FY2016 PROGRESS REPORT
OAK RIDGE NATIONAL LABORATORY'S
TERRESTRIAL ECOSYSTEM SCIENCE — SCIENTIFIC FOCUS AREA
(TES SFA)

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ABSTRACT

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

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1.0 PROGRAM OVERVIEW

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

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

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

TES SFA research is an iterative process (Fig. 1) translating mechanisms to ecosystem models with a quantitative understanding of model uncertainties. This process informs priorities for future measurements. Our paradigm is to identify and target critical uncertainties in coupled climate and terrestrial ecosystem processes and feedbacks, prioritized by their influence over global change predictions on decadal and century timescales. New measurements and experiments are employed to obtain new knowledge required to characterize, quantify, and reduce these uncertainties.

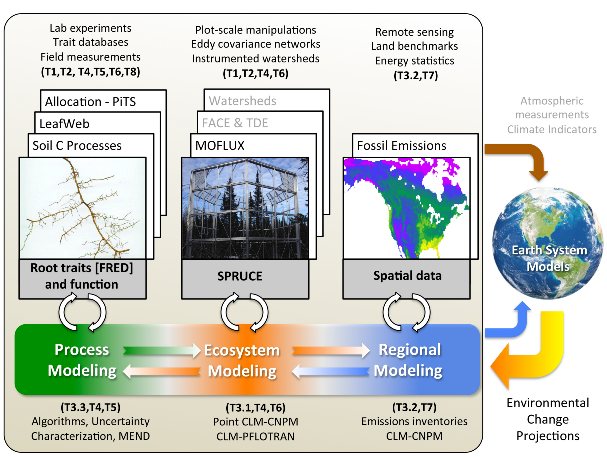


Fig. 1. Diagram of the TES SFA research philosophy and flow illustrating an iterative exchange between model projections, question or hypothesis development and the execution of observations and experiments to better understand impacts of multi-factor environmental changes on ecosystems.

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

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

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

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

2.0 SCIENCE QUESTIONS, GOALS AND MILESTONES

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

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

Goals and Milestones

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

1. Goal 1: Resolve uncertainty in the sign and magnitude of global climate-terrestrial C-Cycle feedbacks under future climatic warming and rising CO_2.
   - Long-term milestone: Provide an operational system to analyze C sources and sinks that integrates global C measurements, data assimilation and experimental results to quantify the sign (net uptake or loss of C from terrestrial ecosystems) and more tightly constrain the magnitude of the global climate-terrestrial C-Cycle feedbacks.
2. Goal 2: Understand and quantify organismal and ecosystem vulnerability to the interactive effects of atmospheric and climatic change through the use of new experimental manipulations employing multi-level warming with appropriate CO_2 exposures and measures of water and nutrient limitations.
   - Long-term milestone: Conduct and complete experimental manipulations and synthesize results including the development of algorithms for characterizing changes in plant growth, mortality and regeneration, and associated changes in water balance, microbial communities and biogeochemistry under climatic change (in a key understudied ecosystem).

3. Goal 3: Develop an improved, process-based understanding of soil C pools and fluxes to improve predictions of net greenhouse gas emissions in terrestrial models and to inform mitigation strategies through ecosystem management.
    - Long-term milestone: Provide a flexible model of soil C storage for ecosystems based on land use metrics for incorporation in fully-coupled ESMs.
4. Goal 4: Incorporate new findings on interannual and seasonal C and water dynamics, episodic events and extreme events revealed by sustained landscape flux measurements into terrestrial components of terrestrial C and ESMs emphasizing the importance of the decadal time scale.
    - Long-term milestone: Achieve predictive capacity to simulate interannual to decadal dynamics important to water balance, biogeochemical cycling, and vegetation and microbial response to climatic and atmospheric change across ecosystems.
5. Goal 5: Search out key uncertainties within global land-atmosphere-climate models and future Earth system diagnosis models as the basis for proposing new measurements and experiments as new knowledge is gained.
    - Long-term milestone: Resolve major components of terrestrial feedback uncertainty for the entire Earth System. New model capabilities will include improved process-based representation of soil organic matter dynamics, microbial communities and new representations of ecosystem climate change response mechanisms derived from experiments.

3.0 TES SFA PROGRAM STRUCTURE AND PERSONNEL

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

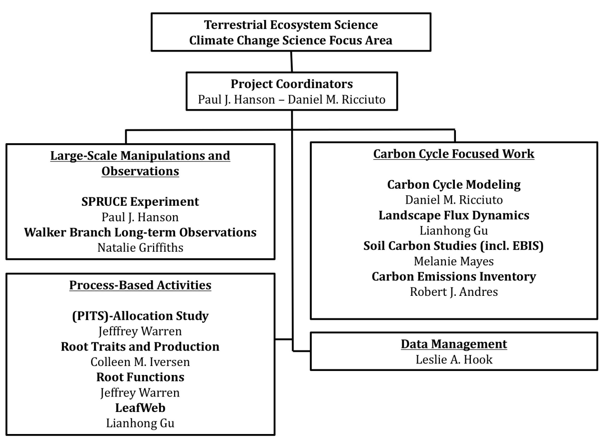


Fig. 2. Organizational chart for the TES SFA effective June 2016.

