FY2020 PROGRESS REPORT
OAK RIDGE NATIONAL LABORATORY'S
TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA
(TES SFA)

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ABSTRACT

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

1) How will atmospheric and climate change affect the structure and functioning of terrestrial ecosystems at spatial scales ranging from local to global and at temporal scales ranging from sub-annual to decades and centuries?
2) How do terrestrial ecosystem processes, and the interactions among them, control biogeochemical cycling of carbon and nutrients, the exchanges of water and energy, and the feedback to the atmosphere, now and in the future?

The proposed science includes manipulations, multi-disciplinary observations, database compilation, and fundamental process studies integrated and iterated with modeling activities. The centerpiece of our climate change manipulations is the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment that tests multiple levels of warming at ambient and elevated CO_2 on the vegetation response and biogeochemical feedbacks from a *Picea-Sphagnum* ecosystem. Other 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 integrates 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 Scientific Focus Area (TES SFA) conducts fundamental research in support of the DOE BER Earth and Environmental Systems Sciences Division (EESSD) as outlined in the most recent Strategic Plan (US DOE 2018). The TES SFA addresses all five EESSD grand challenges by integrating data and models to understand and predict Earth System drivers and biogeochemical cycling, especially in critical ecosystems such as high-latitude regions. The TES SFA strives to expand fundamental knowledge of terrestrial systems and translate that knowledge into mechanistic Earth System Models (ESMs), in particular the Energy Exascale Earth System Model (E3SM). The TES SFA also addresses grand challenges identified in the 2017 BERAC Grand Challenges Report (BERAC 2017) by advancing our understanding of the interactions among key players of the Earth System (e.g., microbial communities, vegetation, and humans) with a systems science approach. The TES SFA emphasizes information translation through levels of ecosystem organization connecting complex fine-scale biological processes with large-scale biosphere-climate feedbacks. Data management and access activities are an integral part of TES SFA efforts to share not only scientific progress but also data products and research results with the broader scientific communities.

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 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 landscape greenhouse gas flux, 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.

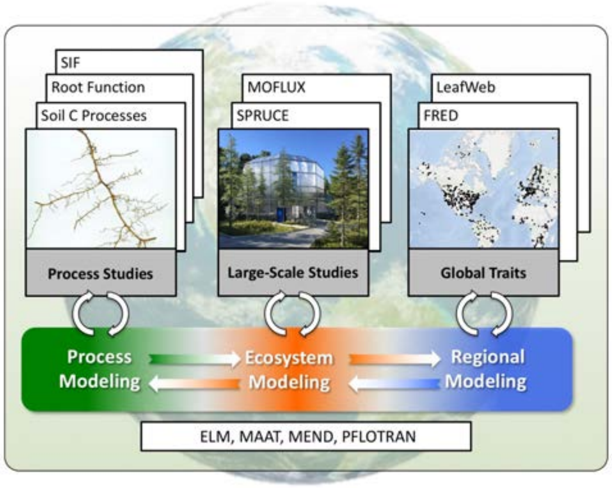


Fig. 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

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 that control vulnerability of organisms and ecosystem processes to important climate change variables which provide data for model development. The TES SFA also supports smaller-scale, process-level manipulations of ecosystem processes ranging from photosynthesis to root function to mechanistic studies of soil carbon cycling, as well as long-term monitoring of landscape flux and sun-induced chlorophyll fluorescence (SIF) measurements at the Missouri flux (MOFLUX) site. TES SFA research on SPRUCE and MOFLUX covers a wide range of ecosystems in eastern North America from cool wet northern systems to warm and relatively dry systems on the forest-prairie transition in Missouri.

Data from large- and small-scale TES SFA observations and experiments are integrated into models to identify and reduce terrestrial process and parameter uncertainties in the global Earth system. The Multi-Assumption Architecture & Testbed (MAAT) and Energy Exascale Earth System Model (E3SM) provide frameworks for this model-data integration and uncertainty quantification. Model predictions are improved through parameterization, calibration, and the development of new process-based submodels focused on key aspects of wetland, boreal and temperate forest systems, for example the Microbial Enzyme Decomposition (MEND) model, which focuses on the belowground ecosystem.

Given the opportunities for serendipity in scientific research, the TES SFA has built-in mechanisms within its overall planned and organized research tasks to allow timely exploration of emerging scientific issues that are unplanned but nevertheless important to the TES SFA vision and relevant to the EESSD’s Strategic Plan. These mechanisms facilitate the formation of novel ideas and new research frontiers, as well as the growth of early career staff.

TES SFA research is ambitious in its scope, effort, and resource requirements. It undertakes the challenge of 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 so that the science can be advanced efficiently and effectively.

2.0 SCIENCE QUESTIONS, GOALS AND MILESTONES

The following overarching science questions and the subsequent description of key goals and milestones are focused on resolving uncertainties in terrestrial ecosystem response to atmospheric and climate change.

1) How will atmospheric and climate change affect the structure and functioning of terrestrial ecosystems at spatial scales ranging from local to global and at temporal scales ranging from sub-annual to decades and centuries?
2) How do terrestrial ecosystem processes, and the interactions among them, control biogeochemical cycling of carbon and nutrients, the exchanges of water and energy, and the feedback to the atmosphere, now and in the future?

Goals and Milestones

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

Goal 1: Understand, quantify and model long-term ecosystem responses to the interactive effects of atmospheric and climatic change in an understudied but globally important ecosystem.

- *Long-term milestone:* Comprehensive predictive understanding of decadal peatland ecosystem responses to a range of technologically-advanced warming and elevated [CO_2] treatments in an ombrotrophic bog in northern Minnesota.

Goal 2: Understand drivers of ecosystem functions and interactions by integrating new process knowledge in the E3SM Land Model (ELM) and related models of varying complexity, and the use of state-of-the-art sensitivity analysis, uncertainty quantification, and model evaluation to obtain novel insights leading to new observations and experiments.

- *Long-term milestone:* Increase confidence in model projections based on improved mechanistic understanding and model representation of ecosystem processes, ranging from canopy photosynthesis to microbially-mediated decomposition, that govern responses to, and interactions with, environmental change.

Goal 3: Improve the understanding and model representation of the linkages among above- and belowground functional traits, their response to changing environmental conditions, and the resulting consequences for ecosystem biogeochemical cycling.

- *Long-term milestone:* Develop global ecological trait databases, available to the broader community of ecologists and terrestrial biosphere modelers and use these databases to target novel observations and experimental manipulations that fill gaps in our mechanistic understanding and modeling of key ecological traits.

Goal 4: Improve process-based understanding of belowground biogeochemical cycling, including processes occurring at the root-soil interface, to support predictions of small- and large-scale belowground pools and fluxes in terrestrial biosphere models.

- *Long-term milestone:* Incorporate a flexible, comprehensive, and tested model of the belowground ecosystem into fully-coupled ESMs.

Goal 5: Achieve a predictive understanding of ecophysiological, biochemical and physical processes controlling the exchanges of carbon, water and energy between land and atmosphere with advanced observational and theoretical approaches.

- *Long-term milestone:* Develop and demonstrate a mechanistic model of photosynthesis involving light reactions for applications in ESMs, a light reactions-based approach for partitioning net ecosystem changes of carbon and water, and a reliable, easy-to-use sun-induced chlorophyll fluorescence (SIF) measurement system for flux communities around the world.

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 in 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.

The TES SFA is supported by 35 dedicated scientific and technical staff at ORNL including 6 current postdocs. Over 80 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 modeling 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.

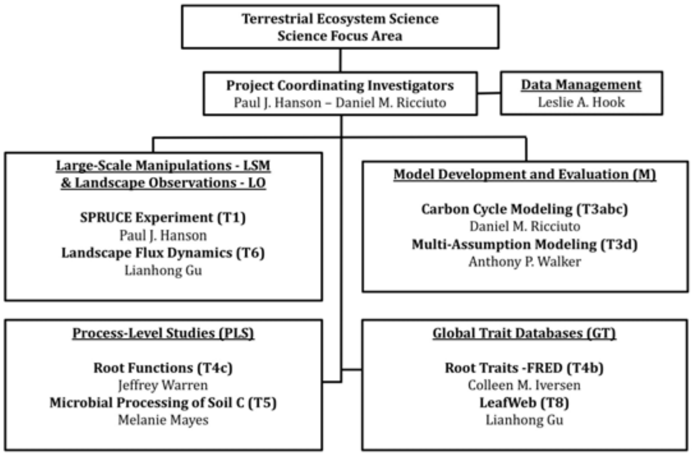


Fig. 2. Organizational chart for the TES SFA effective February 2019.

Individual Task lead responsibilities are as follows:

Large Scale Manipulations (LSM) and Landscape Observations (LO)

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 Kyle Pearson. Robert 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 led characterization of growth and community dynamics of the diverse *Sphagnum* communities until his retirement in April 2020. Over the next annual cycle, these tasks will fall under the purview of David Weston and a post-doctoral associate. 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 and porewater biogeochemistry is led by Natalie Griffiths and Steve Sebestyen (USDA FS) with technical assistance from Keith Oleheiser. 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. Verity Salmon coordinates compilation of peat, plant and porewater data for analysis of ecosystem-level N and P stoichiometry.

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 6 – Lianhong Gu leads activities in the Coordinated Eco-physiology, Eddy covariance, and Sun-Induced chlorophyll Fluorescence Studies (CEESIFS) to advance integrative ecosystem science. Jeff Wood (University of Missouri) operates the MOFLUX on-site activities. Other contributing staff include Colleen Iversen, Melanie Mayes, Anthony Walker, Jana Phillips and Joanne Childs.

Model Development and Evaluation (M)

Task 3abc – C-Cycle modeling activities are led by Daniel Ricciuto. Subtask contributions are made as follows: Wetlands [Xiaoying Shi, Xiaofeng Xu (San Diego State)], Allocation (Jiafu Mao, Dan Ricciuto), Photosynthesis (Anthony King, AnthonyWalker), rhizosphere (Xiaojuan Yang), ecological forecasting [Ricciuto, Yiqi Luo (NAU)], supersites (Jitu Kumar), C flux reanalysis (Mao), detection and attribution [Mingzhou Jin (UTK), Mao], model reduction using representativeness (Kumar), and model intercomparisons (Ricciuto, Mao, Shi, King).

Task 3d – 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.

Process-Level Studies (PLS)

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 and Chris Schadt in microbial ecology to develop an improved microbial process model (MEND) for soil C cycling.

Global Trait Databases (GT)

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 8 – Lianhong Gu supports and manages LeafWeb, a global database of biochemical, physiological and biophysical properties of leaves.

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 FY2020 the active membership of the SPRUCE Advisory Panel included: Molly Cavaleri (Michigan Technological University); Camilo Rey-Sanchez (University of California - Berkeley); Tim Moore (McGill University); Pat Megonigal (Smithsonian Environmental Research Center) and Daniel R. Engstrom (University of Minnesota, Emeritus).

4. PERFORMANCE MILESTONES AND METRICS

This section represents a summary of TES SFA activities accomplished since the review document dated February 2019. The material is organized by research theme and task with parenthetical identification of the goals addressed by each task. Task numbers are unchanged for reference across historical planning and review documents even though task titles may have been edited over time.

Large-scale Manipulations and Landscape Observations

Task 1: Spruce and Peatland Responses Under Changing Environments – SPRUCE (Goals 1,2,3,4,5)

Task 6: Coordinated Eco-physiology, Eddy covariance, and Sun-Induced chlorophyll Fluorescence Studies (CEESIFS) to advance integrative ecosystem science (Goal 1,2,3,4,5)

Carbon-Cycle Focused work

Task 3a: Improving process models with site-level observations and experimental data (Goals 1,2,3,4).

Task 3c: Functional Testing (Goals 1,2,3,4)

Task 3d: Multi-Assumption Systems Modeling (Goals 2,3,5)

Process-Level Studies (PLS)

Task 4c: Root function and modeling (Goals 2,3,4)

Task 5: Microbial processing of soil carbon (Goals 2,4)

Global Trait Databases (GT)

Task 4b: Root traits characterization (Goals 2,3,4)

Task 8: LeafWeb data assimilation tool –New Task (Goal 3)

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

LARGE-SCALE MANIPULATIONS AND LANDSCAPE OBSERVATIONS

Task 1: SPRUCE Infrastructure

SPRUCE warming treatments are running full time throughout COVID-19 site-access limitations 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). Table 1 shows the achieved whole-ecosystem warming treatments and elevated CO_2 treatments for the 2019 calendar year. Treatment data are archived in Hanson et al. (2016).

Table T1.1. Mean annual air and soil temperatures and CO_2 concentrations by SPRUCE plot for 2019. Text in red correspond to elevated CO_2 treatments.

Plot #s	Target Temperature Differential	Mean Air Temperature at +2 m	Mean Soil Temperature at -2 m	Ambient Daylight Mean Growing Season [CO_2]*	Elevated Daylight Mean Growing Season [CO_2]**
	(Delta °C)	(°C)	(°C)	ppm	ppm
Plots 7 & 21	Ambient	3.8 , 3.7	5.3 , 5.8	411	---
Plots 6 & 19	+0	5.6 , 5.0	4.3 , 5.8	417	828
Plots 11 & 20	+2.25	7.7 , 7.6	6.7 , 6.7	411	831
Plots 4 & 13	+4.5	10.0 , 10.2	8.9 , 8.9	420	857
Plots 8 & 16	+6.75	12.3 , 12.2	11.1 , 11.2	422	946
Plots 10 and 17	+9.0	14.3 , 14.3	13.1 , 13.1	421	957

*For the purpose of this enumeration the growing season runs from day of the year 91 through 312 to match the active season in the +9 °C treatment plots.

**Elevated CO_2 would approach 900 ppm in all plots if a variable active season definition were applied.

In 2019, the unique isotopic signatures of the added CO_2 treatments continued to be approximately -27 to -28 ∂ ‰ for ^{13}C and -540 Δ ‰ for ^{14}C. Through 4 full active seasons of eCO_2 exposures new tissue growth under eCO_2 is stabilizing at a new isotopic signatures compensurate with the experimental exposures to elevated CO_2 (Fig. T1.1).

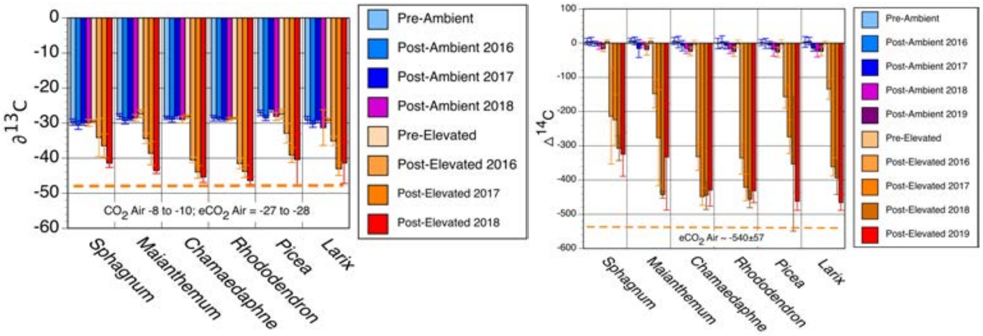


Fig. T1.1. Carbon isotope signatures for new aboveground foliar tissue growth across plots and eCO_2 treatments.

Task 1: SPRUCE Response Data

Carbon Cycle Assessments for the S1 Bog – One of the key goals of SPRUCE is to evaluate the net change of C stocks and fluxes from the bog ecosystem across the range of warming treatments with and without the potential fertilization effect from elevated CO_2. Our unprecedented, long-term, whole-ecosystem warming study enables an initial ecosystem-level analysis of ecosystem changes for the first three full years of whole-ecosystem warming. Warming caused variable responses for vegetation and consistent net losses of both CO_2 and CH_4 for a linear response of -31.3 gC m^{-2} y^{-1} $°C^{-1}$ (Fig. T1.2). Carbon losses with warming of +2.25 to +9 °C were found to be 4.5 to 18 times faster than the historical rate of peatland carbon accumulation. Through 3-years of sustained active season exposure to elevated CO_2, we have not yet observed a dominant and hypothesized increase in C uptake likely due to nutrient limitations.

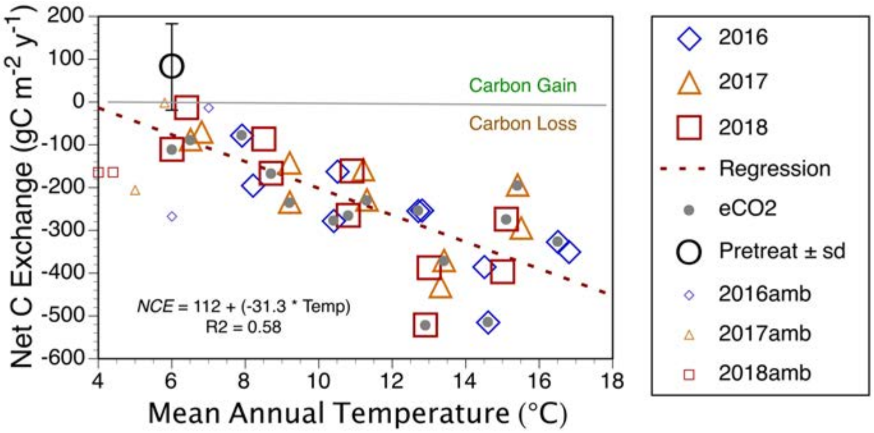


Fig. T1.2. Measured ecosystem net C exchange (NCE; g C m^{-2} y^{-1}) for all treatment plots (+0, +2.25, +4.5, +6.75 and +9 °C treatments) plotted against the mean annual air temperature at +2 m for each plot in 2016, 2017 and 2018. NCE was calculated as the difference in measures of above- and belowground net primary production and C losses via heterotrophic CO_2 efflux, net CH_4 efflux, and combined total organic C and dissolved inorganic C efflux. Treatment plots receiving elevated atmospheric CO_2 exposures (eCO_2) are indicated by a solid grey circle within the plot symbol. Also shown is the NCE for pretreatment conditions in 2014-2015 [open circle ± SD from Griffiths et al., (2017) modified based on new estimates of heterotrophic contributions]. Non-enclosed ambient plot data for 2016, 2017, and 2018 are shown as small open symbols, and are provided for reader reference.

Results of this work are now in press in a paper by Hanson et al. (2020) in *AGU Advances* the American Geophysical Union's new journal for full-length, high-impact research articles across all of the Earth and space sciences.

Net CH_4 and CO_2 efflux and Associated Microbial Processes – In a new paper interpreting the response of microbial processes and the flux of both CH_4 and CO_2 from the SPRUCE experiment, Hopple et al. (2020) in *Nature Communications* reported on long-term warming and elevated CO_2 impacts on anaerobic carbon cycling and CH_4 emissions in the S1 Bog. Large increases in the production and emission of CH_4 and CO_2, not present early in the warming experiment, are now observed after 5 years of warming, with microbial respiration becoming more methanogenic. The entire peat profile is experiencing greater rates of decomposition with warming, but elevated CO_2 continues to show limited effects on soil carbon cycling to date. While the massive soil carbon pool in peatlands has accumulated over millennia, these data suggest that it will be destabilized under prolonged warming and become more methanogenic.

Sphagnum production and Community Response – Norby et al. (2019) documented the rapid loss of the *Sphagnum* community from the SPRUCE treatment plots through a significant linear effect of minimum water table elevation on *Sphagnum* NPP. The response surface of *Sphagnum* was determined across a wide range of elevated temperatures, with additional consideration as to whether elevated CO_2 altered the temperature response surface. Using a new method for measuring annual growth of *Sphagnum*, dry matter increment of *Sphagnum* in the second year of treatment was shown to increase with modest warming to a maximum at 5°C above ambient and decreased with additional warming. After three years of warming, annual *Sphagnum* productivity declined linearly with increasing temperature (Fig. T1.3) due to widespread desiccation and loss of *Sphagnum*. Productivity was less in elevated CO_2 enclosures due to shading by shrubs. Given its keystone role in the bog ecosystem, a rapid decline of the *Sphagnum* community with sustained warming can be expected to have follow-on consequences to the structure and function of similar ecosystems with significant feedbacks to the global carbon cycle and climate change.

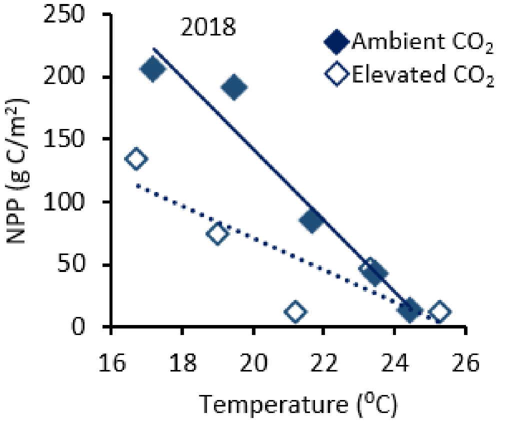


Fig. T1.3. Net *Sphagnum* primary productivity (NPP) combines the observations of *Sphagnum* growth and cover. The response surface indicates a loss 29 g C m^{-2} per °C warming in ambient CO_2 and 13 g C m^{-2} per °C in elevated CO_2, which are significant fractions of the carbon economy of this ecosystem.

Graham et al. (2020) reported on terrestrial laser scanning assessments of the microtopography of the SPRUCE bog surfaces in *Ecosystems*. The paper discusses the importance of the characterization of the nature of the mircoforms (i.e., hummocks and hollows).

Sphagnum acclimation to warming – Our prior research showed that the SPRUCE warming manipulation alters the *Sphagnum*-associated microbiome and influences N_2-fixation potential (Carrell et al., 2019). To investigate the role that the microbiome has on *Sphagnum* growth and acclimation to elevated temperatures, we used microbiome transfer studies to test: 1) whether the thermal origin of the microbiome influences acclimation of *Sphagnum* growth to treatment temperature and 2) whether there are costs related to mis-matches between *Sphagnum* host species and the origin *Sphagnum* species of the microbiome.

To answer these questions, we used microbiomes extracted from *Sphagnum* samples collected at 4 peatland sites including the SPRUCE site, Kulbäcksliden Research Park in northern Sweden, the Jura Mountains in the French Alps, and from Icelandic thermal hot springs. Using a full-factorial design, microbiomes were extracted from five *Sphagnum* donor species across the four different peatlands representing a wide thermal range (11.4-27 °C). The microbiomes were transferred onto three germ-free host *Sphagnum* recipient species in the laboratory. Microbiome donor *Sphagnum* species were either matching or not matching recipient *Sphagnum* species. Microbiome recipients were exposed to a range of experimental temperatures: ambient (+0°C) and three incremental temperatures (+2.25°C, +4.5 °C and +9°C) mimicking SPRUCE July warming scenarios. Growth rate and chlorophyll-a fluorescence were recorded over 4 weeks of experimentation. The largest growth rate of recipient *Sphagnum* was measured when growing with microbiome from a matching donor *Sphagnum* species that was 48% and 252% larger than the maximum growth rate of the germ-free *Sphagnum* and the non-matched host-microbiome pairs (Fig. T1.5), respectively.

Our preliminary results suggest that the composition of the *Sphagnu*m microbiome plays a large role in host plant temperature acclimation. We found that microbiome-provided benefits to the host plant were most pronounced when: 1) the thermal origin of the microbiome is similar to experimental temperatures, and 2) when donor and recipient host plant species are the same. Together, these results suggest that *Sphagnum* temperature acclimation can be modulated, in part, by microbial interactions through mechanisms yet to be discovered.

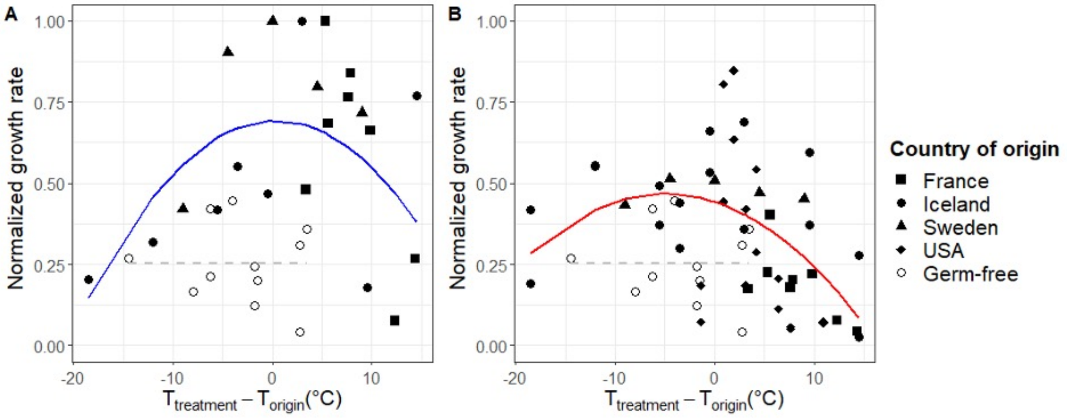


Fig. T1.4. Normalized *Sphagnum* growth as a function of the difference between mean growth chamber temperature (Ttreatment) and mean field temperature (Torigin; ΔTdiff = Ttreament-Torigin) for matched microbiome donor-recipient *Sphagnum* pairs (A, blue) and non-matched microbiome donor-recipient *Sphagnum* pairs (B, red) compared to germ-free *Sphagnum* (control, gray dashed line). Data for matched and non-matched are fitted with the model for plant growth response to temperature and control is a mean value.

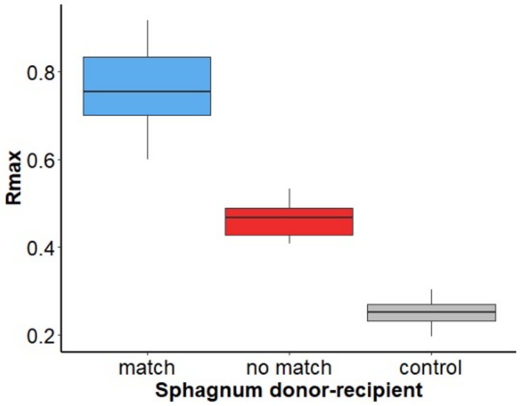


Fig. T1.5. Boxplot represents normalized optimal growth rate parameter (Rmax) for matched and non-matched microbiome donor-recipient *Sphagnum* pairs and mean control (germ-free *Sphagnum*). Horizontal line in each box is a median, whereas boxes represent 25th and 75th percentiles. Vertical lines are the 5th and 95th confidence interval (CI).

<u>*Aboveground vegetation production*</u> – Two papers on SPRUCE tree (Graham et al. 2020b) and shrub-layer (McPartland et al. 2020) growth through the first 4 seasons of manipulations have been produced and are under review. The tree growth showed initial negative responses for *Picea* (black spruce) that have disappated with time, and developing positive responses for *Larix* (*larch*); changes are hypothesized to be driven by nutrient availability increases under warming (see below). Shrub-layer vegetation responses are mixed, with some species showing increases with warming (*Rhododendron*, an ericaceous shrub) and others showing dramatic losses (*Maianthemum*, a forb).

Belowground Response Data - The dynamics and distribution of fine roots in ecosystems underlain by organic soils are some of the least understood processes in belowground ecology. Building on our work to understand fine roots in an ombrotrophic bog prior to initiation of climate change treatments (Iversen et al., 2018), we are leveraging on-going data collection (e.g., from manual and automated minirhizotrons, root ingrowth cores, and ion-exchange resins) to ask two main questions:

How does warming affect the phenology of root and fungal growth, and how is belowground phenology related to aboveground phenology, as well as edaphic and environmental conditions?

Using root ingrowth cores deployed and collected during the active and non-active seasons (data citation: Malhotra et al., 2020), we found that warming linearly increased shrub fine-root production by 1.2 km m^{-2} y^{-1} for every degree increase in soil temperature (Fig. T1.6). This dramatic root growth response (130% increase for a degree of warming) mainly occurred during the active season and was much stronger than found in previous upland warming experiments. Mixed-model analysis indicated that the strongest influence of warming was via the indirect effects of warming on peat drying, with a strong growth response in previously water-saturated hollows (Malhotra et al., 2020). Furthermore, differing plant functional types had different strategies for their response to warming; ericaceous shrubs *Rhododendron groenlandicum* and *Chamaedaphne calyculata* strongly increased fine-root length production while deciduous conifer *Larix laricina* strongly increased fine-root biomass production; *Picea mariana* showed no belowground response to warming. These strategies may be related to both differences in tree physiological response to warming, and differences in the way that shrubs and trees interact with and depend on their ericoid or ectomycorrhizal fungal partners, respectively. The quick adaptation of shrub fine roots to soil warming and drying could be one mechanism explaining the rapid shrubification of northern peatlands in response to warming and has important implications for carbon storage in these organic soils.

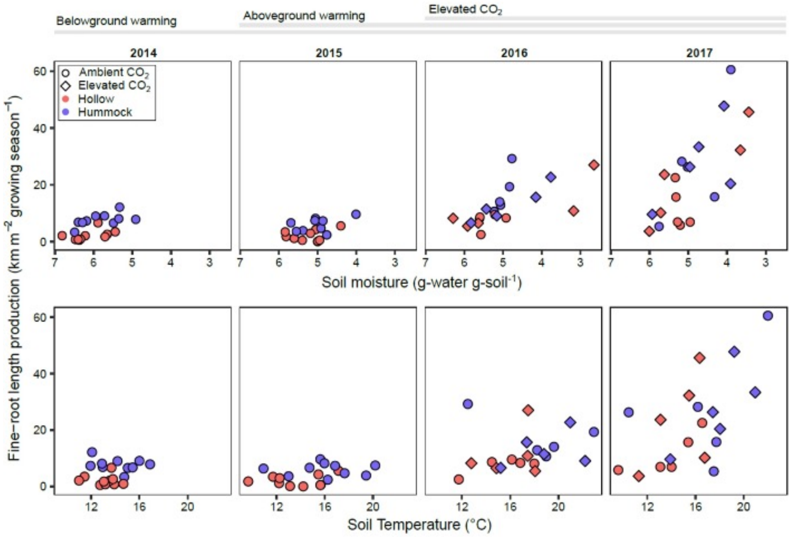


Fig. T1.6. Plot-scale (plant functional types summed) responses of fine-root growth to warming and drying conditions during the active seasons of 2014, 2015, 2016 and 2017.

Post-doctoral researcher, Dr. Camille Defrenne, is a new member of the SPRUCE team focusing on root and fungal interactions. Her preliminary analyses of root and fungal mycelium growth phenology in the automated minirhizotron images taken from the warmest SPRUCE enclosure indicates that the percent cover of fungal hyphae has a bimodal pattern of production (spring and fall) similar to tree and shrub roots (as in Iversen et al., 2018; Childs et al., 2019). In contrast, ectomycorrhizas, fungal rhizomorphs, and sporocarps had a unimodal pattern of production (fall), offset from root phenology.

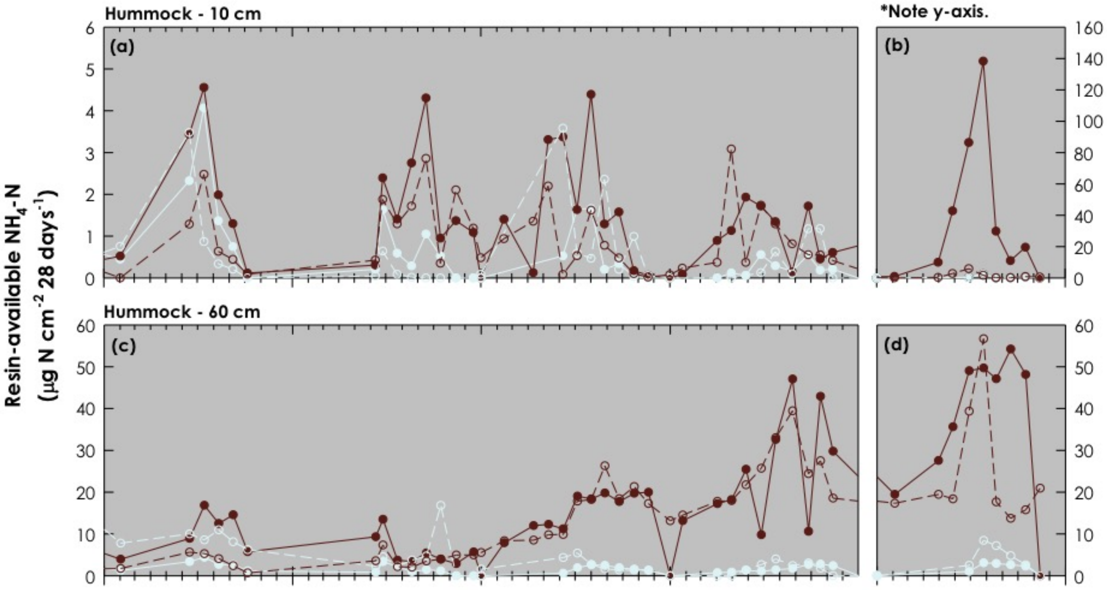


Fig. T1.7. Timing of inorganic nutrient availability in the SPRUCE experimental enclosures, captured as nutrients accumulated on ion-exchange resins, standardized to 28 days. Data shown are for available NH_4-N in surface and deeper peat within the hummock microtopographic position. Dark red is the +9 °C treatment; blue is +0 °C. Ambient [CO_2] is solid lines and filled symbols; elevated [CO_2] is dashed lines and open symbols.

