ, Baker JM, Wood JD, Meyers T, Suyker A (2018) Simulating the long-term carbon budget across agricultural sites using CLM4-Crop, *Agricultural and Forest Meteorology* 256-257:315-333, doi: 10.1016/j.agrformet.2018.03.012.
5. Chen, Z., Griffis TJ, Baker JM, Millet D, Wood JD, Dlugokencky E, Andrews A, Sweeney C, Hu C, Kolka R (2018) Source partitioning of methane emissions and its seasonality in the U.S. Midwest. *Journal of Geophysical Research - Biogeosciences* 123:646-659, doi: 10.1002/2017JG004356.
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7. Dhiman I, Bilheux HZ, DeCarlo KF, Painter SL, Santodonato LJ, Warren JM (2018) Quantifying root water extraction after drought recovery using sub-mm in situ empirical data. *Plant and Soil* 424:73-89; doi: 10.1007/s11104-017-3408-5.
8. Duarte HF, Raczka BM, Ricciuto DM, Lin JC, Koven CD, Thornton PE, Bowling DR, Lai CT, Bible KJ, Ehleringer JR (2017) Evaluating the Community Land Model (CLM4.5) at a coniferous forest site in northwestern United States using flux and carbon-isotope measurements. *Biogeosciences* 14(18):4315-4340.
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Data sets marked with a triple asterisk (***) have been added or updated since June 2017.

SPRUCE Public Data Sets:
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2. 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. 2017. Viewpoints: A global Fine-Root Ecology Database to address belowground challenges in plant ecology. New Phytologist 215: 15-26. https://doi.org/10.1111/nph.14486

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7. **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/.

8. **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.

9. 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

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15. **Tool for Evaluating Mesophyll Impact on Predicting Photosynthesis (TEMIPP).** TEMIPP is a Microsoft Excel spreadsheet-based tool used for demonstrating the impact of lacking an explicit representation of mesophyll diffusion in a photosynthetic model on the predicted response of photosynthesis to the increase in CO_2 partial pressures. TEMIPP is provided as a supplement to the recent publication: Sun Y, Gu L, Dickinson RE, Norby RJ, Pallardy SG, Hoffman FM (2014) Impact of mesophyll diffusion on estimated global land CO_2 fertilization. *Proceedings of the National Academy of Sciences of the United States of America* 15774–15779, doi: 10.1073/pnas.1418075111. Download TEMIPP at http://tes-sfa.ornl.gov/node/80.

16. **Walker Branch Watershed Long-Term Data Archive.** Repository for TES SFA-funded data collections of long-term hydrology, stream ecology, chemistry, and biogeochemistry measurements and research. Data can be accessed at http://walkerbranch.ornl.gov/.

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