The TES SFA is supported by 46 dedicated scientific and technical staff at ORNL. Over 50 individuals from the USDA Forest Service, and various other collaborating universities and laboratories are participating in the SPRUCE and MOFLUX projects. We have brought together exceptional multidisciplinary expertise, and are retaining and building staff flexibility to support new research priorities as they are identified.

- Dr. Paul J. Hanson is the Coordinating Investigator and provides integrated leadership across tasks, and coordinates financial management.
- Dr. Daniel M. Ricciuto is the coordinating investigator for terrestrial C-Cycle modeling taking over for Dr. Peter E. Thornton who continues in an advisory role.

- Dr. Les A. Hook serves as the Data Management Coordinator. He brings expertise and technical skills for data policy, management, and archive planning and implementation.

Individual Task lead responsibilities are as follows:

Task 1 SPRUCE Personnel

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

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

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

Plant Physiology –Plant physiological responses are led by Jeff Warren with the support of Stan Wullschleger and past and current postdoctoral and technical staff. We are actively encouraging external participation in associated tasks: gas exchange, carbohydrate dynamics, C partitioning, and woody respiration assessments.

Biogeochemical cycling responses – Work on hydrologic cycling is led by Steve Sebestyen and Natalie Griffiths. Colleen Iversen leads the subtask focused on plant nutrient availability in the shallow rhizosphere. C-Cycle observations focused on peat changes and C emissions are coordinated by Paul Hanson. Natalie Griffiths coordinates with a number of external investigators on extensive decomposition studies.

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

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

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

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

Task 4a – Jeff Warren leads efforts to translate results from experimental C allocation manipulations into mechanistic representations for ecosystem models in collaboration with Jiafu Mao, Dan Ricciuto, Peter Thornton and Anthony King.

Task 4b – Colleen Iversen leads the root trait initiative including the development of a global root ecology database.

Task 4c –Jeff Warren leads the initiative to experimentally link root function to specific root traits in collaboration with Colleen Iversen and modelers Jitu Kumar, Anthony Walker and Dali Wang.

Task 5 – Melanie Mayes provides expertise in soil C cycling, Chris Schadt in microbial ecology and Gangsheng Wang in modeling to develop an improved process model (MEND) for soil C cycling.

Task 6 – Lianhong Gu leads activities in landscape flux of greenhouse gases associated with climate extremes utilizing eddy covariance data and associated experiments. Jeff Wood operates the MOFLUX on-site activities. Other contributing staff include Colleen Iversen, Anthony Walker, and Joanne Childs.
Task 7 – Robert Andres and Anthony King are responsible for the Emissions task.
Task 8 – Drs. Lianhong Gu, Anthony Walker and Dali Wang support LeafWeb.

The TES SFA benefits from two advisory panels, ORNL's CCSI Science Advisory Panel with periodically rotating membership provides annual input on our activities through their annual review of CCSI activities, and a TES SFA panel dedicated to advising the SPRUCE project exists to provide guidance on the science and operation of our flagship experiment. In FY2016 the membership of the SPRUCE Advisory Panel includes: Mike Goulden (University of California, Irvine); Caitlin Hicks Pries (Lawrence Berkeley National Laboratory); Tim Moore (McGill University); Pat Megonigal (Smithsonian Environmental Research Center); Ted Schuur (Northern Arizona University) and Donald Zak (University of Michigan).

4. PERFORMANCE MILESTONES AND METRICS

This section represents a summary of TES SFA activities accomplished since our last written document submitted in February of 2015. The material is organized by the following task with parenthetical identification of the goals that each addresses (Section 2).

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

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

4AI. REVIEW OF SCIENTIFIC PROGRESS BY TASK

Task 1: SPRUCE Infrastructure

As of June 15, 2016 the SPRUCE project is fully operational with deep peat heating (DPH) operating since June 2014, whole ecosystem warming operating since August 2015, and elevated CO_2 exposures initiated on 15 June 2016. Warming treatments are being maintained day and night throughout the year, but elevated CO_2 treatments are applied only during daytime hours during the active growing season (April through November). The following graphics showcase our ability to sustain the deep soil air warming treatments over time. A complete manuscript detailing the SPRUCE experimental site, methods and performance data is nearly complete and will be submitted for external review this summer following the inclusion of some additional information on internal versus external light and wind conditions (Hanson et al. 2016).

Figures 3 and 4 from Hanson et al. (2016) demonstrate our ability to sustain our deep soil and air warming treatments since their respective inception.