<u>*Plant Available nutrients*</u> – Using ion-exchange resins deployed across peat depths and microtopographic positions (data citation: Iversen et al., 2017), we found that warming increased plant-available nutrients across hummock-hollow microtopography. In 2018, after 3 full years of whole-ecosystem warming, resin-available NH_4-N and PO_4-P were between two- and fifty times greater in surface peat at the warmest temperatures, and the vast majority of increased available nutrients occurred during the active season (Fig. T1.7a). The large peak in available nutrients in 2018 under ambient [CO_2] at the 10-cm depth (Fig. T1.7b) may be due to the decline and crash of the *Sphagnum* population, which was therefore no longer taking up available nutrients from surface peat (Norby et al., 2019). However, the lack of this response under elevated [CO_2] is mysterious, and may be due to additional microbial nutrient uptake; we are investigating this now in a current manuscript.

<u>How does warming affect the distribution of fine roots (and fungi) throughout the peat profile, and their relationship with soil nutrient and water availability?</u>

While warming has not drawn down the water table as much as was expected at the start of the SPRUCE experiment, we have observed drying of the peat with increased warming, indicating that there may be a larger volume of aerobic peat for roots and fungi to colonize. Work from a team led by Dr. Defrenne to visualize the automated minirhizotron tube mosaic (landscape) confirmed that increases in shrub root production were generally constrained to shallow peat, but also found that warming and associated peat drying led to a decrease in the abundance of fungal hyphae, especially dark fungal hyphae which have melanized cell walls, a stress-tolerant trait. In turn, the abundance of fungal rhizomorphs and sporocarps was higher in the +9°C, elevated CO_2 enclosure compared to the +0°C, elevated CO_2 enclosure, and fungal rhizomorphs were also found deeper into the peat profile in the warmed chamber compared to the control (Fig. T1.8).

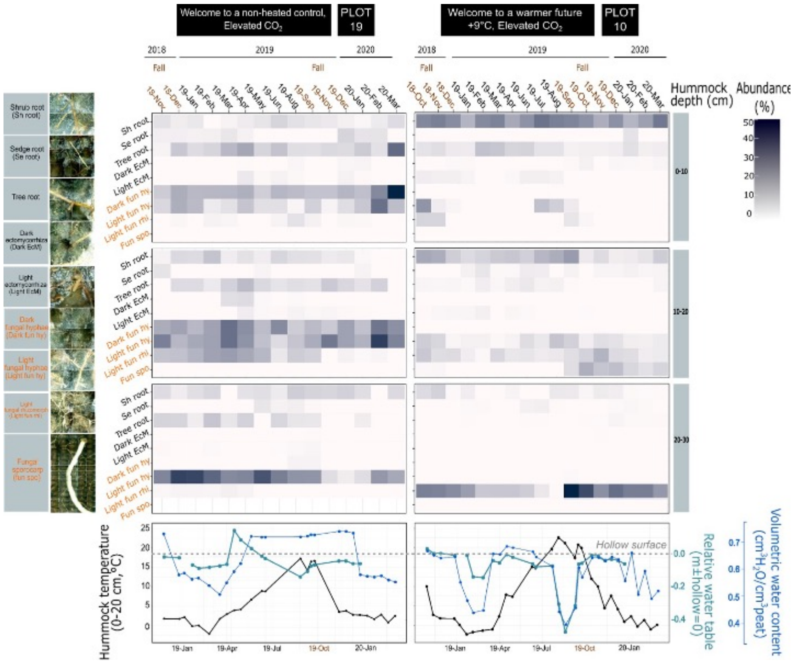


Fig. T1.8. Relative abundance (%) of fine roots, fungal mycelium and sporocarps from October 2018 to March 2020 in the hummock microtopography of the SPRUCE non-heated, elevated CO_2 enclosure and the +9°C, elevated CO_2 enclosure. The bottom panels show the associated time series of hummock temperature, relative water table and peat moisture content.

Furthermore, we observed that prior to 2018 increases in plant-available NH_4-N and PO_4-P were much greater below the rooting zone (Fig. T1.7cd), likely because of increased nutrient uptake by the vegetation or microbes in surface peat layers (i.e., greater competition for nutrients); increased nutrient availability throughout the peat profile does not appear to be driving increases in fine-root growth (Malhotra et al., 2020), but may have consequences for overall vegetation productivity as well as bacterial and fungal decomposition.

<u>*Woody Plant Physiology*</u> – The primary focus of the FY2019 field season was on monitoring and quantifying physiological damage in the woody plant community. We collated a health history for trees that had exhibited damage (discoloration or loss of foliage) from notes, photos and surveys over the past several years and are tracking them individually during subsequent measurement campaigns. A damage index for the tree and shrub species was added to the weekly phenology survey to provide additional information on timing of damage. Damage to the water transport system of the trees was assessed as accumulated hydraulic dysfunction (embolized conduits) at the end of the growing season. This work demonstrates that there is increased hydraulic damage for both tree species (*Picea* and *Larix*) when exposed to increased temperatures. This result is interesting as the past four years of plant water stress indicates divergent hydraulic strategies between the two tree species, with *spruce* exhibiting a conservative response to temperatures with minimal water loss and *Larix* exhibiting more water loss with a riskier hydraulic strategy (Warren et al. 2020).

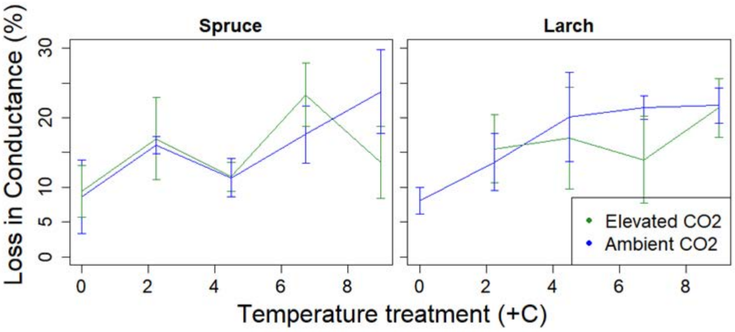


Fig. T1.9. Loss of conductance caused by embolized conduits in the water transport tissues of trees under increasing temperature treatments. Hydraulic dysfunction caused up to 25% loss in hydraulic conductance in both species

As the sap flow measurements have been particularly useful to assess differential hydraulic responses of the two tree species, and considering the crown damage for some trees, and the length of sensor deployment and decline in signal, in FY2019 and FY2020 we reinstalled and fully expanded our sap flow sensor network. This expansion resulted in up to six monitored trees per plot, doubling the number of monitored trees with a priority on better coverage of the Larix trees that are less abundant in the chambered plots. This expanded network will enable us to look at the differences in stem conductivity and transpiration between the two tree species and their responses to temperature and elevated [CO_2] treatments. We will also use these data in concert with soil water content and water flux from chamber measurements at the shrub/ground level to scale up to plot-level total evapotranspiration estimates.

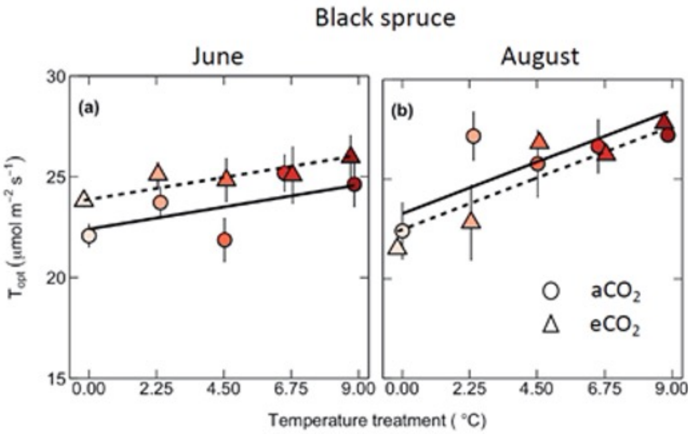


Fig T1.10. The optimum temperature for photosynthesis (Topt) increased with whole ecosystem warming for *Picea* (black spruce) and was more acute in the fully mature late season foliage. Similar results were exhibited by the *Larix* (not shown).

Foliar gas exchange (photosynthesis and respiration) and its response to temperature and elevated [CO_2] continues to be a major focus. We conducted the second annual foliar chlorophyll fluorescence measurement campaign to evaluate the efficiency of the photosynthetic processes and began the second phase of gas exchange campaigns in collaboration with a new PhD student, Jacob Hauger at Western University, Ontario, Canada to continue assessing photosynthetic acclimation to temperature treatments. We have made strong progress on both gas exchange analysis and plant water relations resulting in multiple new publiations under development or in review. Dusenge et al (2020) details thermal acclimation based on an increase in the optimum temperature for photosynthesis (Topt). Thermal acclimation was correlated with changes in the Topt of V_{cmax} and J_{max} for both tree species (Fig T1.10), and for *Chamaedaphne* in August, but no change in Topt was exhibited by *Rhododendron*. Respiration also acclimates to whole ecosystem warming, and we are pushing through a MODEX effort on understanding this response, and which functional equations can be used to represent this in ELM. The effects of CO_2 were less apparent and were species-specific. There was evidence for acclimation to elevated CO_2 by down-regulating photosynthetic capacity in *Picea*, but not in *Larix*. *Rhododendron* also acclimated to elevated CO_2 by reducing V_{cmax}. If acclimation to elevated CO_2 is not accounted for, the current models will over-predict gross primary production (GPP). If acclimation to elevated temperatures is not accounted for, the current models will underpredict GPP. As such, the physiology team continues to work directly with the modeling team to ensure results are correctly informing and helping to refine the model structure.

Hydrology and Water Chemistry – After four years of whole-ecosystem warming, lateral water flux (i.e., stream flow/outflow) continued to respond to warming treatments. Specifically, outflow decreased with warming likely due to increased evapotranspiration. Accurate quantification of outflow requires that the subsurface corral surrounding each enclosure is watertight. Unfortunately, leakage between subsurface corral joints during periods of high water has occurred, and the magnitude of leaks was recently quantified. Hydrograph separation techniques are being used to account for leakage when calculating outflow. Manual application of additional sealants to corral joints are planned for 2020 to minimize these leaks.

Solute concentrations in outflow also continued to respond to warming, with higher total organic carbon (TOC; Fig. T1.11) 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. While increased nutrient concentrations in outflow were not observed in the first two years of the experiment, total N (TN) and total P (TP) concentrations increased in warmer plots in year 3 (2018), again likely reflecting increased mineralization rates. A manuscript describing outflow chemistry responses will be drafted in 2020.

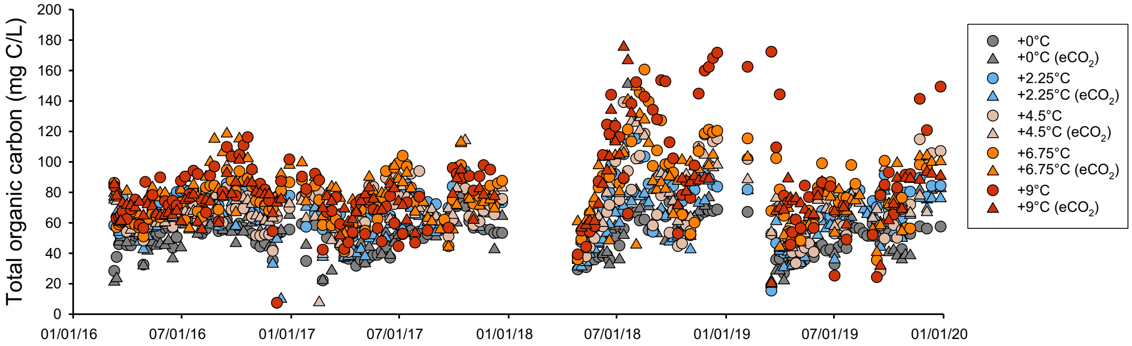


Fig. T1.11. Total organic carbon (TOC) concentrations in lateral outflow (i.e., stream flow) from SPRUCE enclosures and responses to warming over four years (2016-2019). While there is considerable variation in TOC concentration over time and among enclosures, there is a general trend of higher TOC concentrations in outflow from warmer enclosures.

Porewater – After four years of whole-ecosystem warming, TOC and cation concentrations remained elevated in shallow porewater (0-10 cm, 30-40 cm depths) in warmer enclosures, consistent with the observations in outflow (described above). While no changes in porewater nutrient concentrations were observed in the first two years of the experiment, both TN and TP concentrations increased in shallow porewater in response to warming during the third year (2018). Minimal chemistry changes were observed in deeper porewater (50 cm depth and below) in the first two years of SPRUCE, but small changes are now being observed at 50 cm depth (e.g., increased potassium concentrations with warming). No changes in porewater chemistry have been observed at or below 100 cm.

Porewater chemistry was charaterizied across four peatlands at the Marcell Experimental Forest [two ombrotrophic bogs (S1, S2)] and a poor] and rich fen [Bog Lake Fen and S3] to investigate similarities and differences in porewater across peatlands and to put the characteristics of porewater at the SPRUCE site (S1 Bog) into context with other peatlands. These results were published in *Wetlands* (Griffiths et al. 2019).

Decomposition – Litterbags collected from the main decomposition experiment continued to reveal no clear effect of warming on the decomposition of aboveground litter after 2 years of incubation in the 10 SPRUCE enclosures. Decomposition rates of fine roots continued to show a positive response with warming after 2 years, and the differential responses of above- vs. belowground tissues may be due to differences in chemistry, biology (i.e., different decomposers), and methodology (i.e., different mesh sizes, deployment depths). The lack of consistent response to warming may reflect the dominant role of intrinsic characteristics (i.e., litter chemistry) rather than extrinsic factors (i.e., temperature) in driving the early phases of decomposition. We hypothesize that the effects of warming will become more evident in the later stages of decomposition. This hypothesis is based on findings from an additional decomposition study that took place outside of the enclosures. This study focused on moss decomposition found that litter chemistry was the main driver of the early phases of decomposition, and environmental drivers became more important in later phases of decomposition. Data collection and analysis for this study was completed in the past year and a draft manuscript summarizing these findings is in progress in 2020.

<u>*N and P Nurient Cycling*</u> – Over a dozen water, peat, and vegation datasets from SPRUCE have been compiled into a pre-treatment N and P budget for the S1 Bog. This serves as an important benchmark for ELMv1-SPRUCE as well as a reference point for comparing ecosystem stoichiometry under SPRUCE manipulative treatments (Goals 1 and 2). Whole plant N:P ratios show varying degrees of N versus P limitation across plant functional types (PFTs), with trees exhibiting the highest degree of N limitation (Fig. T1.12). On an annual basis, fluxes of deposition, lateral outflow, N fixation, and denitrification are well balanced, with net change in N and P storage near zero. Annual cycling of N and P through NPP of vegetation shows that *Sphagnum* represents a large and dynamic pool of N and P at the S1 Bog: the decline of this species with warming is therefore expected to have dramatic impact on ecosystem stoichiometry (Norby et al. 2019). When comparing our ambient N and P budget to PFT-specific output from ELMv1-SPRUCE, we see the model captures vegetation N cycling more accurately than P cycling. A manuscript detailing this ambient N and P budget is in preparation and will be submitted in 2020.

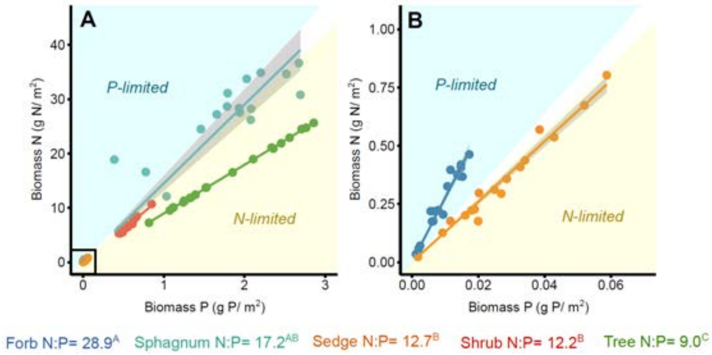


Figure T1.12. Whole-plant biomass N versus P under ambient conditions. B is a re-scaled view of the area within the black box outlined in A. In both A and B, points represent plot-level observations averaged across years and the light blue area corresponds to N:P ratios of over 16 while the yellow area corresponds to N:P ratios under 14 (critical ratios for wetland species identified in Koerselman and Meuleman 1996; Güsewell and Koerselman 2002). Superscript letters in the color-coded legend along the bottom denote significant differences between N:P ratios (α<0.05).

<u>*Microbial Community Responses*</u> – Initial studies of the responses to *in situ* experimental warming of the SPRUCE chambers indicated that the deep peat microbial communities and decomposition rates were resistant to elevated temperatures in the first years of experimental warming (Wilson et al., 2016). Our work in this effort has concentrated on characterizing microbial community structure and their response to treatments using metagenome-based analysis approaches. In depth analyses of these data have resulted in the characterization of over 400 distinct microbial genomes from 83 metagenome samples. Similar to the results of Wilson et al. (2016), metagenomic analyses of microbial communities from 2015 and 2016 have shown striking variation across the depth profile but have provided little evidence for changes in community structure with increased temperature or CO_2. Continued study of experimental warming plots has since shown rapid changes in several biogeochemical process rates, beginning around 2018, that are largely governed by microbial activity. Therefore, in collaboration with the DOE Joint Genome Institute (JGI), we are in the process of completing another metagenomic assessment of 2018 peat samples, with data for 35 of 48 metagenomes having now been completed and having passed genomic assembly QC criteria. We had anticipated completion by this time but have faced some delay due to COVID-19 restrictions at JGI and ORNL. Now that JGI is in phased reopening we are working with them toward a mid-July completion for the remaining samples.

Concurrently with the above metagenomic work, we have been conducting a series of manipulative experiments to understand important microbial processes at play in peatland biogeochemical processes. Prior work in peatland systems has focused on the acetoclastic and hydrogenotrophic methanogenesis pathways as the primary contributiors to methane fluxes. Recently, a new pathway for methanogenesis via the direct utilization of Methylated Aromatic Compounds (MACs) to fuel methanogenesis was described in organisms isolated from coal-bed systems (Mayumi et al., 2016). The parallells between coal formation and peat decomposition led us to investigate the potential for these processes in the SPRUCE S1 Bog ecosystem. Our mesocosm-based study showed large depth and compound specific increases in both the rate of methanogenesis and the ratio of methane to carbon dioxide in headspace gasses (Fig. T1.13). These responses appear late in incubations (>30 days) suggesting either (1) a long lag phase of physiological acclimation for the microbes prior to MAC methanogenesis, (2) an initially modest population size that can utilize the MAC compounds is followed by a population growth response, or 3) that the increased rate of methanogenesis may be due to primary fermentation of MACs, followed by methanogenesis via more traditional methanogenic pathways. Further experiments using $^{13}CH_3$ isotopically labeled versions of these compounds are planned to dissintangle these possibilities once full access to ORNL facilities and the SPRUCE site resumes.

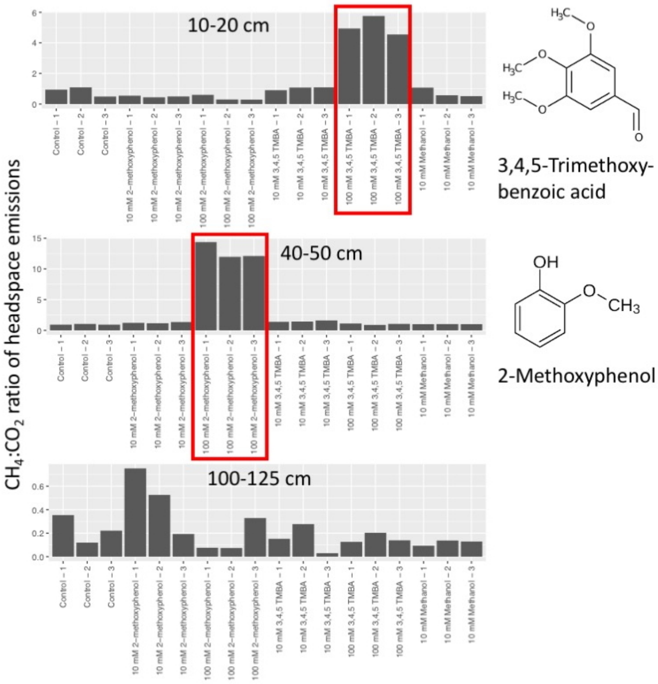


Fig T1.13. Methane to carbon dioxide ratio of mesocosm headspace gas between days 32 and 90 in response to the addition of various MAC additions. Both 3,4,5-trimethoxybenzoic acid and 2-methoxyphenol showed significant increases in all replicates at peat depths of 10-20 and 40-50 cm respectively.

SPRUCE Deliverable Progress

The SPRUCE project is now in its 5th full year of operation with science measurement and modeling tasks representing the dominant effort. The COVID-19 pandemic will have some impacts on the field work that can be accomplished in 2020. The following deliverables cover SPRUCE activities for FY2019 and FY2020.

Task 1 – SPRUCE Deliverable Status FY2019 and FY2020

Date	Deliverable	Status
December 2018	Manuscript on 3-year *Sphagnum* production and community change (Norby et al. 2019)	Completed
December 2018	Publish manuscript on pretreatment gas exchange: “Simulated projections of boreal forest peatland ecosystem productivity are sensitive to observed seasonality in leaf physiology.” Jensen *et al.*	Completed
March 2019	Publish manuscript of initial tree response to whole-ecosystem warming (Dusenge *et al.*2018)	Completed
March 2019	Publish manuscript of initial shrub responses to whole-ecosystem warming and eCO_2 (Ward *et al.* 2019)	Completed
March 2019	Publish manuscript of pretreatment and initial woody plant water responses to whole-ecosystem warming and CO_2 (Warren *et al.*)	To be submitted June 2020
September 2019	Manuscripts on 4-year tree growth and associated TLS Data – Graham/Hanson	To be submitted June 2020
September 2019	Manuscript on multi-year plant-available nutrient response to warming (Iversen *et al.*)	To be submitted September 2020
September 2019	Complete draft manuscript on the responses of lateral outflow and TOC concentration and fluxes to the first 3 years of warming (Griffiths *et al.*)	Planned

September 2019	Complete plant hydraulics measurements on the four main species	Planned
All Year	Sustain continuous SPRUCE treatments and automated data collection efforts	Completed
December 2019	Dataset and Leafweb analysis of photosynthetic and respiration × temperature response curves from intensive 2017 campaign.	Underway
December 2019	Manuscript on 3-Year shrub community growth – McPartland/Hanson	Submitted In Review
December 2019	Publish manuscript on initial woody plant acclimation to whole-ecosystem warming and eCO_2	Planned
May 2020	Submission of SPRUCE manuscript describing initial morphological and xylem anatomical responses to treatments.	Postponed for further data collection
August 2020	Complete 2nd field campaign to collect A-Ci curves to test respiratory and photosynthetic acclimation to temperature	Planned
September 2020	Manuscript on root-fungal interactions with warming and drying	Planned
September 2020	Manuscript on plot-scale C-Budget changes from warming and eCO^2	Completed
All Year	Sustain continuous SPRUCE treatments and automated data collection efforts	On Schedule

Task 1 SPRUCE Publications

Carrell AA, Kolton M, Glass JB, Pelletier DA, Warren MJ, Kostka JE, Iversen CM, Hanson PJ, Weston DJ (2019) Experimental warming alters the composition, diversity and N_2 fixation activity of the peat moss (Sphagnum fallax) microbiomes. *Global Change Biology* 25:2993-3004, doi:10.1111/gcb.14715

Dusenge ME, Ward EJ, Warren JM, Stinziano JR, Hanson PJ, Way DA (2020) Warming impacts on leaf carbon and water dynamics differ between boreal tree species. *Global Change Biology* (submitted)

Graham JD, Glenn NF, Spaete LP, Hanson PJ (2020a) Characterizing Peatland Microtopography Using Gradient and Microform-Based Approaches. *Ecosystems* doi:10.1007/s10021-020-00481-z

Graham JD, Hanson PJ, Phillips JR, Warren JM, Wullschleger SD, Glenn NF (2020b) *Picea mariana* and *Larix laricina* growth responses to elevated temperature and CO_2: a four-year synthesis from the SPRUCE experiment. *Global Change Biology* (Submitted).

Griffiths NA, Sebestyen SD, Oleheiser KC (2019) Variation in peatland porewater chemistry over time and space along a bog to fen gradient. *Science of the Total Environment* 697:134152, doi:10.1016/j.scitotenv.2019.134152

Hanson PJ, Griffiths NA, Iversen CM, Norby RJ, Sebestyen SD, Phillips JR, Chanton JP, Kolka RK, Malhotra A, Oleheiser KC, Warren JM, Shi X, Yang X, Mao J, Ricciuto DM (2020) Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances*, doi:10.1029/2020AV000163, (in press)

Hanson PJ, Walker AP (2020) Invited Commentary: "Advancing global change biology through experimental manipulations: Where have we been and where might we go?" *Global Change Biology* 26:287-299, doi:10.1111/gcb.14894.

Hopple AM, Wilson, RM, Kolton, M, Zalman, CA, Chanton JP, Kostka J, Hanson PJ, Keller JK, Bridgham SD (2020) Massive peatland carbon banks vulnerable to rising temperatures. *Nature Communications* 11:2373, doi: 10.1038/s41467-020-16311-8

Huang Y, Stacy M, Jiang J, Sundi N, Ma S, Saruta V, Jung CG, Shi Z, Xia J, Hanson PJ, Ricciuto D, Luo Y (2019) Realized ecological forecast through an interactive ecological platform for assimilating data (EcoPAD, v 1.0) into models. *Geoscientific Model Development* 12:1119–1137, doi:10.5194/gmd-12-1119-2019.

Jensen AM, Warren JM, King AW, Ricciuto DM, Hanson PJ, Wullschleger SD (2019) Simulated projections of boreal forest peatland ecosystem productivity are sensitive to observed seasonality in leaf physiology. *Tree Physiology* 39:556-572, doi:10.1093/treephys/tpy140.

Kluber LA, Johnston ER, Allen SA, Hendershot JN, Hanson PJ, Schadt CW (2020) Constraints on microbial communities, decomposition and methane production in deep peat deposits. *PLOS ONE* 15(2):e0223744, doi:10.1371/journal.pone.0223744.

Liang J, Wang G, Ricciuto DM, Gu L, Hanson PJ, Wood JD, Mayes MA (2019) Evaluating the E3SM Land Model at a temperate forest site using flux and soil water measurements, *Geoscientific Model Development* 12:1601-1612, doi:10.5194/gmd-12-1601-2019.

Malhotra A, Brice D, Childs J, Graham JD, Hobbie EA, Vander Stel H, Feron SC, Hanson PJ, Iversen CM (2020) Peatland warming strongly increases fine-root growth. *Proceedings of the National Academy of Sciences* (in press).

McPartland MY, Montgomery RA, Hanson PJ, Phillips JR, Kolka RK, Palik B (2020) Vascular plant species response to warming and elevated carbon dioxide in a boreal peatland. *Environmental Research Letters* (submitted).

Norby RJ, Childs J, Hanson PJ, Warren JM (2019) Rapid loss of an ecosystem engineer: Sphagnum decline in an experimentally warmed bog. *Ecology and Evolution* 9:12571-12585, doi:10.1002/ece3.5722.

Ricciuto DM, Xu X, Shi X, Wang Y, Song X, Schadt CW, Griffiths NA, Mao J, Warren JM, Thornton PE, Chanton J, Keller JK, Bridgham S, Gutknecht J, Sebestyen SD, Finzi A, Kolka R, Hanson PJ (2019) An interactive model for soil biogeochemistry and methane processes: I. model structure and sensitivity analyses. *Journal of Geophysical Research -Biogeosciences* (in revision).

Shi X, Ricciuto DM, Thornton PE, Xu X, Yuan F, Norby RJ, Walker AP, Warren J, Mao J, Hanson PJ, Meng L, Weston D, Griffiths NA (2020) Modeling the hydrology and physiology of Sphagnum moss in a northern temperate bog. *Biogeosciences Discussion* doi:10.5194/bg-2020-90, (in review).

Ward EJ, Warren JM, McLennan DA, Dusenge ME, Way DA, Wullschleger SD, Hanson PJ (2019) Photosynthetic and respiratory responses of two bog shrub species to whole ecosystem warming and elevated CO_2 at the boreal-temperate ecotone. *Frontiers in Forests and Global Change* 2:article 54, doi:10.3389/ffgc.2019.00054.

Warren JM, Jensen AM, Ward EJK, Guha A, Childs J, Wullschleger SD, Hanson PJ (2020) Divergent species-specific impacts of whole ecosystem warming on water relations in a Picea mariana peatland. *Global Change Biology* (submitted).

Wilson RM, Tfaily MM, Kolton MM, Petro C, Hanson PJ, Heyman HM, Kyle JE, Hoyt DW, Eder EK, Purvine SO, Kolka RK, Sebestyen SD, Griffiths NA, Schadt CW, Kostka J, Chanton JP (2020) Soil metabolome response to whole-ecosystem warming at the Spruce and Peatland Responses Under Changing Environments experiment. *Proceedings of the National Academy of Sciences* (in review).

Yuan F, Wang Y, Ricciuto DM, Shi X, Yuan F, Hanson PJ, Thornton PE, Xu X (2020) An Integrative Model for Soil Biogeochemistry and Methane Processes: II. Warming and Elevated CO_2 Effects on Peatland CH4 Emission. *Journal of Geophysical Research - Biogeosciences* (in revision).

Task 1 Data Sets

Fifteen new Task 1 data sets have been prepared and posted (Dusenge et al. 2020D; Fernandez et al. 2019D; Graham et al. 2019Dab; Hanson et al. 2020D; Haynes et al. 2019D; Hopple et al. 2019D; Malhotra et al. 2020D; McPartland et al. 2019D; Pierce et al. 2019Dab; Schädel et al. 2019Dab; Visser et al. 2019D; Ward et al. 2019D all in Appendix B).

Task 6: Coordinated Eco-physiology, Eddy covariance, and Sun-Induced chlorophyll Fluorescence Studies (CEESIFS) to advance integrative ecosystem science (formerly MOFLUX)

Solar-induced chlorophyll fluorescence (SIF) and photosynthesis – There have been exciting advances in Task 6 research on SIF and photosynthesis that encompass areas in SIF instrument development, SIF community support and instrument commercialization, improvement of SIF retrieval algorithms, and theoretical light reaction modeling to establish a biophysical basis for photosynthetic remote sensing.

We have substantially improved the design of the prototype SIF instrument Fluorescence Auto-Measurement Equipment (FAME) developed in the previous cycle of the TES SFA (Gu et al., 2019a). The new FAME now fully integrates eddy covariance (EC)/SIF observations, substantially reducing the footprint and volume of the instrumentation. An operator – system interface was developed to facilitate easier and safer operation, maintenance and calibration of FAME, allowing a single operator to accomplish tasks that previously needed two operators. We also redesigned the temperature/humidity control of the inner housing for the spectrometer, enabling better environmental control while also making the system more compact and energy efficient. Additionally, a new curved fiber optic guide was developed to ensure that the minimum bend radius of the fiber optic cable is not exceeded to prevent loss of photons. With these improvements, we now have a quality SIF instrument that can operate at any EC flux site with relative ease, paving the way for use at other AmeriFlux and FLUXNET sites. To enable the broader use of FAME, ORNL has granted a R&D license to Campbell Scientific Inc. (CSI), a well-known US company to many researchers supported by DOE BER programs. With the R&D license, CSI will manufacture and sell up to 10 units of FAME, at which point a commercial license will replace the R&D license to enable CSI to make FAME available to the worldwide research community. We are currently transferring all hardware and software documents related to FAME to CSI and have been helping CSI engineers to understand the FAME design and its operation.

SIF is emitted during the light reactions of photosynthesis. However, currently, there is not a complete model of the light reactions of photosynthesis, which has hindered the mechanistic understanding and interpretation of the dynamics of observed SIF and its relationship with GPP. To ensure a healthy development of SIF research, we have developed a novel biophysical model of photosynthesis that closes the equations of light reactions, with equations developed for both the lake and puddle models of photosynthesis (Gu et al., 2019b). The model is the first to define the mechanistic link between SIF and CO_2 assimilation, via the actual linear electron transport rate (*J*). Once *J* is modeled, GPP and net photosynthetic rate can be predicted as described in Gu et al. (2019b).