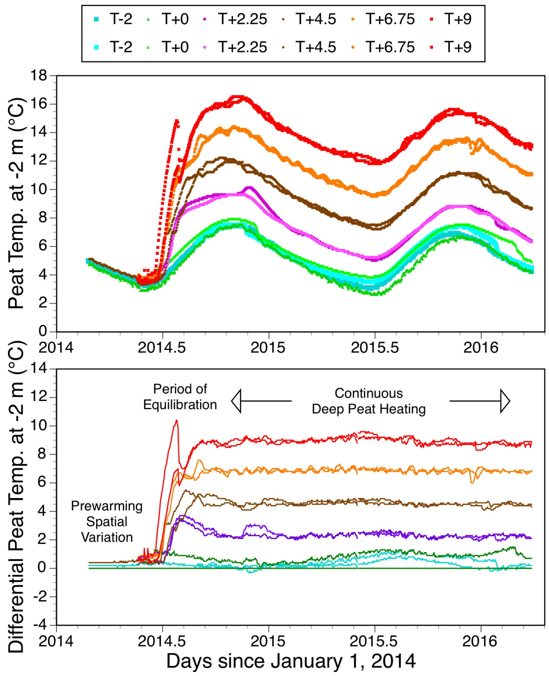


Fig. 3. Daily mean deep peat temperatures (A) and the associated temperature differentials (B) at -2 m by treatment plots since 2014 including the initial warm up periods (June through early September 2014), and the sustained application of deep peat heating with air warming (beginning September 2014). Differential temperatures are referenced to sensors within the fully constructed but no-energy-added control Plot #6. Ambient plot data are also shown as T-2 plots.

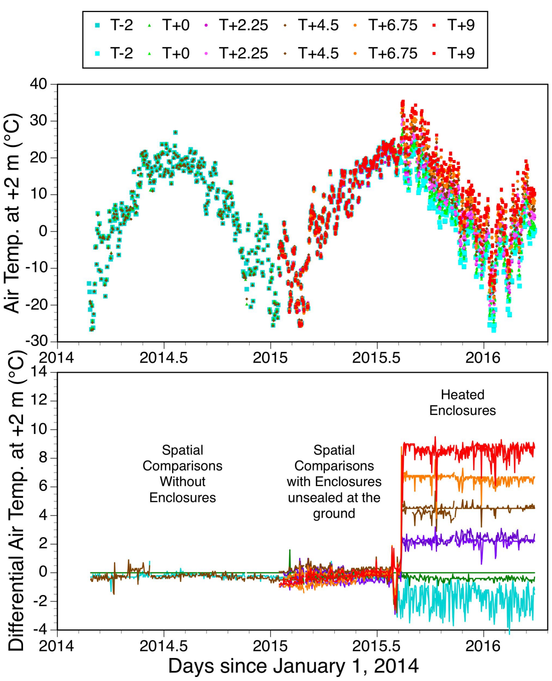


Fig. 4. Daily mean air temperatures (A) and the associated air temperature differentials at +2 m above the bog surface by treatment plots since 2014 including periods prior to enclosure construction (through January 2015), a period when upper enclosures were in place (January to July 2015), and observations since full enclosure of each plot was achieved (27 July through 5 August 2015). Interior blower function was initiated at the time of full plot enclosure. The sustained period of warming began at 14:00 on 12 August 2015. Differential temperatures are referenced to sensors within the fully constructed but no-energy-added control Plot #6. Ambient plot data are also shown as T-2 plots.

Task 1: SPRUCE Response Data

Peat Characterization of the S1-Bog – Pretreatment observations on the S1-Bog peat were conducted in prior years and have been reported in the 2013 and 2014 annual reports. Two new manuscripts under review have now been completed based on these data and associated literature reviews. McFarlane et al. (2016) reconstructed historical carbon accumulation rates in the S1-Bog using radiocarbon and carbon stock measurements from 18 peat cores from randomly-distributed plots associated with a new climate change manipulation on the bog. The large sample set allowed us to assess spatial as well as temporal variability in age-depth profiles and accumulation rates across the 8.1 ha southern Boreal peatland. The bog has been accumulating carbon for at least 11,000 years, but accumulation rates shifted at least twice over this time period. Early Holocene carbon accumulation rates for S1-bog were 30 ± 6 g C m^{-2} y^{-1}, similar to those reported for other northern peatlands. At about 3300 y BP, carbon accumulation rates at

S1-Bog decreased substantially to 15 ± 8 g C m^{-2} yr^{-1} until 53 y BP when accumulation rates increased to 74 ± 57 g C m^{-2} yr^{-1}. Age depth relationships for the S1-Bog (Fig. 5) were also compared to other southern Boreal peatland data for North America and found to be in good agreement suggesting that processes studied in the S1-Bog should have bearing on similar temperate bogs.

Hobbie et al. (2016) used $\delta^{15}N$ and $\delta^{13}C$ patterns from 16 peat depth profiles to interpret changes in C and N cycling in the S1-Bog over the past ~10,000 years. In multiple regression analyses, $\delta^{15}N$ and $\delta^{13}C$ correlated strongly with depth, plot location, C/N, %N, and each other. Continuous variables in the regression model mainly reflected ^{13}C and ^{15}N fractionation accompanying N and C losses, with an estimated 40% of fractionations involving C-N bonds. In contrast, nominal variables such as plot, depth, and vegetation cover reflected peatland successional history and climate. Higher $\delta^{15}N$ and lower $\delta^{13}C$ in plots closer to uplands may reflect distinct hydrology and accompanying shifts in C and N dynamics in the lag drainage area surrounding the bog. Because of multiple potential mechanisms influencing $\delta^{13}C$, there was no clear evidence for the influence of methanogenesis or methane oxidation on bulk $\delta^{13}C$.

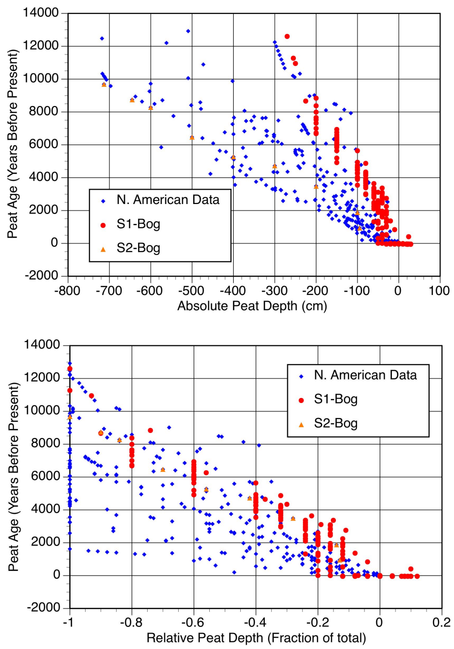


Fig. 5. Age-depth profiles for southern boreal bogs in North America as a function of absolute and relative peat depth. Relative peat depth distributes total peat accumulation over the Holocene across the depth of peat accumulation for each site. Spatial data for the S1-Bog and the S2-Bog on the Marcell Experimental Forest are superimposed with peat age depth information for 31 additional boreal bogs of eastern North America.

<u>*Aboveground production for woody vegetation and forbs*</u> **-** Annual assessments of C stocks and C accumulation in tree tissues (*Picea* and *Larix*) are done annually through remeasurement of tree diameters and periodic evaluations of tree height. Translation of these dimensional data into C stocks is done with allometric data for these species that were generated in 2010 and 2011. Standing stocks of tree wood have been increasing since 2010 at similar rates across the target treatment plots, but no responses to DPH were evident and it is too soon to evaluate changes from whole ecosystem warming. Automated dendrometer bands, installed on 2 trees per plot, are also being used (starting in 2015) to evaluate the seasonality of stem growth by treatment plots. While treatment responses are not yet evident, a clear difference in the timing of growth has been observed, with *Picea* initiating stem growth early in the year ahead of *Larix*.

Standing stocks and net primary production for woody shrubs (*Ledum, Chamaedaphne, Vaccinium*, etc.) sedges (*Eriophorum*) and miscellaneous forbs (e.g., *Smilacina*) are estimated through annual clipping of paired 0.25 m^2 hummock and hollow plots in each treatment area. These have been collected for trees, shrubs, and common forbs each year. Total aboveground standing stock for the non-tree vegetation above the *Sphagnum* surface of the S1-Bog ranges from 180 to 200 g C m^{-2}. Site observations between 2012 and 2015 confirm that shrub production varies from year to year, and most of the production is associated with the development of foliage that cycles annually.

Semi-annual Terrestrial Laser Scanning (TLS) assessments have been contracted through Dr. Nancy Glenn's group at Boise State University to supplement data on direct tree and shrub-layer growth measurements. We expect these data to provide better assessments of tree height, and tree canopy foliage changes through time. Scans done early in the annual cycle before the peatland shrubs have leafed out may also provide us with a detailed assessment of the hummock-hollow topography for each SPRUCE plot.

<u>Phenology</u> – Assessments of site phenology for aboveground plant morphological changes (e.g., budbreak, flowering, senescence) and the accumulation or loss of snow have been carefully noted since the autumn of 2010. Regular and predictable patterns of plant development and seasonal expectations for snow cover have been noted and established as a solid baseline for comparison to warming treatment responses (http://mnspruce.ornl.gov/sites/default/files/presentations/Hanson_S1Pheno_Jan2016_0.pdf). Following the initiation of WEW treatments in August 2015, we saw a discernable extension of the growing season display of green foliage for *Larix* in the +9 and the +6.75 °C treatment plots, and obvious changes in the rate and amount of snow and ice accumulation throughout the winter of 2015 and 2016 (Fig. 6). Similarly, in the spring of 2016 the warming treatments exhibited early flowering and budbreak for most species. These patterns were especially noted for the +4.5 °C and higher warming treatments.