We tested the model with pulse amplitude modulated (PAM) fluorescence and gas exchange measurements on a number of species and found that the model works well for predicting light reaction variables and photosynthetic rate (e.g.., Fig. T6.1). This novel biophysical model of photosynthesis establishes the light reaction basis for photosynthetic remote sensing, provides an analytical solution for simulating the light-carbon reaction balance for crop engineering, and complements carbon reaction models as a comprehensive framework for system modeling of photosynthetic responses to increased atmospheric CO_2 and climate change.

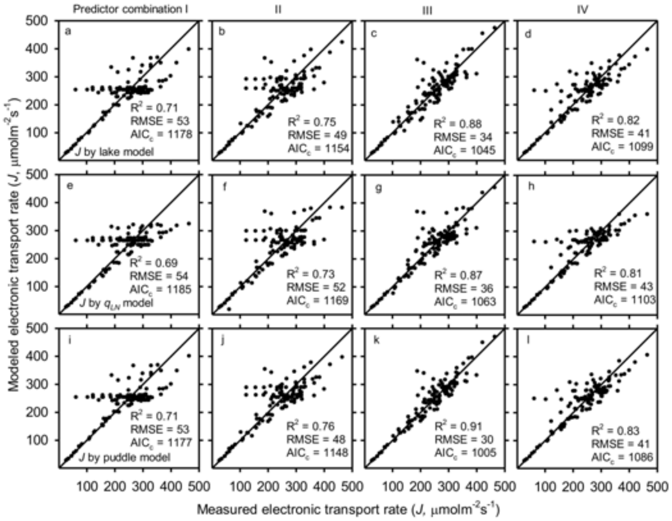


Fig. T6.1. A comparison of modeled vs. measured electron transport rate for cotton dataset under different assumptions of connectivity of photosynthetic units.

Finally, we have contributed to the development of retrieval methods for ground-based SIF observation systems (Chang et al., 2020). Many retrieval methods were developed to estimate top-of-canopy SIF using ground-based spectroscopy, however inconsistencies among methods may confound interpretation of SIF dynamics and its relationship with photosynthesis. Using high temporal- and spectral-resolution ground-based spectroscopy, we (1) evaluated performance of SIF retrieval methods under diverse sky conditions using continuous field measurements; (2) assessed method sensitivity to fluctuating light, reflectance and fluorescence emission spectra; and (3) provided recommendations to users for optimal ground-based SIF retrieval. Analyses included field measurements from bi-hemispherical and hemispherical-conical systems, synthetic upwelling radiance constructed from measured downwelling radiance, and simulated reflectance and simulated fluorescence for benchmarking. We found that Fraunhofer-based retrievals resist atmospheric impacts but are noisier and more sensitive to assumed SIF spectral shape than O2A band-based retrievals. We recommend Fraunhofer-based singular value decomposition or O2A band-based spectral fitting method retrievals using reduced fitting window (759.5-761.5 nm) for robust far-red SIF retrievals across sky conditions.

The hydraulic control of ecosystem carbon dioxide and water fluxes – The plant water transport system controls carbon and water fluxes of individual trees. It remains unclear how such individual plant-level control scales up to influence the dynamics of productivity and water balance of whole ecosystems. Using a novel dataset that combines ecosystem fluxes and leaf water potentials at the MOFLUX site in Missouri, we estimated the "ecosystem hydraulic conductance" (K_{eco}) — the efficiency of water transport through the forest from roots to leaves. We found that K_{eco} displays hydraulic vulnerability to water supply, and strong coordination of K_{eco} with ecosystem gas exchange (Fig. T6.4) as has been observed at tissue and whole plant levels. We also found considerable resiliency of the ecosystem hydraulic system, with rapid leaf rehydration and recovery of ecosystem CO_2 and water vapor fluxes in response to re-wetting after drought. These findings demonstrate the importance of the sensitivity of the plant hydraulic system to the control and predictive modeling of ecosystem scale processes.

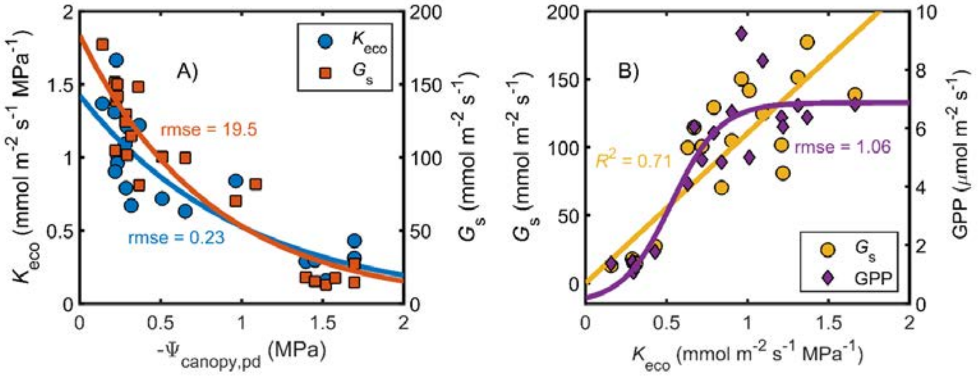


Fig. T6.4. (A) Ecosystem hydraulic conductance (K_{eco}) and surface conductance (G_s) display vulnerability to soil water supply as indicated by canopy mean predawn leaf water potential ($\Psi_{\mathrm{canopy,pd}}$), and (B) ecosystem gas exchange is highly correlated with K_{eco}. $K_{\mathrm{eco}} = -T/\Delta\Psi_{\mathrm{eco}}$, where T is ecosystem transpiration inferred from eddy covariance observations, and $\Delta\Psi_{\mathrm{eco}}$ is the ecosystem average root-to-leaf water potential difference. G_s was estimated by inverting the Penman-Monteith equation. GPP, gross primary productivity.

Photosynthetic and environmental regulations of soil respiration – Although photosynthetic and environmental regulations of the dynamics of soil respiration have been frequently reported, few studies have tested their generality and interactive effects. Using a decade-long continuous measurement of soil respiration and eddy covariance records of net ecosystem exchange of CO_2 at the MOFLUX site, we examined the linkage of photosynthesis and environmental factors with soil respiration. Results showed that GPP regulated soil respiration with monthly mean time lags that varied between four to twelve hours. The variations in this time lag were affected by past trajectories of moisture and temperature. GPP played a more important role in regulating soil respiration during dry rather than wet seasons, probably due to stronger water limitation on soil respiration under dry conditions. Finally, we found that models incorporating GPP as an input explained more variation in soil respiration than using soil temperature and moisture alone. Our findings suggest that photosynthesis and environmental conditions interactively drive the dynamics of soil respiration (Liu et al., 2020).

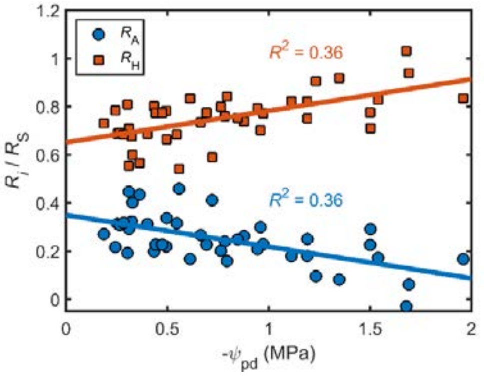


Fig. T6.5. The ratios of (two-week mean) heterotrophic-to-total soil respiration and autotrophic-to-total soil respiration increase and decrease linearly as a function of community predawn leaf water potential (Ψ_{pd}). R_S, soil respiration; R_A, belowground autotrophic respiration; R_H, belowground heterotrophic respiration. R_i represents either R_A or R_H.

<u>*Collaboration with Task 5*</u> – In February 2017, trenched plots were established to help with partitioning heterotrophic (R_H) and autotrophic (R_A) respiration. The continuous measurement of soil respiration from trenched and un-trenched plots has continued, and are presently ongoing, with newly trenched plots established in December 2019. Other work has related to the importance of accurately representing soil water potential and moisture sensitivity on the fidelity of soil respiration simulations and the impact of moisture extreme wetness and dryness on soil microbial C cycling. More complete details regarding these results can be found in the Task 5: Microbial Processing of Soil C Section. We are also working in collaboration with Task 5 to synthesize SIF, partitioned respiration and ecophysiological data sets to examine the impacts of canopy photosynthesis and environmental conditions on belowground C cycling, which builds upon previous work (Liu et al., 2020). Preliminary results show that the fractional contributions of R_H and R_A to the total soil respiration increase and decrease as the plant canopy experiences greater levels of drought stress, respectively (Fig. T6.5).

<u>*Collaborative research activities*</u> – MOFLUX personnel have continued external collaborations with scientists at universities, DOE, NASA and USDA-Agricultural Research Science (ARS) who have fostered improved understanding of surface-atmosphere gas and energy exchanges, ecosystem carbon-water cycle coupling eddy covariance measurements of CH_4 and the remote sensing of plant water status/stress. We are active within the AmeriFlux community, and we attend the annual meetings, contribute to synthesis manuscripts and support researchers who wish to include the MOFLUX site as part of proposals to other federal agencies.

Task 6. Deliverable status FY2019 and FY2020

Date	Deliverable	Status
May 2019	Submit 2018 MOFLUX data to AmeriFlux	Done
Summer 2019	PAM fluorometry and leaf gas exchange measurements at MOFLUX	Done
Summer 2019	Test of the integrated SIF/EC system in SPRUCE enclosures	Done
December 2019	Manuscript on SIF retrieval methods	Done
April 2020	Complete spectroradiometer body temperature control design and test	Done
May 2020	Submit 2019 MOFLUX data to AmeriFlux	Completed by June 2020
Sept 2020	Report on EC applicability in SPRUCE enclosures	Planned
Dec 2020	Manuscript on within-canopy variations of PAM parameters	Planned
April 2021	Complete the development and test of LED/resistor circuit and software for streamlining the FAME absolute irradiance calibration	Already completed, ahead of schedule
May 2021	Submit 2020 MOFLUX data to AmeriFlux	Planned

Task 6 Publications/Manuscripts

Chang CY, Guanter L, Frankenberg C, Köhler P, Gu L, Magney TS, Grossmann K, Sun Y (2020) Systematic assessment of retrieval methods for canopy far-red solar-induced chlorophyll fluorescence (SIF) using high-frequency automated field spectroscopy. *Journal of Geophysical Research: Biogeosciences* e2019JG005533, doi:10.1029/2019JG005533 (in press).

Denham SO, Oishi AC, Miniat CF, Wood JD, Yi K, Benson MC, Novick KA (2020) Eastern US deciduous tree species respond dissimilarly to declining soil moisture but similarly to rising evaporative demand. *Tree Physiology* (in review).

Deventer MJ, Griffis TJ, Roman T, Kolka RK, Wood JD, Erickson M, Baker JM, Millet DB (2019) Error characterization of methane fluxes and budgets derived from a long-term comparison of open- and closed-path eddy covariance systems. *Agricultural and Forest Meteorology* 278:107638, doi:10.1016/j.agrformet.2019.107638.

Griffis TJ, Hu C, Baker JM, Wood JD, Millet DB, Erickson M, Yu Z, Deventer MJ, Winker C, Chen Z (2019) Tall tower ammonia observations and emission estimates in the US Midwest. *Journal of Geophysical Research: Biogeosciences* 124:3432–3447, doi:10.1029/2019JG005172.

Griffis TJ, Roman DT, Wood JD, Deventer MJ, Fachin L, Rengifo J, Castillo DD, Lilleskov E, Kolka R, Chimner RA, del Aguilla J, Wayson C, Hergoualc'h K, Baker JM, Cadillo-Qurroz H, Ricciuto DM (2020) Hydrometeorological sensitivities of net ecosystem carbon dioxide and methane exchange of an Amazonian palm swamp peatland. *Agricultural and Forest Meteorology* (in review).

Gu L, Han J, Wood JD, Chang CY, Sun Y (2019b) Sun-induced Chl fluorescence and its importance for biophysical modeling of photosynthesis based on light reactions. *New Phytologist* 223: 1179–1191, doi:10.1111/nph.15796.

Gu L, Wood JD, Chang C, Sun Y (2019a) A novel automated system for long-term continuous sun-induced chlorophyll fluorescence measurements for integration with eddy covariance flux networks. *Journal of Geophysical Research: Biogeosciences* 123:127–146, doi:10.1029/2018JG004742.

He L, Frankenberg C, Wood JD, Sun Y, Koehler P, Magney T, Dutta D, Zhang Y (2020) Solar-induced fluorescence tracks seasonal and interannual variability in photosynthetic downregulation in response to water stress. *Journal of Geophysical Research: Biogeosciences*, Manuscript # 2018JG005002, (in review).

Hu C, Griffis TJ, Baker JM, Wood JD, Millet DB, Yu Z, Lee X (2020) Modeling the sources and transport processes during extreme ammonia episodes in the U.S. Corn Belt, *Journal of Geophysical Research: Atmospheres* 125:e2019JD031207, doi:10.1029/2019JD031207.

Liang J, Wang G, Singh S, Jagadamma S, Gu L, Schadt C, Wood J, Hanson P, Mayes M (2020) Intensified Soil Moisture Extremes Decrease Soil Organic Carbon Decomposition: A Mechanistic Modeling Analysis. *Journal of Geophysical Research: Biogeosciences* (in review).

Liu XP, Liang JY, Gu L (2020) Photosynthetic and environmental regulations of the dynamics of soil respiration in a forest ecosystem revealed by analyses of decadal time series. *Agricultural and Forest Meteorology* 282–283:107863, doi:10.1016/j.agrformet.2019.107863.

Wood, JD, Sadler EJ, Fox NI, Greer ST, Gu L, Guinan PE, Lupo AR, Market PS, Rochette SM, Speck A, and White LD (2019) Land-atmosphere responses to a total solar eclipse in three ecosystems with contrasting structure and physiology. *Journal of Geophysical Research: Atmospheres* 124:530–543, doi:10.1029/2018JD029630.

Yan B, Mao J, Shi X, Hoffman FM, Notaro M, Zhou T, McDowell N, Dickinson RE, Xu M, Gu L, Ricciuto RM (2019) Predictability of tropical vegetation greenness using sea surface temperatures. *Environmental Research Communications* 1:031003, doi:10.1088/2515-7620/ab178a.

Yu X, Millet DB, Wells KC, Griffis TJ, Chen X, Baker JM, Conley SA, Smith ML, Ghvakharia A, Kort EA, Plant G, Wood JD (2020) Top-down constraints on methane point source emissions from animal agriculture and waste based on new airborne measurements in the US Upper Midwest, *Journal of Geophysical Research: Biogeosciences* 125:e2019JG005429, doi:10.1029/2019JG005429.

Data Sets

Four new data sets have been produced (Pallardy et al. 2019D; Wood et al. 2019D, 2020D; Chang et al. 2020D; Appendix B).

CARBON-CYCLE FOCUSED WORK

Task 3abc: Mechanistic Carbon Cycle modeling

This task incorporates model development and MODEX activities at the point scales (Task 3a) 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 3d; see below).

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

ELM-SPRUCE carbon isotope modeling - We tested the capability of ELM-SPRUCE model to simulate carbon isotopes (^{13}C and ^{14}C) in comparison with SPRUCE ^{13}C and ^{14}C measurements. We evaluated peatland carbon accumulation by comparing the ELM-SPRUCE simulated δ^{14}C vertical profile with observed δ^{14}C vertical profile at SPRUCE site (McFarlane et al., 2019). Generally ELM-SPRUCE captured the shape of δ^{14}C vertical profile very well, suggesting that the representation of peatland carbon turnover in ELM-SPRUCE is reasonable. However, ELM-SPRUCE simulated δ^{14}C near the surface is more depleted than the observations. This may be because the unique chemical properties of *Sphagnum* moss and the associated inhibitive effects on decomposition are not currently considered. We have also evaluated model simulated δ^{14}C in green-leaf tissues under elevated CO_2 against observations for each PFT for years 2015 ,2016, 2017 and 2018. ELM-SPRUCE captured the increasing depletion of δ^{14}C with time under elevated CO_2, consistent with the observed δ^{14}C in green leaf. In addition, we have taken advantage of the δ^{13}C measurements at SPRUCE for model evaluation. Preliminary model results show that ELM-SPRUCE is able to capture the steady depletion of tissue δ^{13}C since the year 1850, which was caused by decreased atmospheric δ^{13}C in the atmosphere (Suess effect) and increased photosynthetic discrimination as atmospheric CO_2 increases. ELM-SPRUCE overestimated δ^{13}C discrimination compared with the observations at the site, most likely due to the lack of consideration of mesophyll conductance overestimated intercellular CO_2 concentration. These results were presented at the SPRUCE isotope workshop in February 2020 and the SPRUCE All-Hands meeting in May 2020. A small model-data integration working group focusing on carbon isotopes has been organized and meets monthly to discuss progress modeling in ELM-SPRUCE. Work is also underway to integrate carbon isotopes into the methane submodule. Code has been pushed to the ELMv0-SPRUCE repository and is being tested.

Sphagnum mosses modeling - *Sphagnum* mosses are strong determinants of nutrient, carbon and water cycling in peatland ecosystems. However, the land model component (ELM) of the E3SM does not include *Sphagnum* or other mosses as represented plant functional types (PFTs), thereby limiting predictive assessment of peatland responses to environmental change. Thus, we introduced a moss PFT into ELM by developing water content dynamics and non-vascular photosynthetic processes for moss. Inclusion of a *Sphagnum* PFT with some *Sphagnum*-specific processes in ELM allows it to capture the observed seasonal dynamics of *Sphagnum* gross primary production (GPP, Fig. T3a.1) and simulate a reasonable annual net primary production (NPP) for moss. In addition, we used our new model to investigate the responses of the peatland ecosystem of SPRUCE to different warming levels with two ambient and elevated atmospheric CO_2 concentrations. We found that different species showed highly variable warming responses under both ambient and elevated atmospheric CO_2 concentrations, with elevated CO_2 reversing the warming response direction for the peatland ecosystem. Microtopography is critical: *Sphagnum* mosses on hummocks and hollows were simulated to show opposite warming responses.

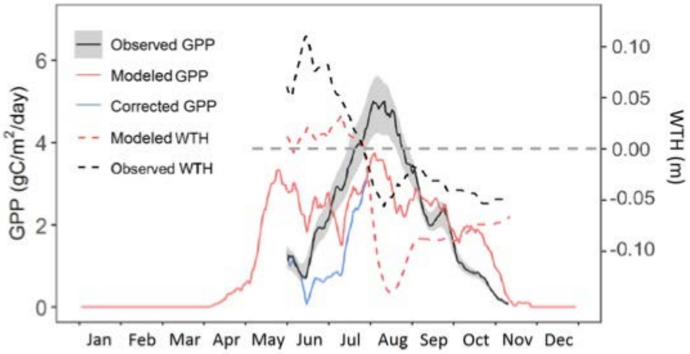


Figure T3a.1. Predicted GPP (red solid line) compared with flux-partitioned GPP (black solid line) of *Sphagnum* mosses for the year 2014. The blue line is the predicted GPP corrected with the observed water table height. The dashed black and red lines are observed and modeled water table height (the dashed gray line is the hollow surface).

Canopy Processes – We have been working to improve understanding of SIF behaviors and how they can be used to inform models, and how they can be represented in models. Research efforts have been focused on: (1) evaluating the capacity of SIF in predicting GPP across the global land of diverse biomes and climates with multiple streams of data, which shed light on how to improve the modelling of the photosynthesis process and parameterization of the ELM with satellite SIF information; and (2) improving ELM modelling of GPP constrained by SIF. We found that the growing season GPP/SIF ratio varied substantially across global land surfaces, with the highest ratios consistently found in boreal regions and tropical rainforests. The spatial variation in GPP/SIF was strongly modulated by climate variables. We have also shown that incorporating satellite SIF into GPP simulations in ELM with machine learning algorithms can enhance its predictability and reduce the uncertainty. A manuscript (Chen et al., 2020) is currently under review in *Global Change Biology* and has received overall favorable review; two other manuscripts are in preparation.

Phenology – We analyzed the changes in the satellite-derived start of season (SOS) and the covariation between SOS and temperature (R_T) in 85 large cities across the conterminous United States for the period 2001–2014. We found the SOS occurred significantly earlier and R_T was significantly weaker in cities than surrounding rural areas, especially in relatively cold regions with an annual mean temperature of <17.3 °C (Fig. T3a.2). In addition, the magnitude of urban-rural difference in both SOS and R_T was identified to be primarily correlated with the intensity of urban heat island. Relevant work was published in *Proceedings of the National Academy of Sciences* (Meng et al., 2020). For the ELM phenology modeling, we completed the phenology model improvement and evaluation using the SPRUCE PhenoCam observations. Specifically, we incorporated selected phenology schemes into the ELM and evaluated the phenological-responses of carbon and water fluxes. The new phenology modules in ELM depend on various environmental cues (e.g., forcing and chilling processes for spring onset, and daylength and temperature for autumn offset). We found the updated version simulated higher land fluxes (e.g., GPP and evapotranspiration) and stronger response to warming then those of the default ELM.

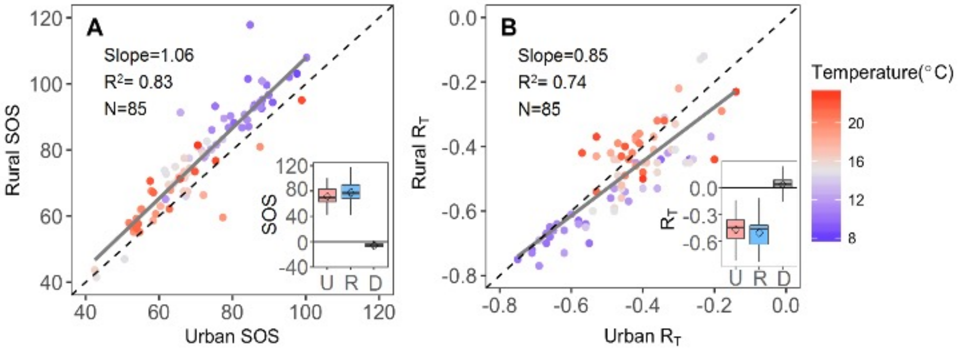


Figure T3a.2. Urban and rural SOS (A) and R_T (B) in 85 study cities. A: SOS is the 14-year mean during 2001–2014 for each city. Point color represents background climate, i.e., 14-year averaged annual mean temperature. 1:1 line (black dashed) and fitted linear regression (gray solid, P < 0.001) are shown. A boxplot for SOS or R_T is shown within each scatterplot. U and R stand for urban and rural SOS (A) and R_T (B), and D is the urban-rural difference (D = U - R).

Moreover, we noticed the soil hydrological variables showed moderate changes in the revised model. Relevant results were presented during the 2019 ESA annual meeting and the 2019 fall AGU meeting, and are being prepared for a manuscript.

Disturbance – To evaluate the capability of the current ELM fire component, we conducted two sets of ELM semi-factorial simulations and performed a comprehensive exploration of the spatial and temporal dynamics of fire disturbances and impacts in continental China over the past two decades. Compared with the satellite-based fire products, we found systematic overestimation of the ELM-simulated burned area. Moreover, we identified that climate change and anthropogenic factors have played critical roles in controlling the spatial and seasonal changes of the regional fire disturbances. Relevant research findings were published in the *Geography and Sustainability* (Chen et al. 2020). For a global fire study, we investigated the regional contribution to global fire interannual variation (IAV) and the sensitivity of wildfire to major climatic variables. Generally, the ELM simulations were comparable with the satellite observations, in terms of the fire IAV and responses to environmental drivers. Tropical savannahs and grasslands were seen to contribute most to the interannual variabilities of global burned area; the interannual fire activities were mainly associated with the changes of precipitation and shortwave radiation. Relevant analysis is still on-going and will presented in a paper.

Task 3a Deliverable status FY2019 and FY2020

Date	Deliverable	Status
2019	Complete integration of FUN into ELM Complete integration of methane module into ELM-PFLOTRAN Integrate mechanistic formulation for seasonal photosynthetic variation Complete manuscript on methane cycling using ELMv0-SPRUCE	Completed By 9/2020 Completed Completed (in review)
2020	Complete new phenology submodel Complete improved fire submodel Complete Improved nutrient cycling submodel (organic leaching, improved N fixation) Complete manuscript on model evaluation with improved nutrient cycling	Completed Underway Underway Underway

Task 3c – Functional testing

SPRUCE leaf repiration model - The response of leaf respiration to short-term (seconds to hours) temperature change is relatively well understood. Less well understood are responses over longer time periods of days to years. For example, how does respiration acclimate to warmer growing temperatures? How should longer-term responses be represented in models? Using observations from SPRUCE, we have explored whether model parameters describing the short-term response of leaf dark respiration (R_d) to temperature are themselves functions of growth temperature as influenced by SPRUCE temperature treatment. Parameters in a suite of ten functional unit models describing the short-term temperature response of R_d were calibrated against observed temperature response curves collected in June and August 2017 on the two dominant shrub species, *Chamaedaphne calyculata* and *Rhododendron groenlandicum*, and the two dominant tree species, *Picea mariana* and *Larix laricinia*. Calibration was the Markov Chain Monte Carlo optimization. We used regression analysis to determine if calibrated parameters were functions of temperature treatment. For example, there are two calibrated parameters in the Q_{10} formulation of R_d in ELM-SPRUCEv0: basal rate of respiration per unit leaf nitrogen at 25°C and the Q_{10} value. Using results for *P. mariana* as an example, there is no change with treatment in either of these parameters in June. In August, however, the Q_{10} is a linear declining function of plot temperature when results are combined across CO_2 treatment (Figure T3c.3). An ecosystem model such as ELM-SPRUCE failing to account for this parameter's temperature dependency would overestimate maintenance respiration under future warming with consequences for simulated net ecosystem production and prediction of the ecosystem as a source or sink of atmospheric CO_2. Results from this analysis were presented at the Fall 2019 AGU Meeting and a manuscript is being prepared. A manuscript has also been drafted which describes how the choice of temperature response function for R_d impacts ELM-SPRUCE's prediction of the SPRUCE S-1 Bog as a carbon source or sink.

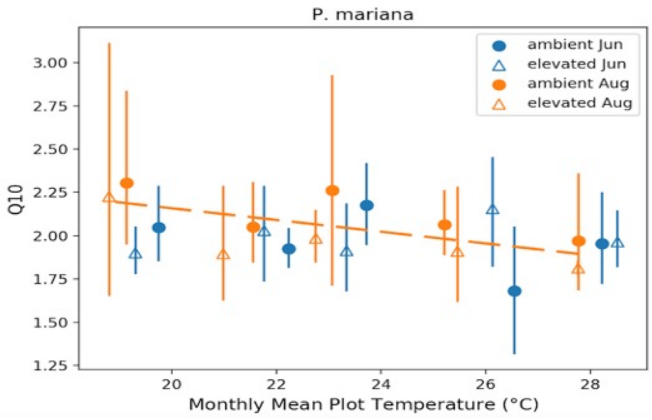


Figure T3c.3 Calibrated Q10 values as a function of monthly plot temperature in June and August for the *Picea mariana* PFT. August Q10 values show a declining trend with temperature.

<u>Model calibration methods</u> - Using a global ELM modeling framework, we also developed a new method for model-data integration. This new method, called the learning-based inversion-free model prediction (LIMP) framework, combines forward modeling with machine learning methods to integrate observation data and produce predictions of specific model outputs with uncertainties (Lu et al, 2019). The framework was applied to the ELM model at 1.9 × 2.5 degree resolution, which was run 200 times with differing values of 10 uncertain input parameters related to leaf and canopy processes. LIMP establishes a statistical relationship between observations and predictions in a reduced dimension. Depending on the nature of this relationship, different machine learning methods can be used including principal component analysis (PCA) and neural networks. We demonstrated that LIMP can be used for efficient model prediction, rapid data assimilation, and cost-effective experimental design for improving robust predictive understanding of ecosystems from site to global scales. LIMP can be used for parameter optimzation and probabilistic prediction. We have computed posterior distributions of several parameters calibrated at a model gridcell using the ILAMB GPP bencmark product. This method will eventually be used to produce optimized parameters for every model gridcell using remote sensing SIF products. It may also be applied to calibrate ELM-SPRUCE with observations and functional unit-based model representations of specific processes. We are investigating applying this approach in the EcoPAD system for near real-time predictions at the SPRUCE site.

Task 3c Deliverable status FY2019 and FY2020

Date	Deliverable	Status
2019	Integrate ELM into EcoPAD (without assimilation) and display output on website Develop GPP, hydrology, phenology and decomposition functional Ωunits/surrogates Complete manuscript on structural uncertainty in leaf respiration T-response	By June 2020 Completed Completed First draft
2020	Develop root function, nutrient cycling, disturbance functional units/surrogates Integrate SIF module into ELM and the canopy functional unit Enable data assimilation capability with ELM-EcoPAD Integrate 4 additional models into EcoPAD for SPRUCE intercomparison	Underway Completed Underway Underway

Task 3abc Publications

Chen A, Tang R, Mao J, Yue C, Li X, Gao M, Shi X, Jin M, Ricciuto D, Rabin S, Ciais P, Piao S (2020) Spatiotemporal dynamics of ecosystem fires and biomass burning-induced carbon emissions in China over the past two decades. *Geography and Sustainability*, https://doi.org/10.1016/j.geosus.2020.03.002.

Chen A, Mao J, Ricciuto D, Xiao J, Frankenberg C, Li X, Gu L, Knapp A (2020) Moisture availability mediates the relationship between terrestrial gross primary production and solar-induced fluorescence: Insights from global scale variations. Under review, *Global Change Biology* (in review).

Meng L, Mao J, Zhou Y, Richardson AD, Lee X, Thornton PE, Ricciuto DM, Li X, Dai Y, Shi X, Jia G, (2020) Urban warming advances spring phenology but reduces temperature response of plants in the conterminous United States. *Proceedings of the National Academy of Sciences of the United States of America*. doi:10.1073/pnas.1911117117.

Lu D, Ricciuto D (2019) Learning-Based Inversion-Free Model-Data Integration to Advance Ecosystem Model Prediction, *2019 International Conference on Data Mining Workshops (ICDMW)*, Beijing, China, pp. 279-287, doi:10.1109/ICDMW.2019.00049.

Ricciuto D, Xu X, Shi XY, Wang Y, Song X, Schadt C, Griffiths N, Mao JF, Warren JM, Thornton PE, Chanton J, Keller JK, Bridgham S, Gutknecht J, Sebestyen S, Finzi AC, Kolka R, Hanson PJ (2020). An integrative model for soil biogeochemistry and methane procsses: I. Model structure and sensitivity analysis. *Journal of Geophysical Research - Biogeosciences* (in review**)**.

Shi X, Ricciuto DM, Thornton PE, Xu X, Yuan F, Norby RJ, Walker AP, Warren J, Mao J, Hanson PJ, Meng L, Weston D, Griffiths NA (2020) Modeling the hydrology and physiology of *Sphagnum* moss in a northern temperate bog, *Biogeosciences Discussion,* doi:10.5194/bg-2020-90.

Task 3d: Multi-Assumption Systems Modeling

Ecosystem models are composed of inter-connected quantitative hypotheses and assumptions that represent the mechanics of the component processes that make up an ecosystem. Viewing models in this way connects them directly with the language of experiments and observations, while recognizing that the models themselves rely on multiple assumptions (Walker et al., 2018). However, few methods and tools exist to rigorously incorporate and evaluate these multiple competing and quantitative hypotheses. With this motivation, new software [the Multi-Assumption Architecture & Testbed (MAAT); Walker et al., 2018] and new mathematical methods (collaboration with Ming Ye at Florida State University; Dai et al., 2017) were developed during the previous phase of the TES-SFA. MAAT is an open-source software framework designed specifically for formal and informal evaluation of alternative model process representations. Task 3d has been developed to further this new, Multi-Assumption (or Multi-Hypothesis) Modeling approach and to extend this approach to some of the tasks across the SFA.

FY2020 and the second half of FY2019 have been busy for Task 3d. In May we brought Abbey Johnson on-board as a full-time ORISE intern after she completed her BS in Mathematics. Abbey originally came to the lab in the summer of 2018 as an intern in the Department of Energy Science Undergraduate Laboratory Internships (SULI). Abbey was awarded the highly competitive “Provost Doctoral Fellowship” as well as a “Graduate Student Fellowship and will begin a PhD program in Mathematical Biology at North Carolina State in fall 2020. In February/March 2019 we interviewed multiple candidates and hired Matt Craig as a postdoc beginning in July 2019. An experiment-focused researcher from Rich Phillip’s lab at Indiana University Bloomington, Matt has made remarkable progress picking up modeling, bringing soil decomposition models into MAAT and connecting with SFA Task 5. At the AGU Fall Meeting in December 2019 we held a well-attended session on “*H13Q− Advances in Stochastic, Multihypothesis, and Other Data-Driven Methods for Environmental and Earth System Modeling*” to provide a forum to develop and build the multi-hypothesis modeling community.