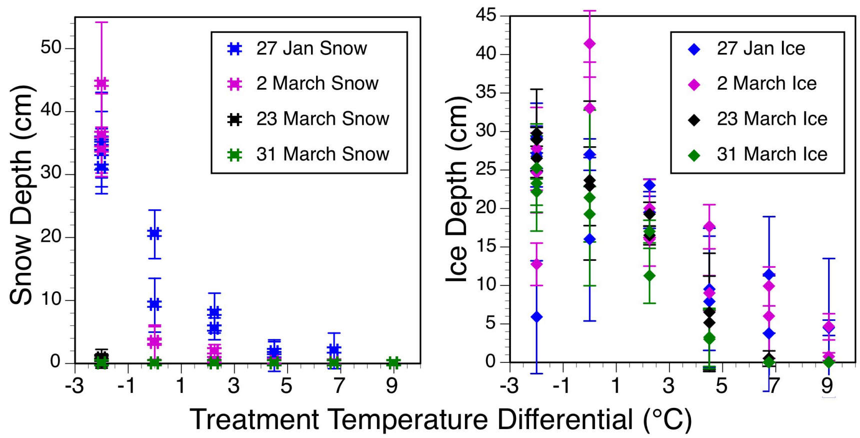


Fig. 6. Patterns of snow (left graph) and ice (right graph) depth by target temperature differential during the winter of 2015/2016.

Due to the loss of winter cold hardiness characteristics and the early onset of spring phenology in the SPRUCE warmed plots, a spring freeze event on the morning of 9 April 2016 caused obvious tissue damage for developing foliage of *Larix* in the +6.75 and +9 °C warming plots. In the coming days, further damage to older cohorts of *Picea* foliage was observed for that species in warmed plots beginning with the +4.5 C treatment. Plants and developing buds that were not active on 9 April 2016 were not negatively impacted. Furthermore, record-breaking temperatures on 5-6 May 2016 led to temperatures reaching 43 °C in the +9 C treatment – extremely hot conditions for the spring. Notwithstanding the visibly dramatic amounts of needle loss for *Larix* and *Picea* in the +6.75 and +9 °C treatment plots following extreme spring weather events, no apparent plant-level mortality has resulted and the plants that showed substantial damage have all subsequently developed new growth.

Phenology continues to be monitored through a combination of automatic cameras that are a part of Andrew Richardson's PHENOCAM network (https://phenocam.sr.unh.edu/webcam/gallery/), and via manual observations collected by ORNL project staff.

<u>Sphagnum production</u> - *Sphagnum* production during 2015 was measured using bundles of 10 stems of 5 cm each that were inserted into the plots in May. Bundles of *S. angustifolium*, *S. fallax*, and *S. magellanicum* were prepared, with two such bundles deployed in each plot. Production was calculated from the increase in length, dry mass per unit stem length, and number of stems per unit area. *S. fallax* in hollows produced 1023 g dry matter m^{-2}, *S. angustifolium* 452 g m^{-2}, and *S. magellanicum* 604 g m^{-2}, with a weighted average of 711 g m^{-2}. Most of this production occurred before aboveground warming treatments were initiated, and there was no significant trend in production across treatments.

A new approach for more direct assessment of Sphagnum production was tested in which 7 cm of *Sphagnum* of known fresh weight and water content was inserted into a mesh column that was then inserted into the surrounding *Sphagnum* community. This approach, which permits a direct measurement of change in dry mass during the growing season, was deployed in May for assessment of production during the 2016 growing season.

Sphagnum community composition was assessed in previously established transects. Changes in composition from the previous year were small and showed no trends across treatment assignments.

In May 2016, Sphagnum water content was measured as part of the set-up of growth columns. There were clear effects of temperature treatment on water content (Fig. 7). Water content of *S. fallax* in the wet hollows declined linearly with increasing temperature. *S. magellanicum* and *S. angustifolium*, residing primarily on drier hummocks, had lesser water content and was least in the +4.5 °C plots, but trends with temperature treatment were not significant.

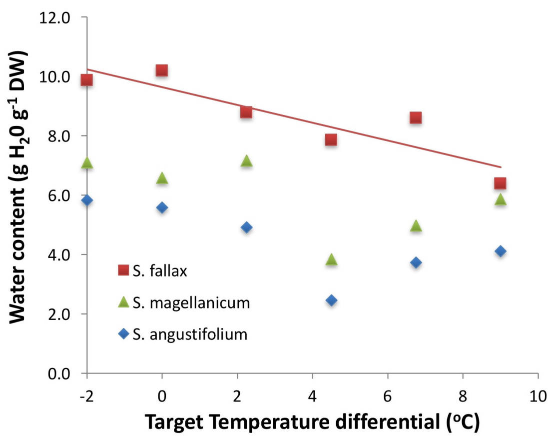


Fig. 7. Water content of *Sphagnum* moss on 9 May 2016. Water content of S. fallax declined with increasing with temperature treatment (R^2 = 0.80, P < 0.02). Trends for the other species were not significant.