Soil C – Matt Craig has begun developing a multi-hypothesis model of soil carbon (C) within MAAT. To support the generalisation of soil C model structure, we have implemented a general matrix method in MAAT that brings the generality of the SoilR functions (Sierra and Müller, 2015) into the flexible MAAT framework. The matrix method is being used to represent an ensemble of current soil C models which differ in their core assumptions. The Microbial Enzyme Decomposition (MEND) model has been incorporated into MAAT and we are in the process of importing MIMICS (Wieder 2014), MILLENNIAL (Abramoff et al., 2018), and CORPSE models (Sulman et al., 2014). While it is established that these models differ in their predictions of soil C responses to global change drivers (Sulman et al., 2018), our efforts will probe the source of this inter-model uncertainty.

The multi-hypothesis soil C model has been used to investigate soil C saturation. Soil C storage potential often diminishes as carbon inputs increase. This “soil C saturation” phenomenon is commonly hypothesized to result from abiotic soil properties (e.g. soil texture), an increasingly frequent hypothesis in soil C models. However, C stabilized by soil minerals is largely microbially-generated and the soil microbial biomass response to C inputs is likely to diminish as inputs increase due to density-dependent ecological factors. We proposed a biotic mechanism for soil C saturation wherein constraints on microbial populations limit the rate of mineral-associated C formation as inputs increase. We explored the consequences of this mechanism in MAAT by simulating microbe-explicit soil C models with alternative hypotheses of microbial density-dependent growth and turnover. Different microbial hypothesis combinations led to multiple previously observed soil C responses to increasing inputs, including the commonly observed pattern where microbial biomass and mineral-associated C saturates, while particulate C increases linearly (Fig. T3d.1). Analysis of 54 C-addition studies suggests a constrained response of microbial biomass to C input rate, supporting our hypothesis. We conclude that density-dependent limitations of microbial populations are a likely alternative mechanism explaining the saturation of soil C as inputs increase, a mechanism that is likely complementary to existing physically-based hypotheses.

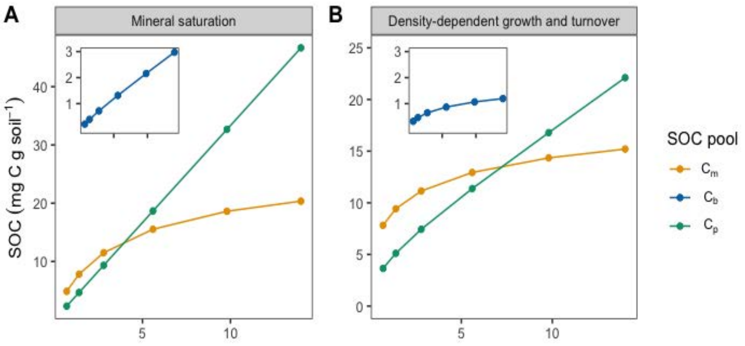


Fig. T3d.1. Simulated steady-state mineral-associated (C_m; yellow) and particulate (C_p; green) soil organic carbon (SOC), and microbial biomass carbon (C_b; blue inset) pools at different C input rates in a conventional model (A) and in a microbe-mediated decay model representing density-dependent constraints on microbial growth and lifespan (B). A limit to mineral-associated C storage is apparent for both hypotheses but the mechanism is different.

Photosynthesis – A manuscript titled ”Multi-hypothesis analysis of Farquhar and Collatz photosynthesis models reveals unexpected influence of empirical assumptions” has been submitted. This manuscript describes the first ever model sensitivity analysis that employs a formal method to include multiple process-representation assumptions. In that study we find the surprising dominance of the limiting-rate selection process in leaf-scale photosynthesis models. We show that this sensitivity propagates through to global simulations in ELM, and FATES, causing a difference in photosynthesis that is equivalent to 50‑160 % of anthropogenic CO_2 emissions. In collaboration with Brookhaven National Lab we use this information to carry out novel measurements to constrain the limiting-rate selection process.

Progress on the MAAT MCMC development was overestimated in the proposal. This was because we were experiencing “false convergence” of the algorithm which gave us a false sense of progress. In addition, we realised that code described as parallel was in actuality not parallelizable in the computational sense. Thus we have focused MAAT development efforts on MCMC and we are now approaching a complete, fully-functional algorithm that can be applied to the general problem. This will likely be completed by the end of July and work on the *Sphagnum* analysis and ‘pbdr’ enabled MAAT will begin then. Revised completion dates for the *Sphagnum* analysis is December 2021 (as a new hire will be required) and for the pbdr code is January 2021.

Task 3d Deliverable status FY2019 and FY2020

Date	Deliverable	Status
April 2019	1. State-of-the-art MCMC routines enabled in MAAT	95 % complete
Oct 2019	2. Parameter estimation and hypothesis testing in SPRUCE *Sphagnum* photosynthesis and respiration data 2014-2018	on hold for completion of MCMC
April 2020	3. pbdr enabled MAAT to run on OLCF	50 % complete
April 2020	4. Multi-assumption soil decomposition model	40 % complete

FY20 Papers

Bastos A, O' Sullivan M, Ciais P, Makowski D, Sitch S, Friedlingstein P, Chevallier F, Rödenbeck C, Pongratz J, Luijkx IT, Patra PK, Peylin P, Canadell JG, Lauerwald R, Li W, Smith NE, Peters W, Goll DS, Jain AK, Kato E, Lienert S, Lombardozzi DL, Haverd V, Nabel JEMS, Poulter B, Tian H, Walker AP, Zaehle S (2020) Sources of Uncertainty in Regional and Global Terrestrial CO2 Exchange Estimates. *Global Biogeochemical Cycles* 34: e2019GB006393, doi:10.1029/2019GB006393

Keller AB, Brzostek ER, Craig ME, Fisher JB, Phillips RP (2020) Root-derived inputs are major contributors to soil carbon in temperate forests. *Ecology Letters* (in review)

Walker AP, Anderson J, Bridges RA, Fisher RA, Johnson AL, Lu D, Ricciuto DM, Rogers A, Serbin SP, Ye M (2020) Multi-hypothesis analysis of Farquhar and Collatz photosynthesis models reveals unexpected influence of empirical assumptions. *AGU Advances* (in review)

PROCESS-LEVEL STUDIES (PLS)

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 linking that to root traits, such as diameter or order (Dhiman et al., 2018). Subsequent modeling of these data revealed that roots and mycorrhizae may affect soil hydraulic properties, which could impact ELM and other process-based modeling efforts. This led to a MS student thesis that did indeed find that the presence of roots significantly changed the shape of the soil water retention curve in two ways: (1) by increasing water content at saturation, and (2) and by reducing the slope of the curve. These changes suggested roots created additional porosity and broadened the pore size distribution. The presence of mycorrhizal fungi further accentuated these effects. Ongoing analysis of neutron radiographs will reveal spatial patterns of dehydration dynamics in situ and linkages to root/fungal biomass. Our recent neutron imaging work has led to two manuscripts submitted to *Plant and Soil*, and which are currently in revision (Decarlo et al., 2020a, b). The first manuscript describes development of novel software for automated root delineation, segmentation and analysis of water content from soil to root. The second paper leverage this software to describes rhizosphere development, and how it is linked to root size, regardless of species. Data are directly applicable to models that assess mechanistic soil to root hydraulics, such as ELM-FATES.

We continue to focus on assessing linkages between root traits, mycorrhizae and root respiratory (Rs) response to environmental dynamics in order to improve autotrophic vs heterotrophic Rs modeling (Ficken & Warren 2019). In collaboration with the Root Traits Task, and to provide additional physiology data to FRED, we have established a relationship with The Morton Arboretum in Lisle, IL, to assess root, hyphal and soil Rs dynamics for tree species with divergent root traits. This effort has led to construction of 108 root/fungal exclusion collars that will be installed in different monoculture stands as soon as work restrictions allow. Collars will be periodically measured for respiration rates and linked to above/below ground traits and environmental conditions to provide novel root functional data for models that increasingly consider root function. This effort has synergy with MAAT, MOFLUX and NIST research.

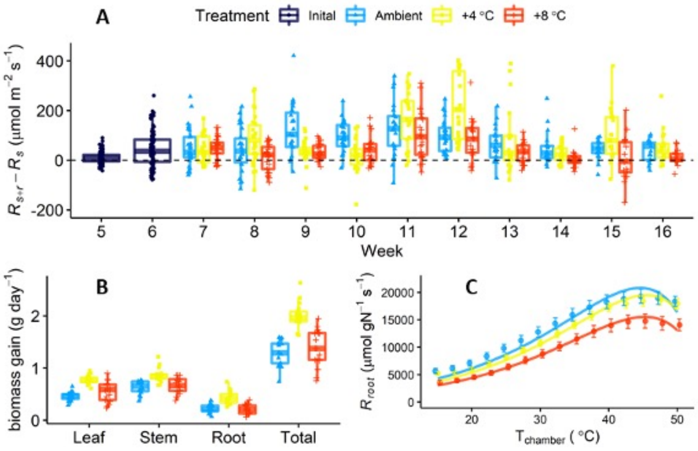


Fig. T4c.1. (A) *Populus trichocarpa* root respiration rates over time in response to temperature treatments and aboveground pruning between weeks 12-13, (B) above and belowground biomass in response to temperature, (C) Root respiration temperature response curves indication acclimation under warmer treatments.

Two other root-respiration related projects have been completed at ORNL this year, facilitated by a DOE Office of Science Graduate Student Research (SCGSR) Program fellowship to PhD student James Hogan. These studies focused on assessing root traits and their linkages to respiration *in situ* using: (1) a novel root tray Rs measurement system containing a single root system attached to different mature trees at the University of Tennessee Arboretum and, (2) a growth chamber study with an ORNL *Populus* bioenergy genotype grown under +4 or +8 °C to assess bulk soil, fungal or root Rs rates over time. In the field study, rates of root microbiome CO_2 efflux ranged between 10 and 90 µmols m^{-2} sec^{-1}, with ectomycorrhizal species having slightly greater rates than arbuscular mycorrhizal species. In the growth chamber study, peak biomass and soil and root Rs were realized under +4 °C, and there was whole plant photosynthetic and respiratory acclimation (Fig. T4c.1).

Task 4c. Deliverable status FY2019 and FY2020

Date	Deliverable	Status
December 2018	Publish manuscript on root respiratory response to drought: “Sensitivity and recovery of soil respiration to extreme drought in AM and ECM mesocosms.” (Ficken & Warren 2019)	Completed
August 2019	Develop and demonstrate successful root respiration temperature response curve techniques	Pending resumption of field work
September 2019	Complete initial assessment of root and hyphal impacts on soil hydraulic properties	Completed
September 2019	Publish new manuscript on root rhizosphere water dynamics based on neutron imaging	Paper in revision
December 2019	Neutron imaging and laboratory analysis of root and hyphal impacts on soil hydraulic properties.	Completed
January 2020	Develop and build *in situ* root and soil hyphal respiration separation chambers	Completed
May 2020	Install respiration separation chambers in key projects, TBD	Pending resumption of field work
June 2020	Publish manuscript on root and hyphal impacts on soil hydraulic properties	Underway

Task 4c New Publications and Manuscripts

DeCarlo KF, Caylor K, Bilheux H, Warren JM (2020a) Integrating fine root morphology and soil distance mapping to characterize the plant-soil interface. *Plant and Soil* (in revision).

DeCarlo KF, Bilheux JC, Bilheux H, Caylor K, Warren JM (2020b) RootProcessing: An open-source python package for root/soil analysis at the neutron imaging beamline at ORNL. *Plant and Soil* (in revision).

Ficken CD, Warren JM (2019) The carbon economy of drought: comparing respiration responses of roots, mycorrhizal fungi, and free-living microbes to an extreme dry-rewet cycle. *Plant and Soil* 435:407, https://doi.org/10.1007/s11104-018-03900-2.

Task 4c Data Sets

One new Task 4c Dataset (Hogan et al. 2020D in Appendix B).

Task 5: Microbial Processing of Soil C

Experimental and modelling studies continued to focus on the key role of microbial activity in influencing CO_2 emissions and soil carbon cycling. We published a review paper in *Science* that presented soil carbon and microbial distribution as a function of latitude, summarized existing knowledge about microbial functional traits, and posited new approaches for incorporating microbial function in models (Crowther et al., 2019).

An older dataset from incubation experiments involving four paired temperate forest and grassland sites across the US, ^{13}C labeled glucose for a short-term (144 hours) incubation, and ^{13}C labeled cellulose for a second short-term study (30 days), and a long-term (729 days) study, was published (Kluber et al., 2020d). The Microbial Enzyme Decomposition (MEND) model was then used to identify the most important microbial parameters controlling soil organic carbon (SOC) decomposition in these incubations, including the intrinsic carbon use efficiency (Y_g; closely relevant to *Carbon Use Efficiency*), initial active fraction of microbes (r_0), half-saturation constant for microbial assimilation of substrate (K_D), maximum specific growth rate (V_g), and a ratio ($\alpha = V_{mt}/(V_g + V_{mt})$) that determines the relationship between V_g and the specific maintenance rate (V_{mt}) (Jian et al. in review). These parameters, particularly Y_g, were found to be much higher in the short-term incubations compared to the long-term incubation. The parameters were then used to simulate future soil warming. Implementing the short-term and long-term parameters, respectively, resulted in SOC loss (–8.2 ± 5.1% or –3.9 ± 2.8%), and minor SOC gain (1.8 ± 1.0%) in response to 5 ºC warming, while only the latter is consistent with a meta-analysis of 149 field warming observations (1.6 ± 4.0%) (Fig. T5.1). This suggests that integrating multi-year datasets of soil incubations with microbial models can thus achieve more reasonable parameterization of key microbial processes and subsequently boost the accuracy and confidence of long-term SOC projections.

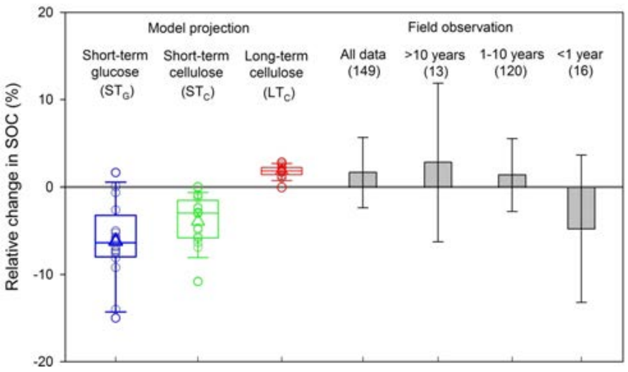


Fig. T5.1. Modeled relative change (%) in total soil organic carbon (SOC) based on a five-decade projection under 5°C warming using short-term glucose (blue), short-term cellulose (green) and long-term cellulose (red) parameters. The meta-analysis results based on all field-warming observations and those over different experimental durations (e.g., >10 years, 1-10 years, and <1 year). For models, boxplots show means (triangle), medians (line), 1st and 3rd quartiles (box, interquartile range or IQR), upper and lower extremes (whiskers). In the meta-analysis, the number of observations is in parentheses. From Jian et al., in review.

While many studies in the literature involving microbial modeling continue to investigate the role of temperature, we continued our focus on moisture sensitivity in both models and experiments. In association with the MOFLUX Task 6, we continued monitoring heterotrophic respiration in the soil chambers (ongoing since 2017). The soil around four chambers was retrenched in late 2019, wrapped with root-inhibiting membranes, and backfilled. Thus, these four chambers represent heterotrophic respiration, to complement the remaining chambers collecting total respiration. Following our recent work with the ELM model at MOFLUX (Liang et al. 2019), this year MEND was parameterized with 11 years of observations from MOFLUX, showing satisfactory model performance in both model calibration (R^2 = 0.67) and validation (R^2 = 0.69) against heterotrophic respiration (Liang et al. in review). We then used the model to simulate the long-term SOC dynamics under five extreme moisture scenarios with different frequencies and severities over a period of 100 years. Results showed that the changes in active microbial biomass C and the corresponding turnover rates of SOC pools were more sensitive to extreme soil drying than soil wetting. As a result, the cumulative soil C emission from microbial respiration decreased by 430 g C m^{-2} after the 100-year simulation in the highest frequency and intensity moisture extreme scenario (Fig. T5.2). This is due to the decrease in active microbial biomass, dissolved organic carbon, and extracellular enzyme concentrations associated with the extreme dryness simulations, that then reduced the decomposition of SOC. We found a nonlinear response of SOC decomposition to soil moisture changes, which causes decreased decomposition by microbes under drying that was not compensated by increased decomposition under wetting conditions. The dominant result was decreased CO_2 emissions under extreme drying.

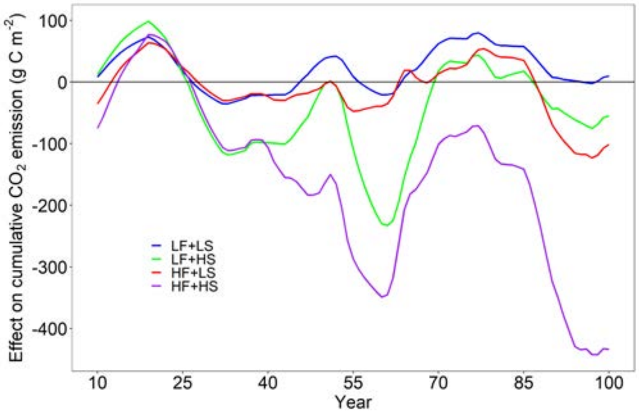


Fig. T5.2. Ten-year running average of cumulative CO_2 emissions in intensified moisture scenarios:
low frequency/low severity = LF + LS;
low frequency/high severity = LF + HS;
high frequency/low severity = HF + LS;
high frequency/high severity = HF + HS.
All are normalized to the control scenario.
From Liang et al. in review.

Field experiments support these interpretations. A moisture manipulation experiment in a soybean field in western Tennessee showed decreases in CO_2 emissions and in enzyme activity under the imposed drought compared to ambient moisture conditions (Fig. T5.3). Interestingly, total microbial biomass measured by chloroform fumigation extraction was increased under the drought treatment, which was determined to be related to increased fungal biomass from hyphal length measurements. The higher extractable organic C concentrations, lower enzyme activities, and lower CO_2 fluxes, however, suggest that the biomass may have become dormant during the drought.

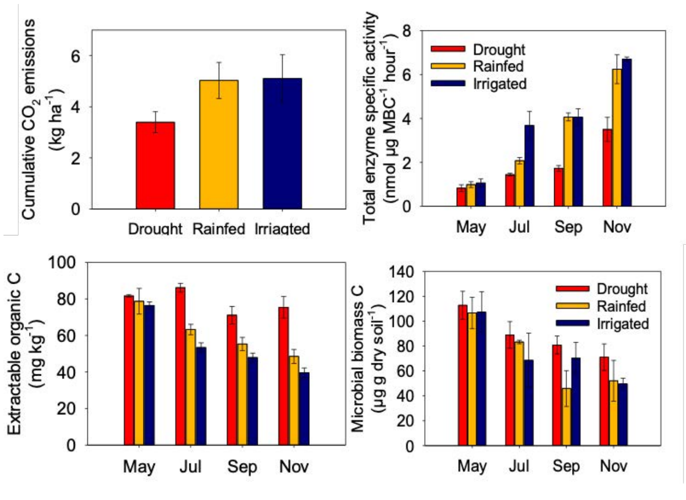


Fig. T5.3. Cumulative CO_2 emissions, total enzyme specific activity, extractable organic carbon (C), and microbial biomass C under soybean crop with drought conditions imposed from May to October and compared with natural rainfall and irrigation.

Two additional sets of incubation experiments simultaneously investigating soil texture and moisture were completed using loamy soils from MOFLUX, sandy soils from Georgia, and clayey soils from Texas (Singh et al., in revision). The experiments were conducted under both steady-state and variable/transient moisture content, and data was collected including CO_2 emissions, microbial biomass from chloroform fumigation, 16S rRNA and ITS sequencing, PLFA, soil aggregate structural changes by wet sieving, and accumulation of osmolytes indicating microbial response to desiccation. These experiments will provide additional mechanistic information about how soil moisture changes affect different pathways of organic carbon protection and turnover.

Finally, a nitrogen cycle was added to the MEND model (Wang et al., 2020), and MEND was applied to a field study in subtropical China, matching the simulation with measured heterotrophic respiration (from trenching) and microbial biomass (Wang et al., 2019). Highlights from these manuscripts are available in previous reports.

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 FY2019 and FY2020

Date	Deliverable	Status
2019	Accounting for the sensitivity of soil CO_2 emissions to soil moisture and texture	Underway
2020	Development and initial offline testing of microbial model coupled to ELM at MOFLUX	Planned

Task 5 Publications/Manuscripts/Datasets

Crowther TW, van den Hoogen J, Averill C, Wan J, Keiser AD, Mayes MA, Mo L, Maynard DS (2019) The global soil community and its control on biogeochemistry. *Science* 365:eaav0550. doi:10.1126/science.aav0550.

Jian S, Li J, Wang G, Kluber LA, Schadt CW, Liang J, Mayes MA (2020) Multi-year incubation experiments boost confidence in model projections of long-term soil carbon dynamics. *Nature Communications* (in review)

Liang J, Wang G, Riccuito DM, Gu L, Hanson PJ, Wood JD, Mayes MA (2019) Evaluating the E3SM Land Model at a temperate forest site using flux and soil water measurements. *Geoscientific Model Development* 12:1601-1612. doi:10.5194/gmd-12-1601-2019.

Liang J, Wang G, Singh S, Jagadamma S, Gu L, Schadt CW, Wood JD, Hanson PJ, Mayes MA (2020) Intensified soil moisture extremes decrease soil organic carbon decomposition: a mechanistic modeling analysis. *Journal of Geophysical Research - Biogeosciences* (in review)

Singh S, Liang J, Kivlin S, Wood, J, Wang G, Schadt CW, DuPont J, Gowda P, Mayes MA (2020) Differential microbial respiration responses to soil texture and moisture in mixed forests. *Geoderma* (being revised).

Wang G, Huang W, Zhoud G, Mayes MA, Zhou, Z (2020) Modeling the processes of soil moisture in regulating microbial and carbon-nitrogen cycling. *Journal of Hydrology* 585:124777. doi.org/10.1016/j.jhydrol.2020.124777.

Task 5 New Datasets

Kluber LA, Phillips JR, Singh S, Jagadamma S, Wang G, Schadt CW, Mayes MA (2020) Soil respiration and microbial biomass from soil incubations with ^{13}C labeled additions. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.010

GLOBAL TRAIT DATABASES (GT)

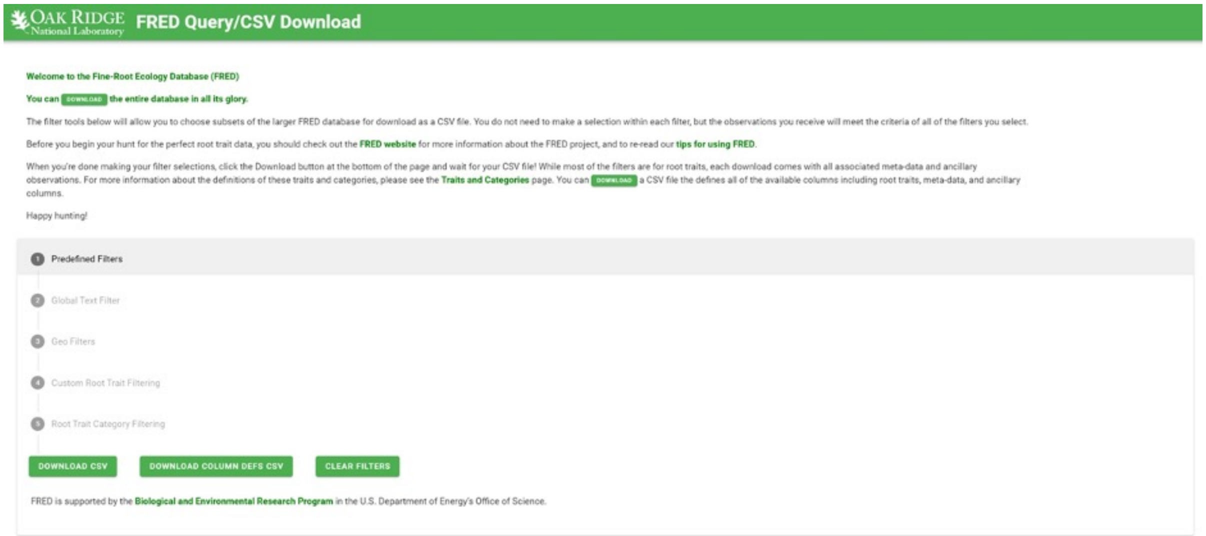
Task 4b: Leveraging root traits to inform terrestrial biosphere models

The Fine-Root Ecology Database – FRED has been and will continue to be a freely-available resource for the broader community of root and rhizosphere ecologists and terrestrial biosphere modelers (FRED 2.0 was released in May 2018; McCormack et al., 2018). Over the past year, we have used existing data to better understand the variation in root traits within and among species and across the globe, we have continued to harvest data from completed studies not yet in FRED (e.g., data from tundra and tropical ecosystems), and we have continued to make new measurements that improve the data available to inform our understanding of belowground processes and below- and aboveground linkages.

Using FRED 2.0 to answer important questions in belowground ecology – We used the empirical root trait relationships derived using FRED 2.0 to parameterize a heuristic model that includes the traits and functional contributions of mycorrhizal fungi for a more holistic view of belowground resource acquisition strategies (McCormack et al., 2019). Dr. Yao Liu, a post-doc co-advised with Anthony Walker, has also conducted a global assessment of the variation in root traits by implementing a hierarchical Bayesian model that simultaneously considers the major controls of root-trait variation in FRED 2.0, including fine-root functional class, plant-species phylogeny, mycorrhizal associations, and environmental conditions (Liu et al., in preparation). A number of groups have also used FRED as a resource to answer their own questions (https://roots.ornl.gov/publications).

We have continued to be involved in international collaborations (https://roots.ornl.gov/synthesis-activities). For example, the sROOT working group within the German Centre for Integrative Biodiversity Research (iDiv) leveraged FRED 2.0 to develop a better understanding of the "Root Economics Space" occupied by plants and their associated fungi (Bergmann et al., 2020, accepted *Science Advances*) as well as a "Ready to Use" database that is a subset of FRED and TRY (Guerrero-Ramirez et al., 2020, accepted *Global Ecology and Biogeography*). FRED 2.4 was integrated into the release of TRY version 5.0 in 2019 (Kattge et al., 2020), and FRED 3.0 will be incorporated into TRY 6.0 in fall of 2020. The root trait framework developed by the FRED team has also been leveraged to develop a "Root Traits Handbook" and companion paper advocating for increased quantification of functional root traits (Freschet et al. 2020a, in review; Freschet et al. 2020b, in review). We are also collaborating with the International Soil Carbon Network (Malhotra et al., 2019), participating in the Open Traits Network (Gallagher et al., 2020), and FRED is providing the foundation for new, biome-specific working groups in the Arctic (the "Arctic Underground", PIs Hewitt and Mack) and the tropics ("Tropical Forest Root Traits", PI Cusack).

Improving the next generation of the FRED database – Data collection from published literature and contributed, unpublished data has continued, and we expect the release of version 3.0 of FRED in early fall 2020. For the release of FRED 3.0, we have drawn upon the technological capabilities within ORNL's Information Technology Division to convert the FRED database, which is currently stored as a flat file (CSV format), to a database with a flexible online interface for data access (Fig. T4b.1). This will allow users to interact more precisely with FRED, and to download the subset of root traits or ancillary data from specific species or geographic regions that inform their scientific questions.



Welcome to the Fine-Root Ecology Database (FRED)

You can DOWNLOAD the entire database in all its glory.

The filter tools below will allow you to choose subsets of the larger FRED database for download as a CSV file. You do not need to make a selection within each filter, but the observations you receive will meet the criteria of all of the filters you select.

Before you begin your hunt for the perfect root trait data, you should check out the **FRED website** for more information about the FRED project, and to re-read our **tips for using FRED**.

When you're done making your filter selections, click the Download button at the bottom of the page and wait for your CSV file! While most of the filters are for root traits, each download comes with all associated meta-data and ancillary observations. For more information about the definitions of these traits and categories, please see the **Traits and Categories** page. You can DOWNLOAD a CSV file the defines all of the available columns including root traits, meta-data, and ancillary columns.

Happy hunting!

FRED is supported by the **Biological and Environmental Research Program** in the U.S. Department of Energy's Office of Science.

Fig. T4b.1 FRED 3.0 searchable interface.

Making new measurements to inform our understanding of FRED observations – The data in FRED are necessarily a mixed compilation of root traits and ancillary data, quantified using a variety of methodologies. These observations need to be placed into a comprehensive framework that will allow us to more effectively use the diversity of traits in FRED to understand above- and belowground linkages across the globe. To advance this framework, we are making new observations across a phylogenetically and ecologically diverse suite of tree species from mature forestry plots at The Morton Arboretum, Lisle, IL (in collaboration with M.L. McCormack). Preliminary results suggest differences among species and functional types in the timing and amount of leaf, wood, and fine-root production that can inform model processes and direct the collection of new observations within a framework of new understanding.

Task 4b. Deliverable status FY2019 and FY2020

Date	Deliverable	Status
2019	Manuscript on belowground resource acquisition strategies	Completed (McCormack *et al.*, 2019)
2020	Manuscript on hierarchical Bayesian model of root-trait variation in FRED 2.0	*Underway* (Liu *et al.*, in final prep)
2020	FRED 3.0 available to community as a relational database	*Underway, fall 2020*

Task 4b Publications/Manuscripts

Bergman J, Weigelt A, van der Plas F, Laughlin DC, Kuyper TW, Guerrero-Ramirez N, Valverde-Barrantes OJ, Bruelheide H, Freschet GT, Iversen CM, Kattge J, McCormack ML, Meier IC, Rillig MC, Roumet C, Semchenko M, Sweeney CJ, van Ruijven J, York LM, Mommer L. (2020) The fungal collaboration gradient dominates the root economics space in plants. bioRxiv 2020.01.17.908905; *Science Advances* (in press).

Freschet, GT, Pagès L, Iversen CM, Comas LH, Rewald B, Roumet C, Klimešová J, Zadworny M, Poorter H, Postma JA, Adams TS, Bagniewska-Zadworna A, Blancaflor EB, Brunner I, Cornelissen JHC, Garnier E, Gessler A, Hobbie SE, Lambers H, Meier IC, Mommer L, Picon-Cochard C, Rose L, Ryser P, Scherer-Lorenzen M, Soudzilovskaia NA, Stokes A, Sun T, Valverde-Barrantes OJ, Weemstra M, Weigelt A, Wurzburger N, York LM, Batterman SA, Bengough AG, Gomes de Moraes M, Janeček Š, Salmon V, Tharayil N, McCormack ML (2020a) A starting guide to root ecology: strengthening ecological concepts and standardizing root classification, sampling, processing and trait measurements. *New Phytologist* (in review).

Freschet GT, Roumet C, Comas LH, Weemstra M, Bengough AG, Rewald B, Bardgett RD, De Deyn GB, Johnson D, Klimešová J, Lukac M, McCormack ML, Meier IC, Pagès L, Poorter H, Prieto I, Wurzburger N, Zadworny M, Bagniewska-Zadworna A, Blancaflor EB, Brunner I, Gessler A, Hobbie SE, **Iversen CM**, Mommer L, Picon-Cochard C, Postma JA, Rose L, Ryser P, Scherer-Lorenzen M, Soudzilovskaia NA, Sun T, Valverde-Barrantes OJ, Weigelt A, York LM, Stokes A (2020b) Root traits as key proxies to unravel plant and ecosystem functioning: current understanding, pitfalls and future research needs. *New Phytologist* (in review).

Gallagher RV, Falster DS, Maitner BS, Salguero-Gómez R, Vandvik V, Pearse WD, Schneider FD, Kattge J, Poelen JH, Madin JS, Ankenbrand M, Penone C, Feng X, Adams VM, Alroy J, Andrew SC, Balk M, Bland LM, Boyle BL, Bravo-Avila CH, Brennan I, Carthey AJR, Catullo R, Cavazos BR, Conde DA, Chown SL, Fadrique B, Gibb H, Halbritter AH, Hammock J, Hogan JA, Holewa H, Hope M, Iversen CM, Jochum M, Kearney M, Keller A, Mabee P, Manning P, McCormack L, Michaletz ST, Park DS, Perez TM, Pineda-Munoz S, Ray CA, Rossetto M, Sauquet H, Sparrow B, Spasojevic MJ, Telford RJ, Tobias JA, Violle C, Walls R, Weiss KCB, Westoby M, Wright IJ, Enquist BJ (2020) Open Science principles for accelerating trait-based science across the Tree of Life. *Nature Ecology & Evolution* 4: 292-303. doi:10.1038/s41559-020-1109-6

Guerrero-Ramirez N, Mommer L, Freschet GT, Iversen CM, McCormack ML, Kattge J, Poorter H, van der Plas F, Bergmann J, Kuyper TW, York LM, Bruelheide H, Laughlin DC, Meier IC, Roumet C, Semchenko M, Sweeney CJ, van Ruijven J, Valverde-Barrantes OJ, Aubin I, Catford JA, Manning P, Martin A, Milla R, Minden V, Pausas JG, Smith SW, Soudzilovskaia NA, Ammer C, Butterfield B, Craine J, Cornelissen JHC, de Vries FT, Isaac ME, Kramer K, König C, Lamb EG, Onipchenko VG, Peñuelas J, Reich PB, Rillig MC, Sack L, Shipley B, Tedersoo L, Valladares F, van Bodegom P, Weigelt P, Wright JP, Weigelt A (2020) Global Root Traits (GRooT) Database. bioRxiv 2020.05.17.095851; *Global Ecology and Biogeography* (accepted).

Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, Tautenhahn S, Werner GDA … **Iversen CM** … 700+ co-authors … Wirth C (2020) TRY plant trait database - enhanced coverage and open access. *Global Change Biology* 26:119-188. doi:10.1111/gcb.14904.

Malhotra A, Brice D, Childs J, Graham JD, Hobbie EA, Vander Stel H, Feron SC, Hanson PJ, Iversen CM. 2020. Peatland warming strongly increases fine-root growth. *Proceedings of the National Academy of Sciences* (accepted).

Malhotra A, Todd-Brown K, Nave LE, Batjes NH, Holmquist JR, Hoyt AM, Iversen CM, Jackson RB, Lajtha K, Lawrence C, Vindušková O, Wieder W, Williams M, Hugelius G, Harden J (2019) The landscape of soil carbon data: emerging questions, synergies and databases. *Progress in Physical Geography* 43:707- 719. doi:10.1177/0309133319873309

McCormack ML, Iversen CM (2019) Physical and functional constraints on viable belowground acquisition strategies. *Frontiers in Plant Science* 10:1215. doi:10.3389/fpls.2019.01215

Task 8: LeafWeb

Website development – To better serve the user community of Leafweb (www.leafweb.org), the Leafweb user interface is undergoing several changes. First, we are adding a user registration system to ensure that users of LeafWeb have legitimate needs to use it (e.g., they are students or researchers of photosynthesis). This registration system will also facilitate communications with data providers in case data quality issues arise after the automated Leafweb analyses have been done. Additionally, we are adding the data search capability to the system.

New automated functionality development and data gathering – Coding is ongoing to integrate the light reaction-based, biophysical model of photosynthesis and associated parameter estimation algorithm into Leafweb. Specific models for nonphotochemical quenching (NPQ), fraction of open photosystem II reaction centers under the lake model (q_L) and the puddle model (q_P) have been developed. Measurements of pulse amplitude modulated fluorescence and gas exchange needed to test these models have been gathered in collaboration with Prof. Joseph A Berry from the Department of Global Ecology, Carnegie Institution of Washington, Albert Porcar-Castell from Department of Forest Sciences, University of Helsinki, and Xinyou Yin from Centre for Crop Systems Analysis, Wageningen University & Research.

Task 8 Publications/Manuscripts

Eckert D, Jensen AM, Gu L (2020) The maximum carboxylation rate of Rubisco affects CO2 refixation in temperate broadleaved forest trees. *Plant Physiology and Biochemistry* (accepted with revision).

Han J, Gu L, Warren JW, Sun Y, Guha A, McLennan DA, Zhang W, Zhang Y (2020) The roles of photochemical and non-photochemical quenching in regulating photosynthesis depend on the phases of fluctuating environment conditions. *The Plant Journal* (submitted).

Li J, Zhang Y, Li Z, Li J, Zhang Q, Zhang Z, Song L, Gu L (2020) Seasonally varying relationship between sun-induced chlorophyll fluorescence and photosynthetic capacity from leaf to canopy in a paddy rice field. *Journal of Experimental Botany* (submitted).

Task 8. Deliverable status FY2019 and FY2020

Date	Deliverable	Status
August 2019	Clear data formatting guidance provided in the LeafWeb site	Completed
Dec 2019	Completion of software for PAM data analysis	Completed
May 2020	LeafWeb ready to accept full PAM fluorometry data	Completed
December 2020	Completion of data search capabilities	Underway
July 2021	Completion of graphic display capabilities for PAM data	Planned
Oct 2021	Manuscript synthesizing the dynamics of NPQ and qL for modeling photosynthesis	Planned

TES SFA DATA SYSTEMS, MANAGEMENT, AND ARCHIVING UPDATE

The open sharing of all data and results from the TES SFA research and modeling tasks among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE BER's Earth and Environmental Systems Sciences Division. Active data sharing facilitates delivery of TES 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., SPRUCE: https://mnspruce.ornl.gov and FRED: https://roots.ornl.gov), access to web-based tools (e.g., LeafWeb: https://leafweb.org) and links to external products (e.g., microbial metagenomes) enable these interactions.

All results of laboratory experiments and sample analyses, synthesis of information, genomics analyses, and model products (inputs, codes, outputs) developed in support of TES SFA tasks and data collected specifically at the SPRUCE experiment facility, are submitted to the respective SPRUCE or TES SFA data archive in a timely manner such that data will be available for use by project scientists and collaborators and, following publication, the public, thru the SPRUCE (https://mnspruce.ornl.gov) and TES SFA (https://tes-sfa.ornl.gov) websites.

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: https://tes-sfa.ornl.gov.

See **APPENDIX B** for the list of newly and previously archived datasets and details of data sharing, archiving, and fair use.

AFFILIATED TES SFA-SUPPORTED PUBLICATIONS

Staff supported by the TES SFA continue to collaborate and complete work funded by US DOE BER in prior fiscal years that may not explicitly be funded under Tasks 1 through 8. The following listing shows additional manuscripts completed since the February 2019 with some TES SFA support.

Graham, J (2020) *Using terrestrial laser scanning to characterize peatland microtopography and assess tree growth responses to elevated temperature and CO_2.* Ph.D. Dissertation, Boise State University, Boise, Idaho USA.

Moore JAM, Sulman BN, Mayes MA, Patterson CM, Classen AT (2019) Plant roots stimulate the decomposition of complex, but not simple, soil carbon. *Functional Ecology* 34(4):899-910.

Paschalis A, Fatichi S, Zscheischler J, Ciais P, Bahn M, Boysen L, Chang J, De Kauwe M, Estiarte M, Goll D, Hanson PJ, Harper AB, Hou E, Kigel J, Knapp AK, Larsen KS, Li W, Lierert S, Luo Y, Meir P, Ogaya R, Parolari AJ, Peng C, Peñuelas J, Pongratz J, Rambal S, Schmidt IK, Shi H, Sternberg M, Tian H, Tschumi E, Ukkola A, Vicca S, Viovy N, Wang Y-P, Wang Z, Wu D, Zhu Q (2020) Rainfall-manipulation experiments as simulated by terrestrial biosphere models: where do we stand? *Global Change Biology* 26:3336-3355 doi: 10.1111/gcb.15024.

Poyatos R, Granda V, Flo V, Mencuccini M, Steppe K, Martínez-Vilalta J, SAPFLUXNET contributors[Hanson PJ, Norby RJ Wullschelger SD] (2020) Global transpiration data from sap flow measurements: the SAPFLUXNET database. *Earth System Science Data* (submitted)

Rewcastle KE, Moore JAM, Henning JA, Mayes MA, Patterson CM, Wang G, Metcalfe DB, Classen AT (2020) Investigating drivers of microbial activity and respiration in a forested bog. *Pedosphere* 30(1):135–145, doi:10.1016/S1002-0160(19)60841-6.

Seward J, Carson MA, Lamit LJ, Basiliko N, Yavitt JB, Lilleskov E, Schadt CW, Smith DS, Mclaughlin J, Mykytczuk N, Willims-Johnson S (2020) Peatland microbial community composition is driven by a natural climate gradient. *Microbial Ecology* – doi:10.1007/s00248-020-01510-z.

Smits AP, Ruffing CM, Royer TV, Appling AP, Griffiths NA, Bellmore R, Scheuerell MD, Harms TK, Jones JB (2019) Detecting signals of large-scale climate phenomena in discharge and nutrient loads in the Mississippi-Atchafalaya River Basin. *Geophysical Research Letters* 46:3791-3801. doi:10.1029/2018GL081166.

Tiegs S, Costello DM, Isken MW, Woodward G, McIntyre PB, Gessner MO, Chauvet E, Griffiths NA, Flecker AS, 142 co-authors (listed alphabetically) (2019) Global patterns and drivers of ecosystem functioning in rivers and riparian zones. *Science Advances* 5:eaav0486. doi:10.1126/sciadv.aav0486.

4AII. SCIENCE HIGHLIGHTS SINCE FEBRUARY 2019

- ORNL TES SFA staff authored 56 papers that have been published or are in press/accepted status since February of 2019. Notable papers include the following high impact totals: 1 in *Science*, 2 in *Science Advances*, 2 in the *Proceedings of the National Academy of Sciences* and 4 in the *Nature* family of journals. An additional 26 manuscripts are in peer review.
- SPRUCE – Warming caused variable responses for vegetation and losses of CO_2 and CH_4 for a linear response of -31.3 gC m-2 y-1 °C-1. Carbon losses with warming of +2.25 to +9 °C are 4.5 to 18 times faster than the historical rate of peatland carbon accumulation (Hanson et al. 2020).
- SPRUCE – After three years of warming, annual *Sphagnum* productivity declined linearly with increasing temperature (Figure) due to wide–spread desiccation and loss of *Sphagnum.* Productivity was less in elevated CO_2 enclosures from shading by shrubs (Norby et al. 2019).
- SPRUCE - The strong response of fine-root growth to warming was accepted at PNAS (Malhotra et al., in press).
- SPRUCE – Two mansucripts in review describing divergent gas exchange and hydraulic stress between the woody plant species indicating potential shift in dominance at the site (Dusenge et al. 2020, Warren et al 2020).
- CC Modeling – A new inversion-free method method was developed to improve ecosystem models using observations and ensembles of simulations. This method is computationally efficient and applicable to calibrating ELM at regional scales (Lu et al., 2019b).
- CC Modeling – We provided the first observational evidence of a reduction in the response of urban phenology to temperature in major US cities. We discovered these urban-rural phenology differences are mainly associated with the changes of background climate and urban heat island (UHI) effect intensity. This work was published in PNAS (Meng et al., 2020)
- MAAT – Post-doc hired (Matt Craig) and close to submitting a soil decomposition MAAT manuscript. Advanced MCMC algorithm coded into MAAT by Abigail Johnson who is moving on to NC State for a PhD in Computational Biology having won a highly-competitive Provost's Doctoral Fellowship.
- Soil C Task 5 – A review paper was published in *Science* on microbial functional trait modeling (Crowther et al., 2019) and added a nitrogen cycle to the MEND model (Wang et al., 2020).
- Root Traits – The sROOT working group, using FRED as a foundation, defined a new understanding of the Root Economics "Space" (Bergmann et al., accepted at *Science Advances*), and the FRED team, in collaboration with ORNL IT, has developed a user interface for a searchable FRED database.
- Root Function (Task 4c) – Two manuscripts in revision describing novel software for automated root delineation, segmentation and analysis of water content from soil to root, and development of the root rhizosphere over time (Decarlo et al. 2020a, b).
- Technology Development (MOFLUX) – ORNL licensed the Fluorescence Auto-Measurement Equipment (FAME) technology to Campbell Scientific, Inc. Sun-Induced chlorophyll Fluorescence (SIF) is the only remotely detectable signal of photosynthesis under natural conditions, and no commercial system was available for unattended monitoring of SIF in the field. The new instrument is for independent use or integration with eddy covariance measurement systems at AmeriFlux or Fluxnet sites.

4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff produced 82 publications or completed manuscripts since our last summary report. This total includes 54 published/in press/accepted journal articles, 2 conference reports, and 26 working through the review process. This level of productivity over 1.3 years (63 y^{-1}) exceeds our average paper production rate from March 2015 through February 2019 (42 y^{-1}). A TES SFA cumulative publication summary since 2015 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 49 different peer-reviewed publications in this reporting period including one paper in *Science* (Crowther et al. 2019), two in *Science Advances* (Tiegs et al. 2019; Bergman et al. 2020), two in *The Proceedings of the National Academy of Sciences* (Malhotra et al. 2020; Meng et al. 2020), one in the new high-profile AGU journal *AGU Advances* (Hanson et al. 2020), and four in the *Nature* family of journals. We also published 10 papers in *Global Change Biology*, 8 papers in *Journal of Geophysical Research – Biogeosciences,* 4 in *New Phytologist*, and 3 in *Agriculture and Forest Meteorology*.

Journal selection for publication of TES SFA work is at the discretion of the author team. 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 all of 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 were detailed in the quadrennial review document submitted 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 ELM. To improve the modeling of gross primary production, we will apply new understanding of canopy processes enabled through the development of the SIF instrument and use to improve the modeling of gross primary production in ELM.

Improved Sphagnum modeling – Within the ELM framework we will continue to improve 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.

Heterotrophic versus autotrophic respiration – Tasks 6 and 5 are using the measured soil chamber respiration data and SIF information from MOFLUX over the last 3 years to examine how seasonal and diurnal patterns and responses to drought influence the proportions of heterotrophic versus autotrophic respiration. Of particular interest is the sensitivity of diurnal time lags between autotrophic and heterotrophic respiration to environmental conditions. This work will eventually lead to improvements in conceptual understanding and quantitative modeling of soil and ecosystem respiration.

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 SPRUCE-ELM, 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.

Carbon cycle analysis clearly shows major losses of C from the SPRUCE ecosystem proportionate to the level of warming. At this time models are overestimating the influence of elevated CO_2 on carbon uptake and may not be adequately accounting for nutrient and water limitations.

Early year 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. Several key areas identified include N and P mineralization, nutrient resorption during fall senescence, and the availability of organic N and P in soils. Field measurements investigating the temperature response of N and P mineralization, as well as organic nutrient availability were originally planned for the summer of 2020 but we are considering making these observations on laboratory incubations instead because of COVID-19 – related travel restrictions. Resorption of N and P during fall senence is being quantified for litter samples collected in the fall of 2019. 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 ELM-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 made this a funded subtask in FY2018 and beyond.
- Drs. Brandy Toner, Ed Nater and colleagues from the University of Minnesota, are examining mercury and sulfur dynamics in the SPRUCE experiment using funding provided through the USDA Forest Service.
- 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 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 multiple 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.
- Dr. M. Luke McCormack (Morton Arboretum) is making new observations across a phylogenetically and ecologically diverse suite of tree species from mature forestry plots at The Morton Arboretum, Lisle, IL to advance our framework of root trait understanding gained from FRED.

- Dr. John Butnor (USDA Forest Service) is developing methodologies for determining cold hardiness responses of the tree and shrub vegetation to warming and elevated CO_2 within the SPRUCE experiment.

CITED REFERENCES (NOT IN THE TES SFA APPENDIX LISTS)

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).

Güsewell S, Koerselman W (2002) Variation in nitrogen and phosphorus concentrations of wetland plants. *Perspectives in Plant Ecology Evolution and Systematics* 5:37–61.

Koerselman W, Meuleman AFM (1996) The vegetation N:P ratio: a new tool to detect the nature of nutrient limitation. *Journal of Applied Ecology* 33:1441–50.

Mayumi D, Mochimaru H, Tamaki H, Yamamoto K, Yoshioka H, Suzuki Y, Kamagata Y, Sakata S (2016) Methane production from coal by a single methanogen. *Science* 354(6309):222-225.

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. FY2020 FUNDING ALLOCATION BY PROGRAM ELEMENT

Total expected available funding for ORNL's TES SFA in FY2020 included $4,932K carryover from FY2019 (including $2,178K for external commitments) and $8,300K of new budget authorization. FY2020 spending is summarized in the following table.

FY2020 Budget expenditures by TES SFA Program Element through 16 June 2020. The data include prior year carryover amounts.

Task	Cost Through 16 June 2020 ($K)	Commitments Through 16 June 2020 ($K)	Remaining Funds 16 June 2020 ($K)
T1: SPRUCE Science	$2,459K	$495K	$1,822K
T6: MOFLUX, etc.	539	64	418
T3ab: Carbon Cycle Modeling	869	92	294
T3d: MAAT	249	13	115
T4c: Process Study - Root Func.	147	54	90
T5: Soil C Studies	198	87	283
T4b: Process Study - Root traits	255	97	175
T8: LeafWeb			
T1.1: SPRUCE – Operations	945	317	702
T1.2: SPRUCE – Materials	143	48	71
T1.3: SPRUCE – Reserve	0	0	432
SFA Contingency	70	0	1,689
SFA Totals	**$5,874K**	**$1,267K**	**$6,091K**

We are currently spending at rates consistent with the spending plans outlined in the February 2019 TES SFA renewal proposal budgets for FY2020 with one exception. Travel expenses associated with field work in Minnesota (SPRUCE), Missouri (MOFLUX) and for science community engagement are down due to the COVID-19 pandemic. We anticipate unspent carry over funds to be approximately $2,500K across all TES SFA tasks and external SFA commitments.

A total of $1,008K carry-over provide through the TES SFA are for closely related activities 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 FY2020 we directly funded the following individuals or groups.

The University of Missouri ($194K) 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 ($150K) – 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 ELM-SPRUCE modeling efforts. This work has contributed to two manuscripts. Work to refine and optimize the model with SPRUCE observations is continuing.

John Latimer ($56K*)* – 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 – The Morton Arboretum ($33K) – Dr. McCormack 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.

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

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

Keith Oleheiser ($90K) - The hydrology and porewater chemistry task greatly benefits from the subcontract for XCEL Engineering technician Keith Oleheiser. Keith 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.

Kyle Pearson ($95K) – A technical contract with XCEL Engineering was established for Kyle to help W. Robert Nettles with the day-to-day operation of SPRUCE treatments and the calibration and upkeep of automated data collections systems.

Andrew Richardson – Northern Arizona University ($98K) – This contract allows Dr. Andrew Richardson's group to maintain the automated phenology observations and greenness calculations for all treatment and ambient plots on the SPRUCE site. Dr. Richardson also leads the phenology task for the SPRUCE project.

Nancy Glenn – Boise State University ($60K) This contract provides twice annual terrestrial lidar scans of the SPRUCE experimental plots to help assess vegetation growth and microform elevation change (hummock and hollow distributions).

Karis McFarlane – Lawrence Livermore National Laboratory ($190K) – 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. Funding was also provided in FY2020 for her group to return to the site to evaluate the isotopic composition of emitted CO_2 and CH_4.

Jianwei Li – Tennessee State University ($50K) – This contract supports a PhD student Siyang Jian to use MEND to model incubation and field studies conducted at ORNL and elsewhere. Mr. Jian successfully defended his thesis in June of 2020 and is currently finalizing his dissertation and manuscripts.

Sindhu Jagadamma – University of Tennessee ($80K) – This contract supports a PhD student Shikha Singh to conduct incubation and field studies investigating the role of soil moisture changes on microbial function and CO_2 emissions. Ms. Singh is expected to defend in the fall of 2020.

Infrastructure subcontracts in support of the SPRUCE project in FY2020 include funds and funding for site maintenance *(***Pokegama Electric $54K)**, electrical service **(Lake Country Power $130K)**, propane supply **(Lakes Gas Co. $300K)**, elevated CO_2 supply *(***PRAXAIR Inc. $115K)**, fiber internet connections **($10K)**, and leased space in Minnesota **($45K**). The amounts required for each of these operational contracts are reevaluated annually as actual usage rates and prices change.

5c. Personnel Actions and Procedures

New Hires and Promotions – Four postdoctoral research associates were hired since February 2019: Dr. Jennifer M. Peters (Task 1 – March 2019), Dr. Mathew Craig (Task 3d – July 2019), Dr. Camille Defrenne (Task 1 – September 2019), and Dr. Tatjana Zivkovic (Task 1- February 2020). Unfortunately, COVID-19 travel restrictions have impacted Dr. Zivkovic leading to her unplanned resignation, but hopefully we will be able to reengage with Dr. Zivkovic in the future. Dr. Verity Salmon was promoted from a postdoctoral position to the fill a staff science role on nutrient cycling for the SPRUCE project (Task 1).

Anticipated Future Hires – Looking ahead to FY2021, the TES SFA plans to pursue hiring additional postdoctoral fellows to sustain effort and to supplement full time staff positions and as the budget allows.

Retirements and Releases – In April 2020 Dr. Richard J. Norby retired after a long and successful career at ORNL.

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 FY2020

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 FY2020.

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. We continue to be engaged with neutron sciences through cutting-edge root and rhizosphere imaging research at the High Flux Isotope Reactor (HFIR) and active participating in science development teams for the future VENUS beamline at SNS and proposed beamlines at the potential Second Target Station. We work with the DOE BER data center ESS-DIVE as our primary permanent data repository (see also Appendix B).

We also use 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 is high, no ORNL TES SFA funds have been used to acquire capital equipment in FY2020. 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

Published, accepted and in review papers since the February 2019 renewal proposal

1. Albert, LP, Restrepo-Coupe N, Smith MN, Wu J, Chavana-Bryant C, Prohaska N, Taylor TC, Martins GA, Ciais P, Mao JF, Arain MA, Li W, Shi XY, Ricciuto DM, Huxman TE, McMahon SM, Saleska SR (2019) Cryptic phenology in plants: Case studies, implications, and recommendations. *Global Change Biology* 25(11): 3591-3608, doi:10.1111/gcb.14759.
2. Ardón, M., L.H. Zeglin, R.M. Utz, S.D. Cooper, W.K. Dodds, R.J. Bixby, A.S. Burdett, J.J. Follstad Shah, N.A. Griffiths, T.K. Harms, S.L. Johnson, J.B. Jones, J.S. Kominoski, W.H. McDowell, A.D. Rosemond, M.T. Trentman, D.J. Van Horn, and A.K. Ward. Experimental nitrogen and phosphorus enrichment stimulates multiple trophic levels of algal and detrital-based food webs: A global meta-analysis from streams and rivers. *Biological Reviews* (in review).
3. Bastos A, O'Sullivan M, Ciais P, Makowski D, Sitch S, Friedlingstein P, Chevallier F, Rödenbeck C, Pongratz J, Luijkx IT, Patra PK, Peylin P, Canadell JG, Lauerwald R, Li W, Smith NE, Peters W, Goll DS, Jain AK, Kato E, Lienert S, Lombardozzi DL, Haverd V, Nabel JEMS, Poulter B, Tian H, Walker AP, Zaehle S (2020) Sources of Uncertainty in Regional and Global Terrestrial CO2 Exchange Estimates. *Global Biogeochemical Cycles* 34: e2019GB006393. doi:10.1029/2019GB006393
4. Bergman J, Weigelt A, van der Plas F, Laughlin DC, Kuyper TW, Guerrero-Ramirez N, Valverde-Barrantes OJ, Bruelheide H, Freschet GT, Iversen CM, Kattge J, McCormack ML, Meier IC, Rillig MC, Roumet C, Semchenko M, Sweeney CJ, van Ruijven J, York LM, Mommer L. (2020) The fungal collaboration gradient dominates the root economics space in plants. bioRxiv 2020.01.17.908905; *Science Advances* (accepted).
5. Caplan JS, SJ Meiners, H Flores-Moreno, ML McCormack (2019) Fine-root traits are linked to species dynamics in a successional plant community. *Ecology* 100: e02588 doi:10.1002/ecy.2588 (in review minor revisions)
6. Carrell AA, Kolton M, Glass JB, Pelletier DA, Warren MJ, Kostka JE, Iversen CM, Hanson PJ, Weston DJ (2019) Experimental warming alters the composition, diversity and N_2 fixation activity of the peat moss (*Sphagnum fallax)* microbiomes. *Global Change Biology* 25:2993-3004, doi:10.1111/gcb.14715.
7. Cao Y, Wang X, Gu L (2020) Resprouting responses dynamics of Schima superba following a severe ice storm in early 2008 in Southern China: A six-year study. *Forests* 11:184. doi:10.3390/f11020184.
8. Chang CY, Guanter L, Frankenberg C, Köhler P, Gu L, Magney TS, Grossmann K, Sun Y (2020) Systematic assessment of retrieval methods for canopy far-red solar-induced chlorophyll fluorescence (SIF) using high-frequency automated field spectroscopy. *Journal of Geophysical Research: Biogeosciences* e2019JG005533. doi:10.1029/2019JG005533.
9. Chen A, Tang R, Mao J, Yue C, Li X, Gao M, Shi X, Jin M, Ricciuto D, Rabin S, Ciais P, Piao S (2020) Spatiotemporal dynamics of ecosystem fires and biomass burning-induced carbon emissions in China over the past two decades. *Geography and Sustainability*. https://doi.org/10.1016/j.geosus.2020.03.002.
10. Chen A, Mao J, Ricciuto D, Xiao J, Frankenberg C, Li X, Gu L, Knapp A (2020) Moisture availability mediates the relationship between terrestrial gross primary production and solar-induced fluorescence: Insights from global scale variations. *Global Change Biology* (in review).
11. Crowther TW, van den Hoogen J, Averill C, Wan J, Keiser AD, Mayes MA, Mo L, Maynard DS (2019) The global soil community and its control on biogeochemistry. *Science* 365: eaav0550. doi:10.1126/science.aav0550.
12. Cui E, Huang K, Arain MF, Fisher JB, Huntzinger DN, Ito A, Luo Y, Jain AK, Mao J, Michalak AM, Niu S, Parazoo NC, Peng C, Peng S, Poulter B, Ricciuto DM, Schaefer KM, Schwalm CR, Shi X, Tian H, Wang W, Wang J, Wei Y, Yan E, Yan L, Zeng N, Zhu Q, Xia J (2019) Vegetation functional properties dominate uncertainty of modeled ecosystem productivity in the East Asian monsoon region. *Global Biogeochemical Cycles.* 33(6):668-689. doi.org/10.1029/2018GB005909.

13. DeCarlo KF, Bilheux JC, Bilheux H, Caylor K, Warren JM (2020b) RootProcessing: An open-source python package for root/soil analysis at the neutron imaging beamline at ORNL. *Plant and Soil* (in revision).
14. DeCarlo KF, Caylor K, Bilheux H, Warren JM (2019) Integrating fine root morphology and soil distance mapping to characterize the plant-soil interface. *New Phytologist* (in revision)
15. Denham SO, Oishi AC, Miniat CF, Wood JD, Yi K, Benson MC, Novick KA. Eastern US deciduous tree species respond dissimilarly to declining soil moisture but similarly to rising evaporative demand. *Tree Physiology* (in review).
16. Dusenge ME, Ward EJ, Warren JM, Stinziano JR, Hanson PJ, Way DA (2020) Warming impacts on leaf carbon and water dynamics differ between boreal tree species. *Global Change Biology* (in review)
17. Deventer MJ, Griffis TJ, Roman T., Kolka RK, Wood JD, Erickson M, Baker JM, Millet DB (2019) Error characterization of methane fluxes and budgets derived from a long-term comparison of open- and closed-path eddy covariance systems. *Agricultural and Forest Meteorology* 278:107638, doi:10.1016/j.agrformet.2019.107638.
18. Eckert D, Jensen AM, Gu L (2020) The maximum carboxylation rate of Rubisco affects CO2 refixation in temperate broadleaved forest trees. *Plant Physiology and Biochemistry* (accepted with revision).
19. Ficken CD, Warren JM (2019) The carbon economy of drought: comparing respiration responses of roots, mycorrhizal fungi, and free-living microbes to an extreme dry-rewet cycle. *Plant and Soil* 435:407. doi:10.1007/s11104-018-03900-2.
20. Forbes W, Mao J, Ricciuto DM, Kao S-C, Shi X, Tavakoly AA, Jin M, Guo W, Zhao T, Wang Y, Thornton PE, Hoffman FM (2019) Streamflow in the Columbia River Basin: Quantifying changes over the period 1951-2008 and determining the drivers of those changes. *Water Resources Research* 55:6640-6652. doi:10.1029/2018WR024256.
21. Freschet, GT, Pagès L, Iversen CM, Comas LH, Rewald B, Roumet C, Klimešová J, Zadworny M, Poorter H, Postma JA, Adams TS, Bagniewska-Zadworna A, Blancaflor EB, Brunner I, Cornelissen JHC, Garnier E, Gessler A, Hobbie SE, Lambers H, Meier IC, Mommer L, Picon-Cochard C, Rose L, Ryser P, Scherer-Lorenzen M, Soudzilovskaia NA, Stokes A, Sun T, Valverde-Barrantes OJ, Weemstra M, Weigelt A, Wurzburger N, York LM, Batterman SA, Bengough AG, Gomes de Moraes M, Janeček Š, Salmon V, Tharayil N, McCormack ML (2020a) A starting guide to root ecology: strengthening ecological concepts and standardizing root classification, sampling, processing and trait measurements. *New Phytologist* (in review).
22. Freschet GT, Roumet C, Comas LH, Weemstra M, Bengough AG, Rewald B, Bardgett RD, De Deyn GB, Johnson D, Klimeov J, Lukac M, McCormack ML, Meier IC, Pag s L, Poorter H, Prieto I, Wurzburger N, Zadworny M, Bagniewska-Zadworna A, Blancaflor EB, Brunner I, Gessler A, Hobbie SE, Iversen CM, Mommer L, Picon-Cochard C, Postma JA, Rose L, Ryser P, Scherer-Lorenzen M, Soudzilovskaia NA, Sun T, Valverde-Barrantes OJ, Weigelt A, York LM, Stokes A (2020) Root traits as key proxies to unravel plant and ecosystem functioning: current understanding, pitfalls and future research needs. *New Phytologist* (in review).
23. Gallagher RV, Falster DS, Maitner BS, Salguero-Gómez R, Vandvik V, Pearse WD, Schneider FD, Kattge J, Poelen JH, Madin JS, Ankenbrand M, Penone C, Feng X, Adams VM, Alroy J, Andrew SC, Balk M, Bland LM, Boyle BL, Bravo-Avila CH, Brennan I, Carthey AJR, Catullo R, Cavazos BR, Conde DA, Chown SL, Fadrique B, Gibb H, Halbritter AH, Hammock J, Hogan JA, Holewa H, Hope M, Iversen CM, Jochum M, Kearney M, Keller A, Mabee P, Manning P, McCormack L, Michaletz ST, Park DS, Perez TM, Pineda-Munoz S, Ray CA, Rossetto M, Sauquet H, Sparrow B, Spasojevic MJ, Telford RJ, Tobias JA, Violle C, Walls R, Weiss KCB, Westoby M, Wright IJ, Enquist BJ (2020) Open Science principles for accelerating trait-based science across the Tree of Life. *Nature Ecology & Evolution* 4:292-303. doi:10.1038/s41559-020-1109-6.
24. Graham JD, Glenn NF, Spaete LP, Hanson PJ (2020a) Characterizing Peatland Microtopography Using Gradient and Microform-Based Approaches. *Ecosystems* https://doi.org/10.1007/s10021-020-00481-z

25. Graham JD, Hanson PJ, Phillips JR, Warren JM, Wullschleger SD, Glenn NF (2020b) *Picea mariana* and *Larix laricina* growth responses to elevated temperature and CO_2: a four-year synthesis from the SPRUCE experiment. *Global Change Biology* (in review).
26. Griffis TJ, Hu C, Baker JM, Wood JD, Millet DB, Erickson M, Yu Z, Deventer MJ, Winker C, Chen Z (2019) Tall tower ammonia observations and emission estimates in the US Midwest, *Journal of Geophysical Research: Biogeosciences* 124:3432-3447, doi:10.1029/2019JG005172.
27. Griffis TJ, Roman DT, Wood JD, Deventer MJ, Fachin L, Rengifo J, Castillo DD; Lilleskov E, Kolka R, Chimner RA, del Aguilla J, Wayson C, Hergoualc'h K, Baker JM, Cadillo-Qurroz H, Ricciuto DM (2020) Hydrometeorological sensitivities of net ecosystem carbon dioxide and methane exchange of an Amazonian palm swamp peatland. *Agricultural and Forest Meteorology* (in review).
28. Griffiths NA, Sebestyen SD, Oleheiser KC (2019) Variation in peatland porewater chemistry over time and space along a bog to fen gradient. *Science of the Total Environment* 697:134152. doi:10.1016/j.scitotenv.2019.134152.
29. Gu L, Han J, Wood J, Chang C, Sun Y (2019) Sun-induced chlorophyll fluorescence and its importance for modeling photosynthesis from the side of light reactions. *New Phytologist* 223:1179-1191. doi:10.1111/nph.15796.
30. Gu L, Wood JD, Chang C, Sun Y (2019a) A novel automated system for long-term continuous sun-induced chlorophyll fluorescence measurements for integration with eddy covariance flux networks. *Journal of Geophysical Research: Biogeosciences* 123:127–146, doi:10.1029/2018JG004742.
31. Guerrero-Ramirez N, Mommer L, Freschet GT, Iversen CM, McCormack ML, Kattge J, Poorter H, van der Plas F, Bergmann J, Kuyper TW, York LM, Bruelheide H, Laughlin DC, Meier IC, Roumet C, Semchenko M, Sweeney CJ, van Ruijven J, Valverde-Barrantes OJ, Aubin I, Catford JA, Manning P, Martin A, Milla R, Minden V, Pausas JG, Smith SW, Soudzilovskaia NA, Ammer C, Butterfield B, Craine J, Cornelissen JHC, de Vries FT, Isaac ME, Kramer K, König C, Lamb EG, Onipchenko VG, Peñuelas J, Reich PB, Rillig MC, Sack L, Shipley B, Tedersoo L, Valladares F, van Bodegom P, Weigelt P, Wright JP, Weigelt A (2020) Global Root Traits (GRooT) Database. bioRxiv 2020.05.17.095851; *Global Ecology and Biogeography* (in press).
32. Han J, Gu L, Warren JW, Sun Y, Guha A, McLennan DA, Zhang W, Zhang Y (2020) The roles of photochemical and non-photochemical quenching in regulating photosynthesis depend on the phases of fluctuating environment conditions. *The Plant Journal* (submitted).
33. Hanson PJ, Griffiths NA, Iversen CM, Norby RJ, Sebestyen SD, Phillips JR, Chanton JP, Kolka RK, Malhotra A, Oleheiser KC, Warren JM, Shi X, Yang X, Mao J, Ricciuto DM (2020) Rapid net carbon loss from a whole-ecosystem warmed peatland. *AGU Advances* (in press)
34. Hanson PJ, Walker AP (2019) Invited Commentary: Advancing global change biology through experimental manipulations: Where have we been and where might we go? *Global Change Biology* 26:287-299. doi:10.1111/gcb.14894.
35. He L, Frankenberg C, Wood JD, Sun Y, Koehler P, Magney T, Dutta D, Zhang Y (2020) Solar-induced fluorescence tracks seasonal and interannual variability in photosynthetic downregulation in response to water stress. *Journal of Geophysical Research: Biogeosciences*, 125:e2019JD031207. doi:10.1029/2019JD031207.
36. Hopple AM, Wilson, RM, Kolton, M, Zalman, CA, Chanton JP, Kostka J, Hanson PJ, Keller JK, Bridgham SD (2020) Massive peatland carbon banks vulnerable to rising temperatures. *Nature Communications* 11:2373. doi:10.1038/s41467-020-16311-8.
37. Hu C, Griffis TJ, Baker JM, Wood JD, Millet DB, Yu Z, Lee X (2020) Modeling the sources and transport processes during extreme ammonia episodes in the U.S. Corn Belt, *Journal of Geophysical Research: Atmospheres* 125:e2019JD031207. doi:10.1029/2019JD031207.
38. Huang M, Piaol S, Ciais P, Peñuelas J, Wang X, Keenan TF, Peng S, Berry JA, Wang K, Mao J, Alkama R, Cescatti A, Cuntz M, De Deurwaerder H, Gao M, He Y, Liu Y, Luo Y, Myneni RB, Niu S, Shi X, Yuan W, Verbeeck H, Wang T, Wu J, Janssens IA (2019) Air temperature optima of vegetation productivity across global biomes. *Nature Ecology and Evolution* 3:772–77. doi:10.1038/s41559-019-0838-x.