<u>*The distribution and dynamics of fine roots in a forested bog –*</u> We determined the distribution and dynamics of fine roots across gradients of microtopography and tree density in the forested, ombrotrophic S1-Bog prior to the initiation of the SPRUCE experimental treatments (Iversen et al. 2016). We characterized relationships among fine-root order, morphology, and chemistry, and quantified fine-root standing crop, production, and mortality throughout the peat profile over a period from 2010-2013. The common woody vascular plant species in the bog encompassed a range of fine-root morphology and chemistry from distal, absorptive fine roots to higher-order transport fine roots. The peak standing crop of tree fine roots was positively related to nearby tree basal area, while shrub fine-root peak standing crop was greatest at intermediate levels of tree basal area. Fine-root production varied many-fold across the bog, ranging from 0 to 254 g m^{-2} $year^{-1}$ for trees and 0 to 39 g m^{-2} $year^{-1}$ for shrubs, and on average represented approximately 45 and 6% of annual net primary production for trees and shrubs, respectively. Fine-root phenology was bimodal for trees and shrubs; the first peak in production occurred early in the growing season after bud break and before peak wood growth, and the second peak occurred later in the growing season after peak woody growth was past (Fig. 8). Fine-root standing crop and production were greater in raised hummocks when compared with saturated hollow depressions. Limited decomposition in anaerobic peat confounded estimates of fine-root biomass distribution in deeper peat; well-preserved, dead fine roots of shrubs were found in peat samples as deep as 2 m, and had a calibrated ^{14}C age of ~5000 years before present.

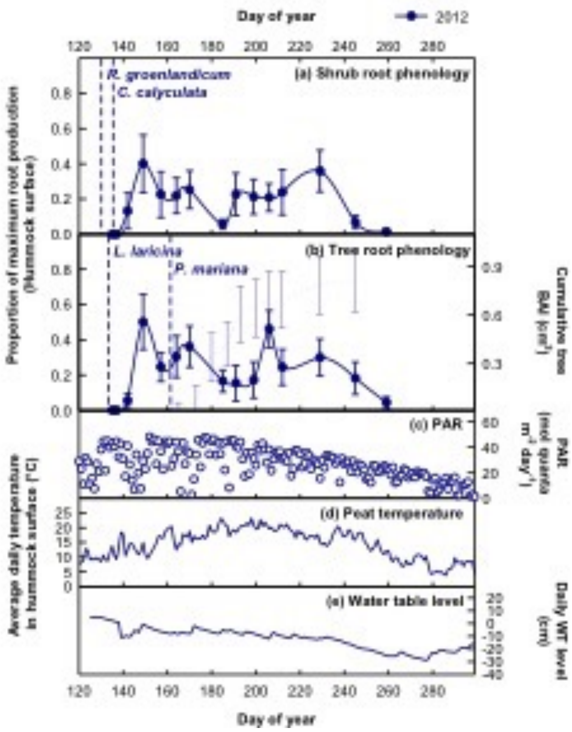


Fig. 8. The timing of the production of new shrub fine roots and leaves (a) and tree fine roots, leaves, and wood (b) in 2012. Data for fine roots and wood are presented as means ± 1 standard error. Root growth phenology was determined from minirhizotron images. Leaf growth phenology was determined from manual observations and daily images, where the dashed lines for shrubs *R. groenlandicum* and *C. calyculata*, as well as trees *L. laricina* and *P. mariana* are annual leaf out. The phenology of wood growth was determined from dendrobands. Environmental data collected from nearby monitoring stations includes photosynthetically active radiation (PAR) measured at 2 m above the peat surface (c), peat temperature measured in the top 5 cm of hummocks (d), and water table level (WT) measured in a hollow (e), where 0 cm was the hollow surface (the surface of the hummocks where minirhizotrons were installed were on average 13 cm above the hollow surface).

The dynamics and distribution of fine roots in this ombrotrophic bog were related to a number of biological, edaphic, and climatic conditions, and we are testing these relationships in the context of the warming treatments.

Manual minirhizotrons – Four minirhizotron tubes were installed in each of 16 SPRUCE experimental plots in early October 2012 in two locations in each plot representing “treed” vegetation (*P. mariana* or *L. laricina* trees within 1.5 m of the minirhizotrons) and “non-treed” vegetation (ericaceous shrubs only within 1.5 m of the minirhizotrons). Image collection began in June 2013, approximately weekly throughout the growing season. Images are digitized to obtain root length and diameter. Collections from 2014-onward has focused on ten SPRUCE experimental plots and two ambient, unchambered plots. In 2013 and 2014, minirhizotron image collection ended in October or November when the surface peat was frozen. Since the onset of aboveground warming in August 2015, warmer peat in the heated plots has allowed minirhizotron image collection to continue throughout the winter months.