39. Huang Y, Stacy M, Jiang J, Sundi N, Ma S, Saruta V, Jung CG, Shi Z, Xia J, Hanson PJ, Ricciuto D, Luo Y (2019) Realized ecological forecast through an interactive ecological platform for assimilating data (EcoPAD, v 1.0) into models. *Geoscientific Model Development* 12:1119-1137. doi:10.5194/gmd-12-1119-2019.
40. Jia, B. Luo HX, Cai XM, Jain A, Huntzinger DN, Xie ZH, Zeng N, Mao JF, Shi XY, Ito A, Wei YX, Tian HQ, Poulter B, Hayes D, Schaefer K (2020) Impacts of land use change and elevated CO2 on the interannual variations and seasonal cycles of gross primary productivity in China, *Earth System Dynamics* 11(1):235-249. doi:10.5194/esd-11-235-2020.
41. Jian S, Li J, Wang G, Kluber LA, Schadt CW, Liang J, Mayes MA (2020) Multi-year incubation experiments boost confidence in model projections of long-term soil carbon dynamics. *Nature Communications* (in review)
42. Jensen AM, Warren JM, King AW, Ricciuto DM, Hanson PJ, Wullschleger SD (2019) Simulated projections of boreal forest peatland ecosystem productivity are sensitive to observed seasonality in leaf physiology. *Tree Physiology* 39:556-572, doi:10.1093/treephys/tpy140.
43. Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, Tautenhahn S, Werner GDA … Iversen CM … 700+ co-authors … Wirth C (2020) TRY plant trait database - enhanced coverage and open access. *Global Change Biology* 26:119-188. doi:10.1111/gcb.14904.
44. Keller AB, Brzostek ER, Craig ME, Fisher JB, Phillips RP (2020) Root-derived inputs are major contributors to soil carbon in temperate forests. *Ecology Letters* (in review)
45. Kluber LA, Johnston ER, Allen SA, Hendershot JN, Hanson PJ, Schadt CW (2020) Constraints on microbial communities, decomposition and methane production in deep peat deposits. *PLOS ONE* 15(2):e0223744. doi:10.1371/journal.pone.0223744.
46. Kolus H, Huntzinger D, Schwalm C, Fisher J, Mckay N, Fang Y, Michalak A, Schaefer K, Wei Y, Poulter B, Mao J, Parazoo N, Shi X (2018) Evaluating vegetation drought response and recovery in terrestrial biosphere models. *Environmental Research Letters* (in review)
47. LeRoy CJ, Hipp AL, Lueders K, Follstad Shah JJ, Kominoski JS, Ardón M, Dodds WK, Gessner MO, Griffiths NA, Lecerf A, Manning DWP, Sinsabaugh RL, Webster JR (2020) Plant phylogenetic history explains in-stream decomposition at a global scale. *Journal of Ecology* 108:17-35. doi:10.1111/1365-2745.13262.
48. Li J, Zhang Y, Li Z, Li J, Zhang Q, Zhang Z, Song L, Gu L (2020) Seasonally varying relationship between sun-induced chlorophyll fluorescence and photosynthetic capacity from leaf to canopy in a paddy rice field. *Journal of Experimental Botany* (submitted).
49. Liang, JY, Wang GS, Ricciuto DM, Gu LH, Hanson PJ, Wood JD, Mayes MA (2019) Evaluating the E3SM land model version 0 (ELMv0) at a temperate forest site using flux and soil water measurements. *Geoscientific Model Development* 12:1601-1612. doi:10.5194/gmd-12-1601-2019.
50. Liang J, Wang G, Singh S, Jagadamma S, Gu L, Schadt CW, Wood JD, Hanson PJ, Mayes MA (2020) Intensified soil moisture extremes decrease soil organic carbon decomposition: a mechanistic modeling analysis. *Journal of Geophysical Research - Biogeosciences* (in review)
51. Liu XP, Liang JY, Gu L (2020) Photosynthetic and environmental regulations of the dynamics of soil respiration in a forest ecosystem revealed by analyses of decadal time series. *Agricultural and Forest Meteorology* 282–283:107863. doi:10.1016/j.agrformet.2019.107863.
52. Liu, YW, Piao SL, Gasser T, Ciais P, Yang PH, Wang H, Keenan TF, Huang MT, Wan SQ, Song J, Wang K, Janssens IA, Penuelas J, Huntingford C, Wang XH, Arain MA, Fang YY, Fisher JB, Huang MY, Huntzinger DN, Ito A, Jain AK, Mao JF, Michalak AM, Peng CH, Poulter B, Schwalm C, Shi CY, Tian HQ, Wei YX, Zeng N, Zhu QA, Wang T (2019) Field-experiment constraints on the enhancement of the terrestrial carbon sink by CO_2 fertilization. *Nature Geoscience* 12:809. doi:10.1038/s41561-019-0436-1.
53. Lu, D, Liu S, Ricciuto D (2019) An efficient Bayesian method for advancing the application of deep learning in Earth science, *2019 International Conference on Data Mining Workshops (ICDMW),* Beijing, China, 2019, pp. 1790287, doi:10,1109/ICDMW.2019.00048.

54. Lu, D, Ricciuto D (2019) Learning-based inversion-free model-data integration to advance ecosystem model prediction, *2019 International Conference on Data Mining Workshops (ICDMW)*, Beijing, China, 2019, pp. 1790287, doi:10,1109/ICDMW.2019.00049.
55. Malhotra A, Brice D, Childs J, Graham JD, Hobbie EA, Vander Stel H, Feron SC, Hanson PJ, Iversen CM (2020) Peatland warming strongly increases fine-root growth. *Proceedings of the National Academy of Sciences* (in press).
56. Malhotra A, Todd-Brown K, Nave LE, Batjes NH, Holmquist JR, Hoyt AM, Iversen CM, Jackson RB, Lajtha K, Lawrence C, Vindušková O, Wieder W, Williams M, Hugelius G, Harden J (2019) The landscape of soil carbon data: emerging questions, synergies and databases. *Progress in Physical Geography* 43:707-719. doi:10.1177/0309133319873309 .
57. McCormack ML, Iversen CM (2019) Physical and functional constraints on viable belowground acquisition strategies. *Frontiers in Plant Science* 10:1215. doi:10.3389/fpls.2019.01215.
58. McPartland MY, Montgomery RA, Hanson PJ, Phillips JR, Kolka RK, Palik B (2020) Vascular plant species response to warming and elevated carbon dioxide in a boreal peatland. *Environmental Research Letters* (submitted).
59. Meng L, Mao J, Zhou Y, Richardson AD, Lee X, Thornton PE, Ricciuto DM, Li X, Dai Y, Shi X, Jia G (2020) Urban warming advances spring phenology but reduces temperature response of plants in the conterminous United States. *Proceedings of the National Academy of Sciences of the United States of America*. doi:10.1073/pnas.1911117117.
60. Moore JAM, Sulman BN, Mayes MA, Patterson CM, Classen AT (2019) Plant roots stimulate the decomposition of complex, but not simple, soil carbon. *Functional Ecology* 34(4):899-910.
61. Norby RJ, Childs J, Hanson PJ, Warren JM (2019) Rapid loss of an ecosystem engineer: Sphagnum decline in an experimentally warmed bog. *Ecology and Evolution* 9:12571-12585. doi:10.1002/ece3.5722.
62. Paschalis A, Fatichi S, Zscheischler J, Ciais P, Bahn M, Boysen L, Chang J, De Kauwe M, Estiarte M, Goll D, **Hanson PJ**, Harper AB, Hou E, Kigel J, Knapp AK, Larsen KS, Li W, Lierert S, Luo Y, Meir P, Ogaya R, Parolari AJ, Peng C, Peñuelas J, Pongratz J, Rambal S, Schmidt IK, Shi H, Sternberg M, Tian H, Tschumi E, Ukkola A, Vicca S, Viovy N, Wang Y-P, Wang Z, Wu D, Zhu Q (2020) Rainfall-manipulation experiments as simulated by terrestrial biosphere models: where do we stand? *Global Change Biology* doi:10.1111/gcb.15024.
63. Rewcastle KE, Moore JAM, Henning JA, Mayes MA, Patterson CM, Wang G, Metcalfe DB, Classen AT (2020) Investigating drivers of microbial activity and respiration in a forested bog. *Pedosphere* 30:135-145. doi:10.1016/S1002-0160(19)60841-6.
64. Ricciuto DM, Xu X, Shi X, Wang Y, Song X, Schadt CW, Griffiths NA, Mao J, Warren JM, Thornton PE, Chanton J, Keller JK, Bridgham S, Gutknecht J, Stephen D. Sebestyen[7], Adrien Finzi[8], Randall Kolka[7], and Hanson PJ (2019) An interactive model for soil biogeochemistry and methane processes: I. model structure and sensitivity analyses. *Journal of Geophysical Research -Biogeosciences* (major revisions).
65. Shi X, Ricciuto DM, Thornton PE, Xu X, Yuan F, Norby RJ, Walker AP, Warren J, Mao J, Hanson PJ, Meng L, Weston D, Griffiths NA (2020) Modeling the hydrology and physiology of Sphagnum moss in a northern temperate bog. *Biogeosciences Discussion* https://doi.org/10.5194/bg-2020-90
66. Singh S, Liang J, Kivlin S, Wood, J, Wang G, Schadt CW, DuPont J, Gowda P, Mayes MA (2020) Differential microbial respiration responses to soil texture and moisture in mixed forests. *Geoderma* (in revision).
67. Singh S, Yan S, Sorochan J, Stier J, Mayes MA, Zhuang J, Jagadamma S (2019) Soil carbon accumulation and nutrient availability in managed and unmanaged ecosystems of East Tennessee. *Soil Science Society of America Journal* 83:458-465. doi.org/10.2136/sssaj2018.09.0359.
68. Smits AP, Ruffing CM, Royer TV, Appling AP, Griffiths NA, Bellmore R, Scheuerell MD, Harms TK, Jones JB (2019) Detecting signals of large-scale climate phenomena in discharge and nutrient loads in the Mississippi-Atchafalaya River Basin. *Geophysical Research Letters* 46:3791-3801. doi:10.1029/2018GL018166.

69. Tiegs S, Costello DM, Isken MW, Woodward G, McIntyre PB, Gessner MO, Chauvet E, Griffiths NA, Flecker AS, et al. (2019) Global patterns and drivers of ecosystem functioning in rivers and riparian zones. *Science Advances* 5:eaav0486, doi:10.1126/sciadv.aav0486.
70. Walker AP, Anderson J, Bridges RA, Fisher RA, Johnson AL, Lu D, Ricciuto DM, Rogers A, Serbin SP, Ye M (2020) Multi-hypothesis analysis of Farquhar and Collatz photosynthesis models reveals unexpected influence of empirical assumptions. *AGU Advances* (submitted)
71. Wang F, Pan X, Gerlein-Safdi C, Cao X, Wang S, Gu L, Wang D, Lu Q (2020) Vegetation restoration in Northern China: A contrasted picture. *Land Degradation and Development* 31:669-676. doi:10.1002/ldr.3314.
72. Wang G, Huang W, Zhoud G, Mayes MA, Zhou, Z (2020) Modeling the processes of soil moisture in regulating microbial and carbon-nitrogen cycling. *Journal of Hydrology* 585:124777. doi:10.1016/j.jhydrol.2020.124777.
73. Wang, YF, Yuan F, Yuan B, Gu M, Hahn M, Torn M, Ricciuto DM, Kumar J, He L, Zona D, Lipson D, Wagner R, Oechel W, Wullschleger S, Thornton P, Xu X (2019) Mechanistic modeling of microtopographic impacts on CO2 and CH4 fluxes in an Alaskan tundra ecosystem using the CLM-Microbe model. *Journal of Advances in Modeling Earth Systems*, doi:10.1029/2019ms001771.
74. Ward EJ, Warren JM, McLennan DA, Dusenge ME, Way DA, Stan D. Wullschleger SD, Hanson PJ (2019) Photosynthetic and respiratory responses of two bog shrub species to whole ecosystem warming and elevated CO_2 at the boreal-temperate ecotone. *Frontiers in Forests and Global Change* 2:54. doi:10.3389/ffgc.2019.00054.
75. Warren JM, Jensen AM, Ward EJK, Guha A, Childs J, Wullschleger SD, Hanson PJ (2020) Divergent species-specific impacts of whole ecosystem warming on water relations in a Picea mariana peatland. *Global Change Biology* (submitted).
76. Wilson RM, Tfaily MM, Kolton MM, Petro C, Hanson PJ, Heyman HM, Kyle JE, Hoyt DW, Eder EK, Purvine SO, Kolka RK, Sebestyen SD, Griffiths NA, Schadt CW, Kostka J, Chanton JP. Soil metabolome response to whole-ecosystem warming at the Spruce and Peatland Responses Under Changing Environments experiment. *Proceedings of the National Academy of Sciences* (in review).
77. Wood, JD, Sadler EJ, Fox NI, Greer S, Gu L, Guinan P, Lupo AR, Market P, Rochette S, Speck A, White L (2019) Land-atmosphere responses to a total solar eclipse in three ecosystems with contrasting structure and physiology. *Journal of Geophysical Research: Atmospheres* 124:530-543 doi:10.1029/2018JD029630.
78. Wood JD, Sadler EJ, Fox NI, Greer ST, Gu L, Guinan PE, Lupo AR, Market PS, Rochette SM, Speck A, White LD. (2019) Eddy Flux and Meteorology over Deciduous Forest, Prairie, and Soybean Ecosystems in Missouri, USA, during the Total Solar Eclipse of 2017. *DOE Data Explorer* doi:10.25581/ornlsfa.017/1579907.
79. Yan B, Mao J, Shi X, Hoffman FM, Notaro M, Zhou T, McDowell N, Dickinson RE, Xu M, Gu L, Ricciuto RM (2019) Predictability of tropical vegetation greenness using sea surface temperatures. *Environmental Research Communications* 1:031003. doi:10.1088/2515-7620/ab178a.
80. Yan BY, Mao JF, Dickinson RE, Thornton. PE, Shi XY, Ricciuto DM, Warren JM Hoffman FM (2020) Modelling tree stem-water dynamics over an Amazonian rainforest. *Ecohydrology* 13(1):e2180. doi:10.1002/eco.2180.
81. Yu X, Millet DB, Wells KC, Griffis TJ, Chen X, Baker JM, Conley SA, Smith ML, Ghvakharia A, Kort EA, Plant G, Wood JD (2020) Top-down constraints on methane point source emissions from animal agriculture and waste based on new airborne measurements in the US Upper Midwest. *Journal of Geophysical Research: Biogeosciences* 125:e2019JG005429, doi:10.1029/2019JG005429.
82. Yuan F, Wang Y, Ricciuto DM, Shi X, Yuan F, Hanson PJ, Thornton PE, Xu X (2020) An Integrative Model for Soil Biogeochemistry and Methane Processes: II. Warming and Elevated CO_2 Effects on Peatland CH4 Emission. *Journal of Geophysical Research - Biogeosciences* (in revision).

ORNL TES SFA Publications March 2015 through February 2019

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. Andres RJ, Boden TA, Higdon DM (2016) Gridded uncertainty in fossil fuel carbon dioxide emission maps, a CDIAC example. *Atmospheric Chemistry and Physics* 16:14979–14995. doi:10.5194/acp-16-1497-2016.
3. 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 (2018) Guidelines and considerations for designing precipitation manipulation experiments in forest ecosystems. *Methods in Ecology and Evolution* 9:2310-2325, doi: 10.1111/2031-210X.13094.
4. Ballantyne AP, Andres R, Houghton R, Stocker BD, Wanninkhof R, Anderegg W, Cooper LA, DeGrandpre M, Tans PP, Miller JB, Alden C, White JWC (2015) Audit of the global carbon budget: Estimate errors and their impact on uptake uncertainty. *Biogeosciences* 12:2565-2584. doi:10.5194/bg-12-2565-2015.
5. 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.
6. Brooks SC, Brandt CC, Griffiths NA (2017) Estimating uncertainty in ambient and saturation nutrient uptake metrics from nutrient pulse releases in stream ecosystems. *Limnology and Oceanography: Methods* 15:22-37. doi:10.1002/lom3.10139.
7. Chen M, Griffis TJ, Baker JM, Wood JD, Meyers T, Suyker A (2018a) 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.
8. Chen, Z., Griffis TJ, Baker JM, Millet D, Wood JD, Dlugokencky E, Andrews A, Sweeney C, Hu C, Kolka R (2018b) 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.
9. Christianson DS, C Varadharajana, B Christoffersen, M Dettod, B Faybishenkoa, KJ Jardine, R Negron-Juareza, BO Gimenez, GZ Pastorello, TL Powell, JM Warren, BT Wolfe, JQ Chambers, LM Kueppers, NG McDowell, D Agarwal (2017) A metadata reporting framework (FRAMES) for synthesis of earth system observations. *Ecological Informatics* 42:148-158, doi:10.1016/j.ecoinf.2017.06.002.
10. Dai H, Ye M, Walker AP, Chen X (2017) A new process sensitivity index to identify important system processes under process model and parametric uncertainty. *Water Resources. Research* 53:2577-3522, doi:10.1002/2016WR019715.
11. 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.
12. D'Odoricoa P, Gonsamob A, Goughc CM, Bohrerd G, Morisone J, Wilkinsone M, Hanson PJ, Gianelleg D, Fuentesh JD, Buchmannaa N (2015) The match and mismatch between photosynthesis and land surface phenology of deciduous forests. *Agricultural and Forest Meteorology* 214:25-38, doi:10.1016/j.agrformet.2015.07.005.
13. 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. doi:10.5194/bg-14-4315-2017.

14. Eberhardt, TL, Labbé N, So C-L, Kim K, Reed KG, Leduc D, Warren JM (2015) Effects of long-term elevated CO_2 treatment on the inner and outer bark chemistry of sweetgum (*Liquidambar styraciflua* L.) trees. *Trees* 29:1735-1747. doi:10.1007/s00468-015-1254-8.
15. Estiarte M, Vicca S, Peñuelas J, Bahn M, Beier C, Emmett BA, Fay PA, Hanson PJ, Hasibeder R, Kigel J, Kröel-Dulay G, Larsen KS, Lellei-Kovács E, Limousin JM, Ogaya R, Ourcival JM, Reinsch S, Sala OE, Schmidt IK, Sternberg M, Tielbörger K, Tietema A, Janssens IA (2016) Few multi-year precipitation-reduction experiments find a shift in the productivity-precipitation relationship. *Global Change Biology* 22:2570–2581, doi:10.1111/gcb.13269.
16. Fang Y, Michalak AM, Schwalm C, Huntzinger D, Berry JA, Ciais P, Piao S, Poulter B, Fisher JB, Cook RB, Hayes D, Huang M, Ito A, Lei H, Mao J, Parazoo N, Shi X, Tao B, Wang W, Wei Y, Yang J (2017) Global land carbon sink response to temperature and precipitation varies with ENSO phase. *Environmental Research Letters* 12:064007, doi:10.1088/1748-9326/aa6e8e.
17. Ficken CD, Warren JM (2019) The carbon economy of drought: comparing respiration responses of belowground roots, mycorrhizal fungi, and free-living microbes soil biota to an extreme dry-rewet cycle. *Plant and Soil* 435:407–422. doi:10.1007/s11104-018-03900-2.
18. 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 and Penuelas 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.
19. Follstad Shah JJ, Kominoski JS, Ardón M, Dodds WK, Gessner MO, Griffiths NA, Hawkins CP, Lecerf A, LeRoy CJ, Manning DWP, Johnson SL, Rosemond AD, Sinsabaugh RL, Swan CM, Webster JR, Zeglin LH (2017) Global synthesis of the temperature sensitivity of leaf litter breakdown in streams and rivers. *Global Change Biology* 23:3064–3075, doi:10.1111/gcb.13609.
20. 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* 13:054023, doi:10.1088/1748-9326/aabb41.
21. Freschet GT, Valverde-Barrantes OJ, Tucker CM, Craine JM, McCormack ML, Violle C, Fort F, Blackwood CB, Urban-Mead KR, Iversen CM, Bonis A, Comas LH, Cornelissen JHC, Dong M, Guo D, Hobbie SE, Holdaway RJ, Kembel SW, Makita N, Onipchenko VG, Picon-Cochard C, Reich PB, de la Riva EG, Smith SW, Soudzilovskaia NA, Tjoelker MG, Wardle DA, Roumet C (2017) Climate, soil and plant functional types as drivers of global fine-root trait variation. *Journal of Ecology* 105:1182–1196, doi:10.1111/1365-2745.12769.
22. Furze ME, Jensen AM, Warren JM, Richardson AD (2018) Seasonal patterns of nonstructural carbohydrate reserves in four woody boreal species. *The Journal of the Torrey Botanical Society* 145:332-339, doi:10.3159/TORREY-D-18-00007.1.
23. Ge X, Zhou B, Wang X, Li Q, Cao Y, Gu L (2018) Imposed drought effects on carbon storage of moso bamboo ecosystem in southeast China: results from a field experiment. *Ecological Research* 33:393-402, doi:10.1007/s11284-017-1529-1.
24. Geron C, Daly R, Harley P, Rasmussen R, Seco R, Guenther A, Karl T, Gu L (2016) Large drought-induced variations in oak leaf volatile organic compound emissions during PINOT NOIR 2012. *Chemosphere* 146:8-21, doi:10.1016/j.chemosphere.2015.11.086.
25. 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:10.1111/gcb.13806
26. 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.
27. Griffiths NA, Sebestyen SD (2016) Dynamic vertical profiles of peat porewater chemistry in a northern peatland. *Wetlands* 36:1119-1130, doi:10.1007/s13157-016-0829-.5
28. Griffiths NA, Tiegs SD (2016) Organic matter decomposition along a temperature gradient in a forested headwater stream. *Freshwater Science* 32:518-533, doi:10.1086/685657.

29. 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.
30. 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* 37:810-825, doi:10.1086/700700.
31. Gu L (2015) Fluxes as functions of ecosystem and drivers of atmosphere, ESA 2015, Book Reviews, *Ecology* 96:1737-1738, doi:10.1890/BR15-24.1.
32. Gu L, Massman WJ, Leuning R, Pallardy SG, Meyers T, Hanson PJ, Riggs JS, Hosman KP, Yang B (2012) The fundamental equation of eddy covariance and its application in flux measurements. *Agricultural and Forest Meteorology* 152:135-148, doi:10.1016/j.agrformet.2011.09.014.
33. Gu L, Pallardy SG, Hosman KP, Y Sun (2015) Drought-influenced mortality of tree species with different predawn leaf water dynamics in a decade-long study of a central US forest. *Biogeosciences* 12:2831-2845, doi:10.1016/j.agrformet.2015.11.014.
34. Gu L, Pallardy SG, Hosman KP, Y Sun (2016b) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. *Agricultural and Forest Meteorology* 217:120-136. doi:10.1016/j.agrformet.2015.11.014.
35. Gu L, Pallardy SG, Yang B, Hosman KP, Mao J, Ricciuto D, Shi X, Sun Y (2016c) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a central USA forest. *Journal of Geophysical Research - Biogeosciences* 121:1884-1902, doi:10.1002/2015JG003302.
36. Gu L, Wood JD, Chang CYY, Sun Y, Riggs JS (2019) Advancing Terrestrial Ecosystem Science with a Novel Automated Measurement System for Sun-Induced Chlorophyll Fluorescence for Integration with Eddy Covariance Flux Networks. *Journal of Geophysical Research - Biogeosciences* 124:127-146, doi:10.1029/2018JG004742.
37. Guha A, Cummings C, Han J, McLennan DA, Warren JM (2018) Differential ecophysiological responses and resilience to heat wave events in four co-occurring temperate tree species. Invited for special issue *Focus on Tree Mortality in a Warming World: Causes, Patterns, and Implications*. *Environmental Research Letters* 13:065008, doi:10.1088/1748-9326/aabcd8.
38. Hanson PJ, Gill AL, Xu X, Phillips JR, Weston DJ, Kolka RK, Riggs JS, Hook LA (2016) Intermediate-scale community-level flux of CO_2 and CH_4 in a Minnesota peatland: Putting the SPRUCE project in a global context. *Biogeochemistry* 129:255-272, doi:10.1007/s10533-016-0230-8.
39. Hanson PJ, Riggs JS, Nettles WR, Phillips JR, Krassovski MB, Hook LA, Richardson AD, Aubrecht DM, Ricciuto DM, Warren JM, Barbier C (2017) Attaining whole-ecosystem warming using air and deep soil heating methods with an elevated CO_2 atmosphere. *Biogeosciences* 14:861–883, doi:10.5194/bg-14-861-2017.
40. 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, doi:10.1016/j.atmosenv.2017.01.049.
41. He H, Wang D, Tan J (2016) Data synthesis in the community land model for ecosystem simulation. *Journal of Computational Science* 13:83-95, doi:10.1016/j.jocs.2016.01.005.
42. He Y, Yang J, Zhuang Q. Harden J, McGuire AD, Liu Y, Wang G, Gu L (2015) Incorporating microbial dormancy dynamics into soil decomposition models to improve quantification of soil carbon dynamics of northern temperate forests. *Journal of Geophysical Research - Biogeosciences* 120:2596-2611, doi:10.1002/2015JG003130.
43. Hill WR, Griffiths NA (2017) Nitrogen processing by grazers in a headwater stream: riparian connections. *Freshwater Biology* 62:17-29, doi:10.1111/fwb.12833.

44. 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.
45. Hogue S, Marland E, Andres RJ, Marland G, Woodward D (2016) Uncertainty in gridded CO_2 emissions estimates. *Earth's Future* 4:225-239, doi:10.1002/2015EF000343.
46. Huang N, Gu L, Black TA, Wang L, Niu Z (2015) Remote sensing-based estimation of annual soil respiration at two contrasting forest sites. *Journal of Geophysical Research - Biogeosciences* 120:2306-2325, doi:10.1002/2015JG003060.
47. 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.
48. Huang MT, Piao S, Zeng Z, Peng S, Philippe C, Cheng L, Mao J, Poulter B, Shi X, Yang H, Wang YP (2016) Seasonal responses of terrestrial ecosystem water-use efficiency to climate change. *Global Change Biology* 22:2165-2177, doi:10.1111/gcb.13180.
49. Hubbart, JA, R Guyette, R-M Muzika (2016) More than drought: precipitation variance, excessive wetness, pathogens and the future of the western edge of the Eastern deciduous forest. *Science of the Total Environment* 566-567:463-467, doi:10.1016/j.scitotenv.2016.05.108.
50. 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, Ricciuto 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.
51. Ito A, Inatomi M, Huntzinger DN, Schwalm C, Michalak AM, Cook R, King AW, Mao J, Wei Y, Post WM, Wang W, Arain MA, Hayes DJ, Ricciuto DM, Shi X, Huang M, Lei H, Tian H, Lu C, Yang J, Tao B, Jain A, Poulter B, Peng S, Ciais P, Fisher JB, Parazoo N, Schaefer K, Peng C, Zeng N, Zhao F (2016) Decadal trends in the seasonal-cycle amplitude of terrestrial CO_2 exchange: an analysis of Multi-scale Terrestrial Model Intercomparison Project ensemble of terrestrial biosphere models. *Tellus B,* 68:28968, doi:10.3402/tellusb.v68.28968
52. 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.
53. 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, doi:10.1111/jph.14486.
54. Jensen AM, Warren JM, Hanson PJ, Childs J, Wullschleger SD (2015) Needle age and season influence photosynthetic temperature response in mature *Picea mariana* trees. *Annals of Botany* 116(5):821-832, doi:10.1093/aob/mcv115.
55. Jensen AM, Warren JM, King AW, Ricciuto DM, Hanson PJ, Stan Wullschleger SD (2019) Simulated projections of boreal forest peatland ecosystem productivity are sensitive to observed seasonality in leaf physiology. *Tree Physiology* 39:556-572, doi:10.1093/treephys/tpy140.
56. Jiang J, Huang Y, Ma S, Stacy M, Shi Z, Ricciuto DM, Hanson PJ, Luo Y (2018a) Forecasting responses of a northern peatland carbon cycle to elevated CO_2 and a gradient of experimental warming. *Journal of Geophysical Research – Biogeosciences* 123:1057-1071, doi:10.1002/2017JG004040.
57. Jian S, Li J, Chen J, Wang G, Mayes MA, Dzantor KE, Hui D, Luo Y (2016) Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. *Soil Biology and Biochemistry* 101:32-43, doi:10.1016/j.soilbio.2016.07.003.
58. Jiang X, Guenther A, Potosnak M, Geron C, Seco R, Karl T, Kim S, Gu L, Pallardy S (2018b) Isoprene emission response to drought and the impact on global atmospheric chemistry. *Atmospheric Environment* 183:69-83, doi:10.1016/j.atmosenv.2018.01.026.