Automated minirhizotrons - Novel, automated minirhizotron (AMR) technology is also being used to track the dynamics of ephemeral roots in the ten SPRUCE experimental plots and two unchambered controls. AMR systems facilitate high-resolution (100×) measurements of root and fungal dynamics. AMR collections have been done weekly (ten SPRUCE experimental plots and two ambient, unchambered plots) since they came on-line in June 2014. This system also tracks the phenology of fungal hyphae. A collaboration with Peter Kennedy at the University of Minnesota, has been initiated, to use the AMR images collected over past years to determine the spatial extent of a specific fungal morphotype their group has found to be associated with the roots of *L. laricina*.

Root in-growth cores - Given the ambiguity of distinguishing between living and dead roots in the anaerobic bog environment where dead tissues are highly preserved, root ingrowth cores are used to capture newly-grown fine roots for nutrient analyses. Paired hummock-hollow ingrowth cores constructed of rigid polypropylene mesh and filled with moist, root-free commercial peat are installed in each of two locations in each SPRUCE experimental plot.

Fine roots sampled from ingrowth cores installed near minirhizotrons at the south end of the bog in June 2013 had similar morphology and chemistry to those sampled from peat cores, with the exception of fine-root tissue density, which was ~30% less on average for roots growing into ingrowth cores (Iversen et al., *submitted*). While the depth distribution of fine roots was similar between minirhizotrons and ingrowth cores, we did not find a good correlation between fine-root biomass production estimates from minirhizotrons and ingrowth cores installed nearby; even the patterns of fine-root growth across gradients of tree density differed (Iversen et al., *submitted*). We found that the growth of *P. mariana* fine roots into our ingrowth cores was relatively poor, while the ingrowth of *L. laricina* and shrub fine roots was relatively strong, especially in hollows. We advocate the use of multiple methodologies to better understand the patterns of fine-root dynamics in these important peatland ecosystems.

<u>*Plant-available nutrients*</u> - Ion-exchange resin capsules (WECSA, LLC, Saint Ignatius, MT, USA) are being used to monitor *in situ* changes in plant-available nutrients (i.e., NH_4-N, NO_3-N, and PO_4^-) in aerobic and anaerobic peat layers in the SPRUCE experimental plots. Resin capsules have been collected approximately ~28 days from two arrays of resin-access tubes in each experimental plot (Fig. 9, left) beginning in the growing season of 2013, and continuing during the non-frozen periods.

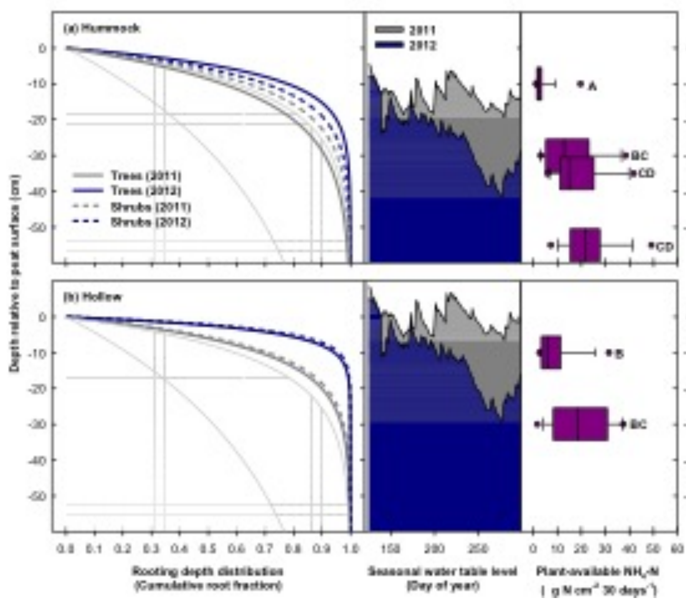


Fig. 9 Rooting depth distributions in the S1-Bog were constrained to nutrient-poor peat by a shallow water table level in hummocks (a) and hollows (b). Fine-root growth data derived from minirhizotrons in 2011 and 2012 have relatively shallow depth coefficients compared with the hatched area, which encompasses the average rooting depth coefficients derived from biomes across the globe. Note that depth values on the y-axis (cm) are expressed as depth from the peat surface rather than absolute depth in order to compare rooting depth, water table level, and nutrient availability. Differing uppercase letters indicate significant differences in NH_4-N with depth across hummock and hollow microtopography, averaged across the SPRUCE experimental plots in 2013.

In years 2013 and 2014, resin collection ended in October or November when the surface peat froze. Since the onset of aboveground warming in August 2015, resin collection has continued in the heated plots throughout the winter months. The ion-exchange resins indicate that plant-available NH_4-N increases with soil depth; approximately 95% of roots were confined to the aerobic zone above the summer water table level where peat nutrient availability was least (Iversen et al., *submitted*). NH_4-N was by far the most available N source in the bog, with NO_3-N making up a negligible fraction of N (at or near detection limits); PO_4^{3-} availability was intermediate.