59. Johnson DM, Wortemann R, McCulloh KA, Jordan-Meille L, Ward E, Warren JM, Palmroth S, Domec JC (2016) A test of the hydraulic vulnerability segmentation hypothesis in angiosperm and conifer tree species, *Tree Physiology* 36:983-993, doi:10.1093/treephys/tpw031.
60. Kang S, Wang D, Nichols JA, Schuchart J, Kline KL, Wei Y, Ricciuto DM, Wullschleger SD, Post WM, Izaurralde RC (2015) Development of mpi_EPIC model for global agroecosystem modeling. *Computers and Electronics in Agriculture* 111:48-54, doi:10.1016/j.compag.2014.12.004.
61. Kim K, Labbé N, Warren JM, Elder T, Rials TG (2015) Chemical and anatomical changes in *Liquidambar styraciflua* L. xylem after long-term exposure to elevated CO_2. *Environmental Pollution* 198:179-185, doi:10.1016/j.envpol.2015.01.006.
62. King AW, Andres RJ, Davis KJ, Hafer M, Hayes DJ, Huntzinger DN, de Jong B, Kurz WA, McGuire AD, Vargas R, Wei Y, West TO, Woodall CW (2015) North America's net terrestrial CO_2 exchange with the atmosphere 1990-2009. *Biogeosciences* 12:399-414, doi:10.5194/bg-12-399-2015, (invited).
63. Klaus J, McDonnell JJ, Jackson CR, Du E, Griffiths NA (2015) Where does streamwater come from in low-relief forested watersheds? A dual isotope approach. *Hydrology and Earth System Sciences* 19:125-135, doi:10.5194/hess-19-125.2015.
64. Kostka JE, Weston DJ, Glass JB, Lilleskov EA, Shaw AJ, Turetsky MR (2016) The *Sphagnum* microbiome: new insights from an ancient plant lineage. *New Phytologist* 211:57–64, doi:10.1111/nph.13993.
65. Koven C, Kueppers L, Iversen CM, Reich P, Thornton PE (2016) Expanding the use of plant trait observations and ecological theory in Earth system models: DOE Workshop Report. A summary report from the Terrestrial Ecosystem Science (TES) and Earth System Modeling (ESM) Workshop on Trait Methods for Representing Ecosystem Change; Rockville, MD, 18-19 November 2015. Report Date: May 31, 2016. Access on-line at: http://science.energy.gov/~/media/ber/pdf/workshop%20reports/Trait_workshop_report_05_31_2016.pdf.
66. Krassovski MB, Lyon GE, Riggs JS, Hanson PJ (2018) Near real time environmental monitoring and large volume data collection over slow communication links. *Geoscientific Instrumentation, Methods and Data Systems* 7:28, doi:10.5194/gi-2018-24.
67. Krassovski MB, Riggs JS, Hook LA, Nettles WR, Boden TA, Hanson PJ (2015) A comprehensive data acquisition and management system for an ecosystem-scale peatland warming and elevated CO_2 experiment. *Geoscientific Instrumentation Methods and Data Systems* 4:203–213, doi:10.5194/gi-4-203-2015.
68. Kravitz B, Guenther AB, Gu L, Karl T, Kaser L, Pallardy S, Peňuelas J, Potosnak MJ, Seco R (2016) A new paradigm of quantifying ecosystem stress through chemical signatures. *Ecosphere* 7:e01559, doi:10.1002/ecs2.1559.
69. Kueppers LM, Iversen CM, Koven CD (2016) Expanding the use of plant trait observations in Earth system models. *Eos* 97 doi:10.1029/2016EO049947.
70. Lamberti GA, Entrekin SA, Griffiths NA, Tiegs SD (2017) Coarse particulate organic matter: storage, transport, and retention. pp. 55-69 In *Methods in Stream Ecology: Volume 2: Ecosystem Function* [Lamberti GA, Hauer FR Eds.], Elsevier, Academic Press.
71. 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. doi:10.5194/essd-10-405-2018.

72. Le Quéré C, Moriarty R, Andrew RM, Canadell JG, Sitch S, Korsbakken JI, Friedlingstein P, Peters GP, Andres RJ, Boden TA, Houghton RA, House JI, Keeling RF, Tans P, Arneth A, Bakker DCE, Barbero L, Bopp L, Chang J, Chevalier F, Chini LP, Ciais P, Fader M, Feely RA, Gkritzalis T, Harris I, Hauck J, Ilyina T, Jain AK, Kato E, Kitidis V, Klein Goldewijk K, Koven C, Landschützer P, Lauvset SK, Lefèvre N, Lenton A, Lima ID, Metzl N, Millero F, Munro DR, Murata A, Nabel JEMS, Nakaoka S, Nojiri Y, O'Brien K, Olsen A, Ono T, Pérez FF, Pfeil B, Pierrot D, Poulter B, Rehder G, Rödenbeck C, Saito S, Schuster U, Schwinger J, Séférian R, Steinhoff T, Stocker BD, Sutton AJ, Takahashi T, Tilbrook B, van der Laan-Luijkx IT, van der Werf GR, van Heuven S, Vandemark D, Viovy N, Wiltshire A, Zaehle S, Zeng N (2015) Global carbon budget 2015. *Earth System Science Data* 7:349-396. doi:10.5194/essd-7-349-2015.
73. Li J, Jian, S, de Joff, JP, Lane, CS, Wang, G, Mayes, MA, Hui, D (2018a) Differential effects of warming and nitrogen fertilization on soil respiration and microbial dynamics in switchgrass croplands. *Global Change Biology Bioenergy* 10:575-576, doi:10.1111/gcbb.12515.
74. Li J, Wang G, Mayes MA, Allison SD, Frey SD, Shi Z, Hu XM, Luo Y, Mellilo JM (2018b) Reduced carbon use efficiency and increased microbial turnover with soil warming. *Global Change Biology* 25:900-910, doi:10.1111/gcb.14517.
75. Liang J, Wang G, Ricciuto DM, Gu L, Hanson PJ, Wood JD, Mayes MA (2019) Evaluating the E3SM Land Model at a temperate forest site using flux and soil water measurements. *Geoscientific Model Development Discussion* 12:1601-1612, doi:10.5194/gmd-12-1601-2019.
76. Liu S, Zhuang Q, Chen M, Gu L (2016a) Quantifying spatially and temporally explicit CO_2 fertilization effects on global terrestrial ecosystem carbon dynamics. *Ecosphere* 7:7, doi:10.1002/ecs2.1391.
77. Liu S, Zhuang Q, Chen J, Gu L, Noormets A (2016b) Evaluating atmospheric CO_2 effects on gross primary productivity and net ecosystem exchanges of terrestrial ecosystems in the conterminous United States using the AmeriFlux data and an artificial neural network approach. *Agricultural and Forest Meteorology* 220:38-49, doi:10.1016/j.agrformet.2016.01.007.
78. Liu Z, Bambha RP, Pinto JP, Zeng T, Boylan J, Huang MY, Lei HM, Zhao C, Liu SS, Mao J, Schwalm CR, Shi XY, Wei YX, Michelsen HA (2014) Toward verifying fossil fuel CO_2 emissions with the CMAQ model: Motivation, model description and initial simulation. *Journal of the Air & Waste Management Association* 64:419-435, doi:10.1080/10962247.2013.816642.
79. Liu Z, Guan D, Wei W, Davis SJ, Ciais P, Bai J, Peng S, Zhang Q, Hubacek K, Marland G, Andres RJ, Crawford-Brown D, Lin J, Zhao H, Hong C, Boden TA, Feng K, Peters GP, Xi F, Liu J, Li Y, Zhao Y, Zeng N, He K (2015) Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* 524:335-338. doi:10.1038/nature14677.
80. Lokupitiya E, Denning AS, Schaefer K, Ricciuto D, Anderson R, Arain MA, Baker I, Barr AG, Chen G, Chen JM, Cook DR, Dietze M, El Maayar M, Fischer M, Grant R, Hollinger D, Izaurralde C, Jain A, Kucharik C, Li Z, Liu S, Li L, Matamala R, Peylin P, Price D, Running SW, Sahoo A, Sprintsin M, Suyker AE, Tian H, Tonitto C, Torn M, Verbeeck H, Verma SB, Xue Y (2016) Carbon and energy fluxes in cropland ecosystems: A model-data comparison. *Biogeochemistry* 129:53-86, doi:10.1007/s10533-016-0219-3.
81. 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* 10:1337-1356, doi:10.1002/2017MS001134.
82. 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* 14:4295-4314, doi:10.5194/bg-14-4295-2017.
83. 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 CO_2 and warming. *Journal of Geophysical Research – Biogeosciences* 122:2841-2861, doi:10.1002/2017JG003932.
84. Mao J, Ribes A, Yan B, Shi X, Seferian R, Ciais P, Dai Y, Dickinson RE, Douville H, Hoffman FM, Jin M, Myneni RB, Piao S, Ricciuto D, Thornton PE, Zhu Z (2016a) Human-induced

greening of the northern high-latitude land surface. *Nature Climate Change* 6:959-963, doi:10.1038/nclimate3056.

85. Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016b) Evaluating the Community Land Model in a pine stand with shading manipulations and $^{13}CO_2$ labeling. *Biogeosciences* 13:641-657, doi:10.5194/bg-13-641-2016.
86. Mao JF, Fu WT, Shi XY, Ricciuto DM, Fisher JB, Dickinson RE, Wei YX, Shem W, Piao SL, Wang KC, Schwalm CR, Tian HQ, Mu MQ, Arain A, Ciais P, Cook R, Dai YJ, Hayes D, Hoffman FM, Huang MY, Huang S, Huntzinger DN, Ito A, Jain A, King AW, Lei HM, Lu CQ, Michalak AM, Parazoo N, Peng CH, Peng SS, Poulter B, Schaefer K, Jafarov E, Thornton PE, Wang WL, Zeng N, Zeng ZZ, Zhao F, Zhu QA, Zhu ZC (2015) Disentangling climatic and anthropogenic controls on global terrestrial evapotranspiration trends. *Environmental Research Letters* 10:094008, doi:10.1088/1748-9326/1010/1089/094008.
87. Mayes MA, Lajtha K, Bailey V (2016) Advancing Soil Carbon Cycle Science: Workshop to celebrate 2015–2024 International Decade of Soil; Boulder, Colorado, 14–16 March 2016. *EOS Meeting report* https://eos.org/meeting-reports/advancing-soil-carbon-cycle-science.
88. McCormack ML, Dickie IA, Eissenstat DM, Fahey TJ, Fernandez CW, Guo D, Helmisaari H-S, Hobbie EA, Iversen CM, Jackson RB, Leppälammi-Kujansuu J, Norby RJ, Phillips RP, Pregitzer KS, Pritchard SG, Rewald B, Zadworny M (2015) Redefining fine roots improves understanding of belowground contributions to terrestrial biosphere processes. *New Phytologist* - Tansley Review 207:505-518, doi:10.1111/nph.13363.
89. McCormack ML, Guo D, Iversen CM, Chen W, Eissenstat DM, Fernandez CW, Li L, Ma C, Ma Z, Poorter H, Reich PB, Zadworny M, Zanne A (2017) Building a better foundation: Improving root-trait measurements to understand and model plant and ecosystem processes. *New Phytologist* 215:27-37, doi:10.1111/nph.14459.
90. McCormack ML, Iversen CM, Eissenstat DM (2016) Moving forward with fine-root definitions and research. *New Phytologist* 212:313, doi:10.1111/nph.14100.
91. McCormack ML, Powell AS, Iversen CM (2018) Better plant data at the root of ecosystem models. *EOS* 99, doi:10.1029/2018EO104093.
92. 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* 219:851-869, doi:10.1111/nph.15027.
93. McDowell N, Hanson PJ, Ibanez I, Phillips RP, Ryan MG (2016) Physiological Responses of Forests to Drought. pp. 49-58. In *Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis.* [Vose JM, Clark JS, Luce CH, Patel-Weynand T eds.] General Technical Report WO-93b. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office.
94. 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.
95. Medlyn BE, Zaehle S, De Kauwe MG, Walker AP, Dietze MC, Hanson PJ, Hickler T, Jain AK, Luo Y, Parton W, Prentice IC, Thornton PE, Wang S, Wang Y-P, Weng E, Iversen CM, McCarthy HR, Warren JM, Oren R, Norby RJ (2015) Using ecosystem experiments to improve vegetation models. *Nature Climate Change* 5:528-534, doi:10.1038/NCLIMATE2621.
96. Medvedeff CA, Bridgham SD, Pfeifer-Meister L, Keller JK (2015) Can *Sphagnum* leachate chemistry explain differences in anaerobic decomposition in peatlands? *Soil Biology and Biochemistry* 86:34-41, doi.org/10.1016/j.soilbio.2015.03.016.
97. 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.

98. 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.
99. Norby RJ, Gu L, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Xu C, Winter K. (2016) Informing models through empirical relationships between foliar phosphorus, nitrogen and photosynthesis across diverse woody species in tropical forests of Panama. *New Phytologist* 215: 1425-1437, doi:10.1111/nph.14319.
100. Norby RJ, Iversen CM (2017) Introduction to a Virtual Special Issue on root traits. *New Phytologist* 215:5-8, doi:10.1111/nph.14522.
101. 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, doi:10.1002/ecy.2009.
102. Ossler F, Santodonato LJ, Warren JM, Finney CAE, Bilheux J-C, Mills RA, Skorpenske HD, Bilheux HZ (2018) In situ monitoring of hydrogen loss during pyrolysis of wood by neutron imaging. *Proceedings of the Combustion Institute* 37:1273-1280, doi:10.1016/j.proci.2018.07.051.
103. Piao SL, Yin GD, Tan JG, Cheng L, Huang MT, Li Y, Liu RG, Mao JF, Myneni RB, Peng SS, Poulter B, Shi XY, Xiao Z, Zeng N, Zeng ZZ, Wang YP (2015) Detection and attribution of vegetation greening trend in China over the last 30 years. *Global Change Biology* 21:1601-1609, doi:10.1111/gcb.12795.
104. 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.
105. 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, doi:10.1002/2017MS000962.
106. Richardson AD, Hufkens K, Milliman T, Aubrecht DM, Furze ME, Seyednasrollah B, Krassovski MB, Latimer JM, Nettles WR, Heiderman RR, Warren JM, Hanson PJ (2018) Ecosystem warming extends vegetation activity but heightens cold temperature vulnerability. *Nature* 560:368-371, doi:10.1038/s41586-018-0399-1.
107. Raczka B, Duarte HF, Koven CD, Ricciuto D, Thornton PE, Lin JC, Bowling DR (2016) An observational constraint on stomatal function in forests: evaluating coupled carbon and water vapor exchange with carbon isotopes in the Community Land Model (CLM4.5). *Biogeosciences* 13:5183-5204, doi:10.5194/bg-13-5183-2016, 2016.
108. Safta C, Ricciuto DM, Sargsyan K, Debusschere B, Najm HN, Williams M, Thornton PE (2015) Global sensitivity analysis, probabilistic calibration, and predictive assessment for the data assimilation linked ecosystem carbon model. *Geoscientific Model Development* 8:1899-1918, doi:10.5194/gmd-8-1899-2015.
109. Schwalm CR, Huntzinger DN, Fisher JB, Michalak AM, Bowman K, Ciais P, Cook R, El-Masri B, Hayes D, Huang MY, Ito A, Jain A, King AW, Lei HM, Liu JJ, Lu CQ, Mao JF, Peng SS, Poulter B, Ricciuto D, Schaefer K, Shi XY, Tao B, Tian HQ, Wang WL, Wei YX, Yang J, Zeng N (2015) Toward "optimal" integration of terrestrial biosphere models. *Geophysical Research Letters* 42:4418-4428, doi:10.1002/2015GL064002.
110. Sebestyen SD, Griffiths NA (2016) SPRUCE Enclosure Corral and Sump System: Description, Operation, and Calibration. Climate Change Science Institute, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi:10.3334/CDIAC/spruce.030.
111. Seco R, Karl T, Guenther A, Hosman KP, Pallardy SG, Gu L, Geron C, Harley P, Kim S (2015) Ecosystem-scale VOC fluxes during an extreme drought in a broad-leaf temperate forest

of the Missouri Ozarks (central USA). *Global Change Biology* 21:3657-74. doi:10.1111/gcb.12980.

112. Shao J, Zhou X, Luo Y, Li B, Aurela M, Billesbach D, Blanken P, Bracho R, Chen J, Fischer M, Fu Y, Gu L, Han S, He Y, Kolb T, Li YN, Nagy Z, Niu SL, Oechel WC, Pinter K, Shi PL, Suyker A, Torn M, Varlagin A, Wang HM, Yan JH, Yu GR, Zhang JH (2015) Biotic and climatic controls on interannual variability in carbon fluxes across terrestrial ecosystems. *Agricultural and Forest Meteorology* 205:11-22, doi:10.1016/j.agrformet.2015.02.007.

113. Shao J, Zhou X, Luo Y, Zhang G, Li B, Dan L, Gao Z, He Y, Huntzinger D, Jain A, Mao J, Meng J, Michalak A, Peng C, Poulter B, Schwalm CR, Shi X, Sun R, Tao F, Zeng N, Zhu Q, Zhu W (2016a) Uncertainty analysis of terrestrial net primary productivity and net biome productivity in China during 1901-2005. *Journal of Geophysical Research-Biogeosciences* 121:1372-1393, doi:10.1002/2015JG003062.

114. Shao J, Zhou X, Luo Y, Li B, Aurela M, Billesbach D, Blanken PD, Bracho R, Chen J, Fischer M, Fu Y, Gu L, Han S, He Y, Kolb T, Li Y, Nagy Z, Niu S, Oechel WC, Pinter K, Shi P, Suyker A, Torn M, Varlagin A, Wang H, Yan J, Yu G, Zhang J (2016b) Direct and indirect effects of climatic variations on the interannual variability in net ecosystem exchange across terrestrial ecosystems. *Tellus B* 68:30575, doi:10.3402/tellusb.v68.30575.

115. Shaw AJ, Schmutz J, Devos N, Shu S, Carrell AA, Weston DJ (2016) Chapter Five - The *Sphagnum* genome project a new model for ecological and evolutionary genomics. *Advances in Botanical Research* 78:167-187, doi:10.1016/bs/abr.2016.01.003.

116. Shi X, Thornton PE, Ricciuto DM, Hanson PJ, Mao J, Sebestyen SD, Griffiths NA, Bisht G (2015) Representing northern peatland microtopography and hydrology within the Community Land Model. *Biogeosciences* 12:6463-6477, doi:10.5194/bg-12-6463-2015.

117. 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.

118. 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* 125:244-250, doi:10.1016/j.soilbio.2018.07.001.

119. Sulman BN, Moore JAM, Abramoff R, Averill C, Kivlin S, Georgiou K, Sridhar B, Hartman MD, Wang G, Wieder WR, Bradford MA, Luo Y, Mayes MA, Morrison E, Riley WJ, Salazar A, Schimel JP, Tang J, Classen AT (2018) Multiple models and experiments underscore large uncertainty in soil carbon dynamics. *Biogeochemistry* 141:109–123, doi:10.1007/s10533-018-0509-z.

120. 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.

121. Sun Y, Fu R, Dickinson R, Joiner J, Frankenberg C, Gu L, Xia Y, Fernando N (2015) Satellite solar-induced chlorophyll fluorescence reveals drought onset mechanisms: Insights from two contrasting extreme events. *Journal of Geophysical Research - Biogeosciences* 120:2427, doi:10.1002/2015JG003150.

122. 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, doi:10.1002/ecm.1280.

123. 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, doi:10.1002/2017JG004007.

124. Tian HQ, Lu CQ, Yang J, Banger K, Huntzinger DN, Schwalm CR, Michalak AM, Cook R, Ciais P, Hayes D, Huang MY, Ito A, Jain AK, Lei HM, Mao JF, Pan SF, Post WM, Peng SS, Poulter B, Ren W, Ricciuto D, Schaefer K, Shi XY, Tao B, Wang WL, Wei YX, Yang QC, Zhang BW, Zeng N (2015) Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models: Current status and future directions. *Global Biogeochemical Cycles* 29:775-792, doi:10.1002/2014GB005021.

125. Tiegs S, Costello DM, Isken MW, Woodward G, McIntyre PB, Gessner MO, Chauvet E, Griffiths NA, Flecker AS, *et al.* (2019) Global patterns and drivers of ecosystem functioning in rivers and riparian zones. *Science Advances* 5:eaav0486, doi:10.1126/sciadv.aav0486

126. Torn MS, Chabbi A, Crill P, Hanson PJ, Janssens IA, Luo Y, Hicks Pries C, Rumpel C, Schmidt MWI, Six J, Schrumpf M, Zhu B (2015) A call for international soil experiment networks for studying, predicting, and managing global change impacts. *Soil* 1:575-582, doi:10.5194/soil-1-575-2015.

127. Walker AP (2018) Commentary - A scalable multi-process model of root nitrogen uptake. *New Phytologist* 218:8-11, doi:10.1111/nph.15022.

128. 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.

129. 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): R code for generating ensembles with dynamic model structure and analysis of epistemic uncertainty from multiple sources. *Geoscientific Model Development* 11:3159–3185, doi:10.5194/gmd-11-3159-2018.

130. Walker AP, Zaehle S, Medlyn BE, De Kauwe MG, Asao S, Hickler T, Parton W, Ricciuto DM, Wang YP, Warlind D, Norby RJ (2015) Predicting long-term carbon sequestration in response to CO_2 enrichment: How and why do current ecosystem models differ? *Global Biogeochemical Cycles* 29:476-495, doi:10.1002/2014BG004995.

131. Wang D, Janjusic T, Iversen C, Thornton PE, Krassovski M, Wu W, Xu Y (2015a) A scientific function test framework for modular environmental model development: application to the community land model. *Software Engineering for High Performance Computing in Science (SE4HPCS), 2015 IEEE/ACM 1st International Workshop*, Florence, Italy, pp. 16-23, doi:10.1109/SE4HPCS.2015.10.

132. Wang G, Jagadamma S, Mayes MA, Schadt C, Steinweg JM, Gu L, Post WM (2015b) Microbial dormancy improves development and experimental validation of ecosystem model. *The ISME Journal* 9:226-237, doi:10.1038/ismej.2014.120.

133. Wang G, Huang W, Mayes MA, Liu, X, Zhang, D, Zhang, Q, Han, T, Zhou, G (2018) Soil moisture drives microbial controls on carbon decomposition in subtropical forests. *Soil Biology and Biochemistry* 130:185-194, doi:10.1016/j.soilbio.2018.12.017.

134. 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.

135. Wang SS, Pan M, Mu QZ, Shi XY, Mao JF, Brummer C, Jassal RS, Krishnan P, Li JH, Black TA (2015c) Comparing evapotranspiration from eddy covariance measurements, water budgets, remote sensing, and land surface models over Canada. *Journal of Hydrometeorology* 16:1540-1560, doi:10.1175/JHM-D-14-0189.1.

136. Warren, JM, Hanson PJ, Iversen CM, Kumar J, Walker AP, Wullschleger SD (2015a) Root structural and functional dynamics in terrestrial biosphere models – Evaluation and recommendations (Tansley Review). *New Phytologist* 205:59-78, doi:10.1111/nph.13034.

137. Warren JM, Jensen AM, Medlyn BE, Norby RJ, Tissue DT (2015b) Carbon dioxide stimulation of photosynthesis in *Liquidambar styraciflua* is not sustained during a 12-year field experiment. *AoB Plants* 7:plu074, doi:10.1093/aobpla/plu074.

138. Warren MJ, Lin X, Gaby JC., Kretz CB, Kolton M, Morton PL, Pett-Ridge J, Weston DJ, Schadt CW, Kostka JE, Glass JB (2017a) Molybdenum-based diazotrophy in a *Sphagnum* peatland in northern Minnesota. *Applied and Environmental Microbiology*, *83*(17):e01174-17, doi:10.1128/AEM.01174-17.

139. Warren MJ, Lin X, Gaby JC, Kretz CB, Morton PL, Pett-Ridge J, Weston DJ, Schadt CW, Kostka JE, Glass JB (2017b) Alphaproteobacteria fix nitrogen in a *Sphagnum*-dominated peat bog using molybdenum-dependent nitrogenase. *Applied and Environmental Microbiology*, 83:e01174-17, doi:10.1128/AEM.01174-17.

140. Wenk ES, Callaham MA Jr., Hanson PJ (2016) Soil macro-invertebrate communities across a productivity gradient in deciduous forests of eastern North America. *Northeastern Naturalist* 23:25-44, doi:10.1656/045.023.0103.

141. Wilson RM, Hopple AM, Tfaily MM, Sebestyen SD, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane KJ, Kostka JE, Kolton M, Kolka R, Kluber LA, Keller JK, Guilderson TP, Griffiths NA, Chanton JP, Bridgham SD, Hanson PJ (2016) Stability of a peatland carbon bank to rising temperatures. *Nature Communications* 7:13723, doi:10.1038/NCOMMS13723.

142. 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.

143. Wohlfahrt G, Amelynck C, Ammann C, Arneth A, Bamberger I, Goldstein AH, Gu L, Guenther A, Hansel A, Heinesch B, Holst T, Hörtnagl L, Karl T, Laffineur Q, Neftel A, McKinney K, Munger JW, Pallardy SG, Schade GW, Seco R, Schoon N (2015) An ecosystem-scale perspective of the net land methanol flux: synthesis of micrometeorological flux measurements. *Atmospheric Chemistry and Physics Discussions* 15:2577-2613, doi:10.5194/acp-15-7413-2015.

144. Wohlfahrt G, Gu L (2015) Opinion: The many meanings of gross photosynthesis and their implication for photosynthesis research from leaf to globe. *Plant Cell and Environment* 38:2500-2507, doi:10.1111/pce.12569.

145. Wood JD, Griffis TJ, Baker JM, Frankenberg C, Verma M, Yuen K (2017) Multiscale analyses of solar-induced fluorescence and gross primary production. *Geophysical Research Letters* 44:533-541, doi:10.1002/2016GL070775.

146. 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.

147. 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* 15:3421-3437, doi:10.5194/bg-15-3421-2018.

148. Wu X, Ju W, Zhou Y, He M, Law B, Black T, Margolis H, Cescatti A, Gu L, Montagnani L, Noormets A, Griffis TJ, Pilegaard K, Varlagin A, Valentini R, Blanken PD, Wang SQ, Wang HM, Han SJ, Yan JH, Li YN, Zhou BB, Liu YB (2015) Performance of Linear and Nonlinear Two-Leaf Light Use Efficiency Models at Different Temporal Scales. *Remote Sensing* 7:2238-2278, doi:10.3390/re70302238.

149. Wullschleger SD, Warren JM, Thornton PE (2015) Leaf respiration (GlobResp) – global trait database supports Earth System Models – Commentary. *New Phytologist* 206: 483-485, doi:10.1111/nph.13364.

150. 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.

151. Xu X, Yuan F, Hanson PJ, Wullschleger SD, Thornton PE, Riley WJ, Song X, Graham DE, Song C, Tian H (2016) Reviews and syntheses: four decades of modeling methane cycling in terrestrial ecosystems. *Biogeosciences* 13:3735-3755, doi:10.5194/bg-13-3735-2016.

152. Xu XF, Elias DA, Graham DE, Phelps TJ, Carroll SL, Wullschleger SD, Thornton PE (2015a) A microbial functional group-based module for simulating methane production and consumption: Application to an incubated permafrost soil. *Journal of Geophysical Research-Biogeosciences* 120:1315-1333, doi:10.1002/2015JG002935.

153. Xu XF, Hui DF, King AW, Song X, Thornton PE, Zhang LH (2015b) Convergence of microbial assimilations of soil carbon, nitrogen, phosphorus, and sulfur in terrestrial ecosystems. *Scientific Reports* 5:17445, doi:10.1038/srep17445.

154. Xu Y, Wang D, Iversen CM, Walker A, Warren J (2017) Building a virtual ecosystem dynamic model for root research. *Environmental Modelling & Software* 89:97-105, doi:10.1016/j.envsoft.2016.11.014.

155. 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, doi:10.1016/j.soilbio.2017.11.025.

156. 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 (2017a) Drought impacts on photosynthesis, isoprene emission and atmospheric formaldehyde in a mid-latitude forest. *Atmospheric Environment* 167: 190-201, doi:10.1016/j.atmosenv.2017/08.017.

157. Zeng ZZ, Piao SL, Li LZX, Zhou LM, Ciais P, Wang T, Li Y, Lian X, Wood ER, Friedlingstein P, Mao J, Estes LD, Myneni RB, Pen SS, Shi XY, Seneviratne SI, Wang YP (2017b) Climate mitigation from vegetation biophysical feedbacks during the past three decades. *Nature Climate Change* 7:432-436, doi:0.1038/NCLIMATE3299.

158. Zhang J, Gu L (Corresponding Author), *et al.* (2017) The interaction between nitrogen and phosphorous is a strong predictor of intra-plant variation in nitrogen isotope composition in a desert species. *Biogeosciences,* 14:1–14, doi:10.5194/bg-14-1-2017.

159. Zhang J, Gu L, Bao F, Cao Y, Hao Y, He J, Li J, Li Y, Ren Y, Wang F, Wu R, Yao B, Zhao Y, Lin G, Wu B, Lu Q and Meng P (2015) Nitrogen control of ^{13}C enrichment in heterotrophic organs relative to leaves in a landscape-building desert plant species. *Biogeosciences* 12:15-27, doi:0.5194/bg-12-15-2015.

160. Zhang JX, Gu LH, Zhang JB, Wu R, Wang F, Lin GH, Wu B, Lu Q, Meng P (2017) The interaction between nitrogen and phosphorous is a strong predictor of intra-plant variation in nitrogen isotope composition in a desert species. *Biogeosciences* 14:131-144, doi:10.5194/bg-14-131-2017.

161. Zhang L, Mao J, Shi X, Ricciuto D, He H, Thornton P, Yu G, Han S, Li Y, Yan J, Hao Y, Wang H (2016) Evaluation of the Community Land Model simulated carbon and water fluxes against observations over ChinaFLUX sites. *Agricultural and Forest Meteorology* 226-227:174-185, doi:10.1016/j.agrformet.2016.05.018.

162. Zhou BZ, Wang XM, Cao YG, Ge XG, Gu LH, Meng JL (2017a) Damage assessment to subtropical forests following the 2008 Chinese ice storm. *iForest* 10:406-415, doi:10.3832/ifor1619-009.

163. 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 (2017b) Response of water use efficiency to global environmental change based on output from terrestrial biosphere models. *Global Biogeochemical Cycles* 31(11):1639-1655, doi:10.1002/2017GB005733.

164. Zhu Z, Piao S, Myneni RB, Huang M, Zeng Z, Candell JG, Ciais P, Sitch S, Friedlingstein P, Arneth A, Stocker BD, Poulter B, Koven C, Cao C, Kato E, Yang H, Mao J, Penuelas J, Cheng L, Zeng N, Zaehle S, Pugh T, Pan Y, Wang Y, Li Y (2016) Greening of the Earth and its drivers. *Nature Climate Change* 6:791-795, doi:10.1038/nclimate3004.

APPENDIX B: TES SFA DATA SETS AND POLICIES

Data Policy for Archiving, Sharing, and Fair-Use

The open sharing of ORNL TES-SFA data, modeling products, and documentation among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE BER's Earth and Environmental Systems Sciences Division. The policy is applicable to all TES-SFA participants including ORNL, cooperating independent researchers, and to the users of data products. Data collected by TES-SFA researchers, results of analyses and syntheses of information, and model algorithms and codes will be quality assured, documented, and archived and will be made available to the public.

Archived data products are freely available to the public. Users should acknowledge the contribution of the data provider with the citation (with DOI) as provided in the documentation and acknowledge the U.S. DOE BER Earth and Environmental Systems Sciences Division. A complete copy of our data policy may be found at:

https://mnspruce.ornl.gov/sites/default/files/ORNL_TES-SFA_Policy_2090515.pdf

TES-SFA data management plans and policies align with the most recent DOE policies for "Public Access to the Results of DOE-Funded Scientific Research"

https://mnspruce.ornl.gov/sites/default/files/DOE_Public_Access%20Plan_FINAL.pdf

and the "Statement on Digital Data Management"

https://science.osti.gov/Funding-Opportunities/Digital-Data-Management

Data Products Archived

SPRUCE has archived and shared with the public 62 data products. There are currently 7 products, available to the project only, that are awaiting publication of a paper and a few others in a development queue at any one time.

For ongoing TES-SFA tasks, 22 products are available to the public.The products include regularly updated time-series of SPRUCE environmental data, peat analyses, modelling archives, results of laboratory incubations, links to genomic products at JGI, "supporting validation data" for specific publications (e.g., organic matter characterization), web-based tools (e.g., LeafWeb), historical Walker Branch data, literature compilations (e.g., FRED 2.0), and characterization of SPRUCE plots (e.g., elevation).

Persistent identifiers (digital object identifiers, DOIs) for all products are registered through the OSTI (DOE Office of Scientific and Technical Information) E-Link System. SPRUCE products as 10.25581/spruce.0XX/zzzzzz and TES SFA products as 10.25581/ornlsfa.0XX/zzzzzz. Comprehensive metadata can be entered that facilitate the transfer of metadata, documentation, and data to the DOE's Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE) archive.

Transfer of Data Products to DOE ESS-DIVE Archive

Data management staff of the TES SFA are working with archive staff to continue transferring copies of selected TES-SFA and SPRUCE data products to the ESS-DIVE Archive. The first set of transferred datasets included those currently publicly accessible and considered final, that is, they will not be updated with periodic new data additions. Product data and metadata are reviewed and updated as needed to meet archive requirements and to ensure efficacious data search and discovery. To date, copies of 19 SPRUCE and 3 TES-SFA data products have been transferred to ESS-DIVE.

Code Sharing

Public release of SPRUCE-specific E3SM code will be managed by the E3SM project as part of a collaboration agreement between the ORNL TES SFA and E3SM and subject to E3SM policies and licensing (https://e3sm.org/resources/policies/). Development branches of the E3SM code for research purposes will also be available through https://github.com/E3SM-Project/E3SM/. Code developments will be discussed and agreed upon by the TES SFA modeling team, with the understanding that our goal as a group is to make the developments here available to the larger community as soon as possible. For reproducibility, publications using model output will include information about the specific release or development branch used in the simulations. Public release removes the 'rights' of code developers to be automatically considered for co-authorship. However, we encourage users of the released model to consider informing or including those developers to the extent it would benefit the users' analyses.

Collaboration across DOE BER Projects

TES-SFA participants Paul Hanson and Daniel Ricciuto are serving as members of the U.S. Department of Energy's (DOE) Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS–DIVE) Archive Partnership Board (APB). In this capacity the TES SFA stays current with community expectations for data and model archiving.

Websites Upgrades

The FRED, SPRUCE and TES SFA Websites are being upgraded to the latest version of Drupal (content management system) while transferring the websites to the ORNL Web Services organization for all future Drupal maintenance, security updates, and upgrade services. Website content will still be managed by TES SFA Staff. The FRED Website and TES SFA Websites have been upgraded. The SPRUCE website will be upgraded by the end of FY 2020.

TES SFA Software:

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

SPRUCE Public Data Sets (**New since February 2019):

1. **Dusenge ME, Ward EJ, Warren JM, McLennan DA, Stinziano JR, Murphy BK, King AW, Childs J, Brice DJ, Phillips JR, Stefanski A, Villanueva R, Wullschleger SD, Cruz M, Reich PB, Way DA (2020D) **SPRUCE Photosynthesis and Respiration of *Picea mariana* and *Larix laricina* in SPRUCE Experimental Plots, 2016-2017**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.056/1455138
2. Dusenge ME, Stinziano RJ, Warren JM, Ward EJ, Wullschleger SD, Hanson PJ, Way DA (2018D) **SPRUCE Whole Ecosystem Warming (WEW) Photosynthesis and Respiration of *Picea* and *Larix* in Experimental Plots, 2016.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.056/1455138
3. **Fernandez CW, Heckman K, Kolka R, Kennedy PG (2019D) **SPRUCE Fungal Necromass Litter Bag Decomposition Study in SPRUCE Experimental Plots, 2016-2018.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.063/1503589
4. Finzi AF, Giasson MA, Gill AL (2016D) **SPRUCE Autochamber CO_2 and CH_4 Flux Data for the SPRUCE Experimental Plots.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/SPRUCE.016
5. Furze ME, Jensen AM, Warren JM, Richardson AD (2018D) **SPRUCE S1 Bog Seasonal Patterns of Nonstructural Carbohydrates in Larix, Picea, Rhododendron, and Chamaedaphne, 2013.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.037/1473917
6. **Graham JD, Glenn NF, Spaete LP. 2019Da. **SPRUCE Terrestrial Laser Scanning of Experimental Plots Beginning in 2015.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.067/1515552
7. **Graham JD, Glenn NF, Spaete LP. 2019Db. **SPRUCE Microtopography of Experimental Plots Derived from Terrestrial Laser Scans Beginning in 2016.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.068/1515553
8. Griffiths NA, Hook LA, Hanson PJ (2016D) **SPRUCE S1 Bog and SPRUCE Experiment Location Survey Results, (2015)** Carbon Dioxide Information Analysis Center, Oak Ridge National

Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.015

9. Griffiths NA, Sebestyen SD (2016D) **SPRUCE S1 Bog Porewater, Groundwater, and Stream Chemistry Data: 2011-2013.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.018
10. Griffiths NA, Sebestyen SD (2016D) **SPRUCE Porewater Chemistry Data for Experimental Plots Beginning in 2013**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.028
11. Griffiths NA, Sebestyen SD (2017D) **SPRUCE Hollow Elevation Data for Experimental Plots Beginning in 2015**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.035
12. Gutknecht J, Kluber LA, Hanson PJ, Schadt CW (2017D) **SPRUCE Whole Ecosystem Warming (WEW) Peat Water Content and Temperature Profiles for Experimental Plot Cores Beginning June 2016.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.041
13. Hanson PJ, U.S. Forest Service Staff, and SPRUCE Team (2012D) **SPRUCE S1-Bog Vegetation Survey and Peat Depth Data: 2009.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.003.
14. Hanson PJ, Brice D, Garten CT, Hook LA, Phillips J, Todd DE (2012D) **SPRUCE S1-Bog Vegetation Allometric and Biomass Data: 2010-2011**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.004.
15. Hanson PJ, Krassovski MB, Hook LA (2015D) **SPRUCE S1 Bog and SPRUCE Experiment Aerial Photographs.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.012
16. Hanson PJ, Phillips JR, Brice DJ, Hook LA (2018Da) **SPRUCE Shrub-Layer Growth Assessments in S1-Bog Plots and SPRUCE Experimental Plots beginning in 2010**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.052/1433837
17. Hanson PJ, Phillips JR, Brice DJ, Hook LA (2018Db) **SPRUCE Bog Surface Elevation Assessments with SET Instrument Beginning in 2013.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.055/1455014
18. Hanson, PJ, Phillips JR, Riggs JS, Nettles WR (2017D) **SPRUCE Large-Collar in Situ CO_2 and CH_4 Flux Data for the SPRUCE Experimental Plots: Whole-Ecosystem-Warming**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.034
19. Hanson PJ, Phillips JR, Riggs JS, Nettles WR, Todd DE (2014D) **SPRUCE Large-Collar in Situ CO_2 and CH_4 Flux Data for the SPRUCE Experimental Plots**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.006.
20. Hanson PJ, Phillips JR, Wullschleger SD, Nettles WR, Warren JM, Ward EJ (2018Dc) **SPRUCE Tree Growth Assessments of Picea and Larix in S1-Bog Plots and SPRUCE Experimental Plots beginning in 2011**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.051/1433836
21. **Hanson PJ, Phillips JR, Nettles WR, Pearson KJ, Hook LA (2020D) **SPRUCE Plot-Level Water Table Data Assessments for Absolute Elevations and Height with Respect to Mean Hollows Beginning in 2015.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.079/1608615

22. Hanson PJ, Riggs JS, Dorrance C, Nettles WR, Hook LA (2015D) **SPRUCE Environmental Monitoring Data: 2010-2016.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.001. (Includes recent additions of annual data files.)
23. Hanson PJ, Riggs JS, Hook LA, Nettles WR, Dorrance C (2015D) **SPRUCE S1-Bog Phenology Movies, 2010-2106.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.011.
24. Hanson PJ, Riggs JS, Nettles WR, Krassovski MB, Hook LA (2015D) **SPRUCE Deep Peat Heating (DPH) Environmental Data, February 2014 through July 2105.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.013
25. Hanson PJ, Riggs JS, Nettles WR, Krassovski MB, Hook LA (2016D) **SPRUCE Whole Ecosystems Warming (WEW) Environmental Data Beginning August 2015.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.032
26. **Haynes KM, Mitchell CPJ, Kolka RK (2019D) **SPRUCE Total Gaseous Mercury Fluxes and Peat Mercury Concentrations, 2014-2015.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.066/1512288
27. Hofmockel KS, Chen, J, Hobbie EA (2016D) **SPRUCE S1 Bog Pretreatment Fungal Hyphae Carbon and Nitrogen Concentrations and Stable Isotope Composition from In-growth Cores, 2013-2014**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.025
28. **Hopple AM, Pfeifer-Meister L, Zalman CA, Keller JK, Tfaily MM, Wilson RM, Chanton JP, Bridgham SD (2019D) **SPRUCE Does dissolved organic matter or solid peat fuel anaerobic respiration in peatlands?: Supporting Data.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.062/1500027
29. Iversen CM, Hanson PJ, Brice DJ, Phillips JR, McFarlane KJ, Hobbie EA, Kolka RK (2014D) **SPRUCE Peat Physical and Chemical Characteristics from Experimental Plot Cores, 2012**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.005.
30. Iversen CM, Childs J, Norby RJ, Garrett A, Martin A, Spence J, Ontl TA, Burnham A, Latimer J. (2017D) **SPRUCE S1 Bog fine-root production and standing crop assessed using with minirhizotrons in the Southern and Northern ends of the S1 Bog**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.019.
31. Iversen CM, Garrett A, Martin A, Turetsky MR, Norby RJ, Childs J, Ontl TA (2017D) **SPRUCE S1 Bog tree basal area and understory community composition assessed in the Southern and Northern ends of the S1 Bog**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.024.
32. Iversen CM, Latimer J, Burnham A, Brice DJ, Childs J, Vander Stel HM (2017D) **SPRUCE plant-available nutrients assessed with ion-exchange resins in experimental plots, beginning in 2013**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.036.
33. Iversen CM, Ontl TA, Brice DJ, Childs J (2017D) **SPRUCE S1 Bog plant-available nutrients assessed with ion-exchange resins from 2011-2012 in the Southern end of the S1 Bog.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.022.
34. Jensen, AM, JM Warren, PJ Hanson, J Childs and SD Wullschleger. (2015D) **SPRUCE S1 Bog Pretreatment Photosynthesis and Respiration for Black Spruce: 2010-2013.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.007

35. Jensen AM, Warren JM, Hook LA, Wullschleger SD, Brice DJ, Childs J, Vander Stel HM (2018D) **SPRUCE S1 Bog Pretreatment Seasonal Photosynthesis and Respiration of Trees, Shrubs, and Herbaceous Plants, 2010-2015.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.008
36. Kluber LA, Allen SA, Hendershot JN, Hanson PJ, Schadt CW (2017D) **SPRUCE Deep Peat Microbial Diversity, CO_2 and CH_4 Production in Response to Nutrient, Temperature, and pH Treatments during Incubation Studies**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.040
37. Kluber LA, Phillips JR, Hanson PJ, Schadt CW (2016D) **SPRUCE Deep Peat Heating (DPH) Peat Water Content and Temperature Profiles for Experimental Plot Cores, June 2014 through June 2015.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.029
38. Kluber LA, Yang ZK, Schadt CW (2016D) **SPRUCE Deep Peat Heat (DPH) Metagenomes for Peat Samples Collected June 2015.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.033
39. Kluber LA, Yip DZ, Yang ZK, Schadt CW (2018D) **SPRUCE Deep Peat Heating (DPH) to Whole Ecosystem Warming (WEW) Metagenomes for Peat Samples Collected June 2016**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.053/1444071
40. Lin X, Tfaily MM, Steinweg JM, Chanton P, Esson K, Yang ZK, Chanton JP, Cooper W, Schadt CW, Kostka JE (2014D) **Microbial metabolic potential in carbon degradation and nutrient (nitrogen and phosphorus) acquisition in an ombrotrophic peatland.** Applied and Environmental Microbiology 80:3531-3540, doi:10.1128/AEM.00206-14. [**Access SPRUCE Microbial Community Metagenome** (SPRUCE Metagenome Lin *et al.* 2014)
41. **Malhotra A, Brice DJ, Childs J, Vander Stel HM, Bellaire SE, Kraeske E, Letourneau SM, Owens L, Rasnake LM, Iversen CM (2020D) **SPRUCE Production and Chemistry of Newly-Grown Fine Roots Assessed Using Root Ingrowth Cores in SPRUCE Experimental Plots beginning in 2014.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.077/1607860
42. **McPartland MY, Falkowski MJ, Reinhardt JR, Kane ES, Kolka R, Turetsky MR, Douglas TA, Anderson J, Edwards JD, Palik B, Montgomery RA (2019D) **SPRUCE: Hyperspectral Remote Sensing of Vegetation Communities in SPRUCE Experimental Plots, 2016**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.070/1546787
43. McPartland MY, Kane ES, Falkowski MJ, Kolka R, Turetsky MR, Palik B, Montgomery RA (2019D) **SPRUCE: LAI Data from SPRUCE Experimental Plots, 2017-2018.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.058/1491566
44. McPartland MY, Kane ES, Falkowski MJ, Kolka R, Turetsky MR, Palik B, Montgomery RA (2019D) **SPRUCE: NDVI Data from Selected SPRUCE Experimental Plots, 2016-2018.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.057/1490190
45. Norby RJ, Childs J (2018D) **SPRUCE: *Sphagnum* Productivity and Community Composition in the SPRUCE Experimental Plots.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.049/1426474
46. Ontl TA, Iversen CM (2016D) **SPRUCE S1 Bog areal coverage of hummock and hollow microtopography assessed along three transects in the S1 Bog**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.023.
47. **Pierce CE, Psarska S, Brozowski J, Sebestyen SD, Kolka RK, Nater EA, Toner BM (2019Da) **SPRUCE Porewater Total Mercury and Methylmercury from Experimental Plots, Beginning in**

2016. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.064/1504231

48. **Pierce CE, Psarska S, Brozowski J, Sebestyen SD, Kolka RK, Nater EA, Toner BM (2019Db) **SPRUCE Outflow Total Mercury and Methylmercury from Experimental Plots, Beginning in 2017.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.065/1504234
49. Phillips JR, Brice DJ, Hanson PJ, Childs J, Iversen CM, Norby RJ, Warren JM (2017D) **SPRUCE Pretreatment Plant Tissue Analyses, 2009 through 2013**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.038
50. Richardson AD, Hufkens K, Milliman T, Aubrecht DM, Furze ME, Seyednasrollah B, Krassovski MB, Hanson PJ (2018Da) **SPRUCE Vegetation Phenology in Experimental Plots from PhenoCam Imagery, 2015-2017.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.045
51. Richardson AD, Latimer JM, Nettles WR, Heiderman RR, Warren JM, Hanson PJ (2018Db) **SPRUCE Ground Observations of Phenology in Experimental Plots, 2016-2017**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/spruce.044
52. **Schädel C, Nettles WR, Heiderman RR, Pearson KJ, Richardson AD, Hanson PJ (2019Da) **SPRUCE Ground Observations of Phenology in Experimental Plots 2018.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.073/1557731
53. **Schädel C, Richardson AD, Hufkens K, Milliman T, Seyednasrollah B, Nettles WR, Krassovski MB, Hanson PJ (2019Db) **SPRUCE Vegetation Phenology in Experimental Plots from Phenocam Imagery, 2015-2018**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.071/1556082
54. Shi X, Thornton PE, Ricciuto DM, Hanson PJ, Mao J, Sebestyen SD, Griffiths NA, Bisht G (2016D) **SPRUCE Representing Northern Peatland Microtopography and Hydrology within the Community Land Model: Modeling Archive**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.031
55. Shuang M, Jiang J, Huang Y, Shi Z, Wilson RM, Ricciuto D, Sebestyen SD, Hanson PJ, Luo Y (2017D) **SPRUCE Data-constrained Projections of Methane Fluxes in a Northern Minnesota Peatland in Response to Elevated CO_2 and Warming: Modeling Archive**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.046
56. Slater L, Hanson PJ, Hook LA (2012D) **SPRUCE S1-Bog Peat Depth Determined by Push Probe and GPR: 2009-2010.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.002.
57. Smith RJ, Nelson PR, Jovan S, Hanson PJ, McCune B (2018D) **SPRUCE Epiphytic Lichen Annual Biomass Growth in Experimental Plots, 2013-2016.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.048/1425889
58. **Visser A, Griffiths NA, Sebestyen SD (2019D) **SPRUCE Tritium in Porewater of SPRUCE Experimental Plots and Neighboring Peatlands, and in Groundwater, Stream Water, and Precipitation of the S1 Bog, 2014-2016**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.069/1532523
59. Walker AP, Carter KR, Hanson PJ, Nettles WR, Philips JR, Sebestyen SD, Weston DJ (2017D) **SPRUCE S1 Bog *Sphagnum* CO_2 Flux Measurements and Partitioning into Re and GPP**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.039

60. **Ward EJ, Warren JM, McLennan D, Wullschleger SD (2019D) **SPRUCE Photosynthesis and Respiration of *Rhododendron groenlandicum* and *Chamaedaphne calyculata* in SPRUCE Experimental Plots, 2016.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.061/1493603
61. Wilson RM, Hopple AM, Tfaily MM, Sebestyen SD, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane KJ, Kostka JE, Kolton M, Kolka R, Kluber LA, Keller JK, Guilderson TP, Griffiths NA, Chanton JP, Bridgham SD, Hanson PJ (2016D) **SPRUCE Stability of Peatland Carbon to Rising Temperatures: Supporting Data.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.026
62. Wilson RM, Tfaily MM, Keller JK, Bridgham SD, Zalman CM, Hanson PJ, Pfeifer-Meister L, Chanton JP, and Kostka JE (2017D) **SPRUCE Geochemical Changes in Porewater from Northern Peatlands at Multiple Depths in Field Samples and over Time in Peat Incubations**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.042
63. Wilson RM, Tfaily MM (2018D) **SPRUCE Advanced Molecular Techniques Provide a Rigorous Method for Characterizing Organic Matter Quality in Complex Systems: Supporting Data**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.050/1431334
64. Zalman CA, Meade N, Chanton J, Kostka JE, Bridgham SD, Keller JK (2017D) **SPRUCE Methylotrophic Methanogenesis in Sphagnum-dominated Peatland Soils - CH_4 and CO_2 Production in Laboratory Incubations.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.047/1413216
65. Zalman CA, Keller JK, Tfaily M, Kolton M, Pfeifer-Meister L, Wilson RM, Lin X, Chanton J, Kostka JE, Gill A, Finzi A, Hopple AM, Bohannan BJM, Bridgham SD (2018D) **SPRUCE Small Differences in Ombrotrophy Control Regional-Scale Variation in Methane Cycling among *Sphagnum*-Dominated Peatlands: Supporting Data.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.043/1434643

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

66. Childs J, Iversen CM, Latimer J, Burnham A, Norby RJ (2019D) **SPRUCE Manual Minirhizotron Images from Experimental Plots Beginning in 2013.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.060/1490356
67. Furman OS, Tfaily MM, Nicholas SL, Wasik JC, Sebestyen SD, Kolka RK, Nater EA, Toner BM (2016D) **SPRUCE Peat Mercury, Methylmercury and Sulfur Concentrations from Experimental Plot Cores, 2012.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.027
68. Heiderman RR, Nettles WR, Ontl TA, Latimer JM, Richardson AD, Hanson PJ (2018D) **SPRUCE Manual Phenology Observations and Photographs Beginning in 2010**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.054/1444106
69. Krassovski MB, Hanson PJ (2020D) **SPRUCE Experimental Plot Top View Aerial Photographs beginning June 2019.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.076/1604061
70. McPartland MY, MJ, Kolka R, MR, Palik B, Montgomery RA (2019D) **SPRUCE: Vegetation Community Survey Data from SPRUCE Experimental Plots, 2014-2018.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.059/1499107

71. Pierce CE, Psarska S, Brozowski J, Sebestyen SD, Kolka RK, Gutknecht JLM, Nater EA, Toner BM (2019D) **SPRUCE Peat Mercury, Methylmercury and Sulfur Concentrations from Experimental Plot Cores, Beginning in 2014**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/spruce.074/1579555

Other TES SFA Public Data Sets and Tools:

1. **Chang CY, Guanter L, Frankenberg C, Köhler P, Gu L, Magney TS, Grossmann K, Sun Y (2020D) **Data from: Systematic assessment of retrieval methods for canopy far-red solar-induced chlorophyll fluorescence (SIF) using automated high-frequency field spectroscopy**. Cornell University Library eCommons Repository. https://doi.org/10.7298/wqx5-ba07.
2. Griffiths NA, Tiegs SD (2016D) **Walker Branch Watershed: Temperature Response of Organic-Matter Decomposition in a Headwater Stream.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.003
3. Griffiths NA, Johnson LT (2018D) **Walker Branch Watershed: Effect of Dual Nitrogen and Phosphorus Additions on Nutrient Uptake and Saturation Kinetics**, 2011-2012. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/ornlsfa.015/1484490
4. Gu L, Norby RJ, Haworth IC, Jensen AM, Turner BL, Walker AP, Warren JM, Weston DJ, Winter K (2016Da) Photosynthetic parameters and doi:10.15486/NGT/1255260.nutrient content of trees at the Panama crane sites. OSTI Identifier:1255260,
5. **Hogan JA, Baraloto C, Ficken CD, Clark MD, Weston DM, Warren JM (2020D) **Physiological Responses of *Populus trichocarpa* to Warming.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/ornlsfa.018/1617459
6. 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 (2017D) 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
7. Iversen CM, Powell AS, McCormack ML, Blackwood CB, Freschet GT, Kattge J, Roumet C, Stover DB, Soudzilovskaia NA, Valverde-Barrantes OJ, van Bodegom PM, Violle C (2016D) **Fine-Root Ecology Database (FRED): A Global Collection of Root Trait Data with Coincident Site, Vegetation, Edaphic, and Climatic Data, Version 1.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. Access on-line at: https://doi.org/10.3334/CDIAC/ornlsfa.005
8. Iversen CM, Powell AS, McCormack ML, Blackwood CB, Freschet GT, Kattge J, Roumet C, Stover DB, Soudzilovskaia NA, Valverde-Barrantes OJ, van Bodegom PM, Violle C (2018D) **Fine-Root Ecology Database (*FRED*): A Global Collection of Root Trait Data with Coincident Site, Vegetation, Edaphic, and Climatic Data, Version 2.** Oak Ridge National Laboratory, TES SFA U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. Access on-line at: https://doi.org/10.25581/ornlsfa.012/1417481
9. Jagadamma S, Mayes MA, Steinweg JM, Wang G, Post WM (2014D) **Organic Carbon Sorption and Decomposition in Selected Global Soils.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.002
10. Kluber LA, Phillips JR, Wang G, Schadt CW, Mayes MA (2017D) **Soil Respiration and Microbial Biomass from Soil Incubations with ^{13}C Labeled Additions.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.010
11. **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/.

12. **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.
13. Mulholland PJ, Griffiths NA (2016D) **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
14. Mulholland PJ, Griffiths NA (2016D) **Walker Branch Watershed: 15-minute and Daily Stream Discharge and Annual Runoff**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.007
15. Mulholland PJ, Griffiths NA (2016D) **Walker Branch Watershed: Hourly, Daily, and Annual Precipitation**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.006
16. Mulholland PJ, Griffiths NA (2016D) **Walker Branch Watershed: 15-minute and Daily Stream Discharge and Annual Runoff**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.007
17. Mulholland PJ, Griffiths NA (2016D) **Walker Branch Watershed: Daily Climate and Soil Temperature Data**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.008
18. Mulholland PJ, Griffiths NA (2016D) **Walker Branch Watershed: Weekly Stream Water Chemistry**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.009
19. Pallardy, SG, Gu, L, Wood, JD, Hosman, KP, Sun, Y, Hook, L. (2017D) **Predawn Leaf Water Potential of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2017**. United States: N. p., 2018. https://doi.org/10.3334/CDIAC/ornlsfa.004
20. **Pallardy SG, Gu L, Wood JD, Hosman KP, Hook LA (2019D) **Vegetation Inventory of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2017.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. Access on-line at: https://doi.org/10.25581/ornlsfa.016/1498529
21. Shi X, Wang D (2014D) **GSOD Based Daily Global Mean Surface Temperature and Mean Sea Level Air Pressure** (1982-2011)", doi:10.15149/1130373.
22. **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.
23. **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/.
24. Warren JM, Iversen CM, Garten Jr CT, Norby RJ, Childs J, Brice D, Evans RM, Gu L, Thornton P, Weston DJ (2013D) PiTS-1: **Carbon Partitioning in Loblolly Pine after ^{13}C Labeling and Shade Treatments**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.3334/CDIAC/ornlsfa.001.
25. **Wood JD, Pallardy SG, Gu L, Hosman KP (2020D) **Litter Production of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2015**. Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/ornlsfa.019/1619052.

26. **Wood JD, Sadler EJ, Fox NI, Greer ST, Gu L, Guinan PE, Lupo AR, Market PS, Rochette SM, Speck A, White LD (2019D) **Eddy Flux and Meteorology over Deciduous Forest, Prairie, and Soybean Ecosystems in Missouri, USA, during the Total Solar Eclipse of 2017.** Oak Ridge National Laboratory, TES SFA, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. https://doi.org/10.25581/ornlsfa.017/1579907

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

1. Barr AG, Ricciuto DM, Schaefer K, Richardson A, Agarwal D, Thornton PE, Davis K, Jackson B, Cook RB, Hollinger DY, van Ingen C, Amiro B, Andrews A, Arain MA, Baldocchi D, Black TA, Bolstad P, Curtis P, Desai A, Dragoni D, Flanagan L, Gu L, Katul G, Law BE, Lafleur P, Margolis H, Matamala R, Meyers T, McCaughey H, Monson R, Munger JW, Oechel W, Oren R, Roulet N, Torn M, Verma S (2013) **NACP Site: Tower Meteorology, Flux Observations with Uncertainty, and Ancillary Data.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA http://dx.doi.org/10.3334/ORNLDAAC/1178.
2. Huntzinger DN, Schwalm CR, Wei Y, Cook RB, Michalak AM, Schaefer K, Jacobson AR, Arain MA, Ciais P, Fisher JB, Hayes DJ, Huang M, Huang S, Ito A, Jain AK, Lei H, Lu C, Maignan F, Mao J, Parazoo N, Peng C, Peng S, Poulter B, Ricciuto DM, Tian H, Shi X, Wang W, Zeng N, Zhao F, Zhu Q, Yang J, Tao B (2016) **NACP MsTMIP: Global 0.5-deg Terrestrial Biosphere Model Outputs (version 1) in Standard Format.** ORNL DAAC, Oak Ridge, Tennessee, USA, https://doi.org/10.3334/ORNLDAAC/1225.
3. Ricciuto DM, Schaefer K, Thornton PE, Davis K, Cook RB, Liu S, Anderson R, Arain MA, Baker I, Chen JM, Dietze M, Grant R, Izaurralde C, Jain AK, King AW, Kucharik C, Liu S, Lokupitiya E, Luo Y, Peng C, Poulter B, Price D, Riley W, Sahoo A, Tian H, Tonitto C, Verbeeck H (2013) **NACP Site: Terrestrial Biosphere Model and Aggregated Flux Data in Standard Format.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1183.
4. Ricciuto DM, Schaefer K, Thornton PE, Cook RB, Anderson R, Arain MA, Baker I, Chen JM, Dietze M, Grant R, Izaurralde C, Jain AK, King AW, Kucharik C, Liu S, Lokupitiya E, Luo Y, Peng C, Poulter B, Price D, Riley W, Sahoo A, Tian H, Tonitto C, Verbeeck H (2013) **NACP Site: Terrestrial Biosphere Model Output Data in Original Format.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1192.
5. Seyednasrollah B, Young AM, Hufkens K, Milliman T, Friedl MA, Frolking S, Richardson AD, Abraha M, Allen DW, Apple M, Arain MA, Baker J, Baker JM, Baldocchi D, Bernacchi CJ, Bhattacharjee J, Blanken P, Bosch DD, Boughton R, Gu L, Wood JD, ... Zona D (2019) PhenoCam Dataset v2.0: Vegetation Phenology from Digital Camera Imagery, 2000-2018 (Version 2). ORNL Distributed Active Archive Center. https://doi.org/10.3334/ORNLDAAC/1674.
6. Wei Y, Hayes DJ, Thornton MM, Post WM, Cook RB, Thornton PE, Jacobson A, Huntzinger DN, West TO, Heath LS, McConkey B, Stinson G, Kurz W, de Jong B, Baker I, Chen J, Chevallier F, Hoffman F, Jain A, Lokupitiya R, McGuire DA, Michalak A, Moisen GG, Neilson RP, Peylin P, Potter C, Poulter B, Price D, Randerson J, Rodenbeck C, Tian H, Tomelleri E, van der Werf G, Viovy N, Xiao J, Zeng N, Zhao M (2013) **NACP Regional: National Greenhouse Gas Inventories and Aggregated Gridded Model Data.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA http://dx.doi.org/10.3334/ORNLDAAC/1179.
7. Wei Y, Liu S, Huntzinger D, Michalak AM, Viovy N, Post WM, Schwalm C, Schaefer K, Jacobson AR, Lu C, Tian H, Ricciuto DM, Cook RB, Mao J, Shi X (2014) **NACP MsTMIP: Global and North American Driver Data for Multi-Model Intercomparison.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1220.

8. Yang X, Post WM, Thornton PE, Jain A (2014) **Global Gridded Soil Phosphorus Distribution Maps at 0.5-degree Resolution.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1223.
9. Yang X, Post WM, Thornton PE, Jain A (2014) **A Global Database of Soil Phosphorus Compiled from Studies Using Hedley Fractionation.** Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1230.

TES SFA Task 7 Data Sets:

1. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.ndp058.2013.
2. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyMass.2013.
3. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.AnnualIsomass.2013.
4. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyIsomass.2013.
5. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.db1013.2013.
6. Boden TA, Marland G, Andres RJ (2013) **Global, Regional, and National Fossil-Fuel CO_2 Emissions.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi 10.3334/CDIAC/00001_V2013.
7. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.ndp058.2012.
8. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyMass.2012.
9. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.AnnualIsomass.2012.
10. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyIsomass.2012.
11. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2009.** ORNL/CDIAC, electronic database. doi: 10.3334/CDIAC/ffe.db1013.2012.
12. Andres RJ, Boden TA (2016) **Annual Fossil-Fuel CO_2 Emissions: Uncertainty of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2013**. ORNL/CDIAC, electronic database. doi: 10.3334/CDIAC/ffe.AnnualUncertainty.2016.
13. Andres RJ, Boden TA (2016) **Monthly Fossil-Fuel CO_2 Emissions: Uncertainty of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2013.** ORNL/CDIAC, electronic database. doi: 10.3334/CDIAC/ffe.MonthlyUncertainty.2016.
14. Andres RJ, Boden TA, Marland G (2016) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2013**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.ndp058.2016.

15. Andres RJ, Boden TA, Marland G (2016) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2013.** ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.MonthlyMass.2016.
16. Andres RJ, Boden TA, Marland G (2016) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2013**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.AnnualIsomass.2016.
17. Andres RJ, Boden TA, Marland G (2016) **Monthly Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2013**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.MonthlyIsomass.2016.
18. Andres RJ, Boden TA, Marland G (2016) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2013**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.db1013.2016.
19. Andres RJ, Boden TA, Marland G (2015) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2011**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.ndp058.2015.
20. Andres RJ, Boden TA, Marland G (2015) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2011**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.MonthlyMass.2015.
21. Andres RJ, Boden TA, Marland G (2015) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2011.** ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.AnnualIsomass.2015.
22. Andres RJ, Boden TA, Marland G (2015) **Monthly Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2011**. ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.MonthlyIsomass.2015.
23. Andres RJ, Boden TA, Marland G (2015) **Annual Fossil-Fuel CO_2 Emissions: Global Stable Carbon Isotopic Signature, 1751-2011.** ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/ffe.db1013.2015.
24. Boden TA, Andres RJ, Marland G (2012) **Global, Regional, and National Fossil-Fuel CO_2 Emissions: 1751-2009.** ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/00001_V2012.
25. Boden TA, Andres RJ, Marland G (2015) **Global, Regional, and National Fossil-Fuel CO_2 Emissions: 1751-2011.** ORNL/CDIAC, electronic database. doi:10.3334/CDIAC/00001_V2015.
26. Boden TA, Andres RJ, Marland G (2016) **Global, Regional, and National Fossil-Fuel CO_2 Emissions: 1751-2013. ORNL/CDIAC, electronic database.** doi:10.3334/CDIAC/00001 V2016.
27. Global Carbon Project (2013) **Global Carbon Atlas**. http://www.globalcarbonatlas.org.
28. Global Carbon Project (2015) **Global Carbon Atlas.** http://www.globalcarbonatlas.org.
29. Maksyutov S, Takagi H, Belikov DA, Saeki T, Zhuravlev R, Ganshin A, Lukyanov A, Yoshida Y, Oshchepkov S, Bril A, Saito M, Oda T, Valsala VK, Saito R, Andres RJ, Conway T, Tans P, Yokota T (2012) **Estimation of regional surface CO_2 fluxes with GOSAT observations using two inverse modeling approaches.** Proc. SPIE 8529, Remote Sensing and Modeling of the Atmosphere, Oceans, and Interactions IV, 85290G. doi:10.1117/12.979664.