<u>*Woody Plant Physiology*</u> **–**In Fall 2015 we began long-term automated measurements of sap flow and stem diameter in trees and soil water content within the hummock hollow complex in the 10 chambered SPRUCE plots. In late summer 2016, we plan to add additional sensors to the two un-chambered SPRUCE control plots. Plant water relations measurements will continue throughout the growing seasons during 2016-2018. The chambers create a strong impact on soil, plant and atmospheric water relations through the increase in temperature (~2-11 °C for the +0 and +9 chambers), increased turbulence, and increased evaporative losses. In contrast to external conditions, the dew point is rarely reached in the chambers, thus the foliage and sphagnum remain under chronic water stress overnight (Fig. 10), with full recovery largely dependent on periods of precipitation. In response to the drier and warmer conditions, we expect a shift in leaf area and leaf display through accelerated loss of older foliar cohorts in favor of the new tissue developed under treatment conditions. Since the temperature treatments were expected to shift the onset of spring phenology, we conducted three spring physiology trips in FY16, during the first week of April, May and June. Measurements included predawn and midday leaf xylem water potential for the two trees (*Larix* and *Picea*) and two dominant shrub species (*Ledum* and *Chamaedaphne*).

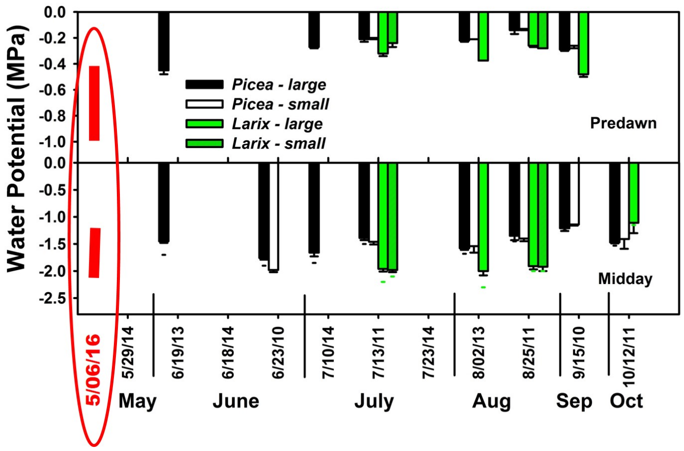


Fig 10. Predawn and midday leaf xylem water potential for *Larix* and *Picea* prior to chamber construction (2011-2014) and in Spring 2016 after chambers were installed and temperature treatments running. Red bars indicate the range of values for trees in all 10 chambered plots. Lower values indicate greater water stress.

A relatively warm May 2016 induced plants in the warmest plots (+6.75 and +9 °C) to de-harden early, which exposed them to substantial foliar damage when a strong April freeze event occurred. In addition, four weeks later a record-breaking heat wave occurred that exposed plants in the +9 °C treatments to the highest temperatures reached to date (~43 °C), substantially hotter than any summer temperatures previously recorded for the site. We continue to monitor plants as they adjust their morphological traits such as leaf area, leaf size, and sapwood area to leaf area ratio to the new conditions. Since we now have a SPRUCE physiology post-doc on site, we will be able to collect opportunistic measurements during extreme events to further characterize the morphological and biochemical responses of woody vegetation.

To assess biochemical temperature acclimation of foliage, we have also been measuring spring and seasonal light-saturated photosynthesis (A_{sat}) for the two trees and two dominant shrub species. We have engaged Dr. Danielle Way's group at University of Western Ontario to help with these tedious, time-consuming measurements, with a focus on photosynthetic and respiratory temperature acclimation of the tree foliage. This year we are collecting point measurements of A_{sat} and dark respiration (R_d) at ambient T conditions, based on the prior 10-day mean temperature in ambient, unchambered plots – a condition that ALM-SPRUCE uses to control photosynthetic rates – as well as at the chamber treatment temperature (+ ~2-11 °C). This will give us an early indication of thermal acclimation during this transition year, and will be continued through the growing season. In summer 2017, we plan to conduct full temperature response curves, including at ambient and elevated CO_2. Such data will be used to produce the photosynthetic response surfaces (Fig. 11) needed to parameterize and validate the modeling efforts. In addition to these A-Ci curves (photosynthesis vs CO_2) we plan to assess light response curves and respiration of excised woody and foliar tissue of the 4 primary woody species. In 2017, we will also quantify leaf level chlorophyll fluorescence and PSII quantum yield of the primary species. These data will be used to develop a scalable fluorescence model (see also Task 6). As with past data from the site, gas exchange and PAM fluorescence output will be processed by the standardized LeafWeb platform (see Task 8).

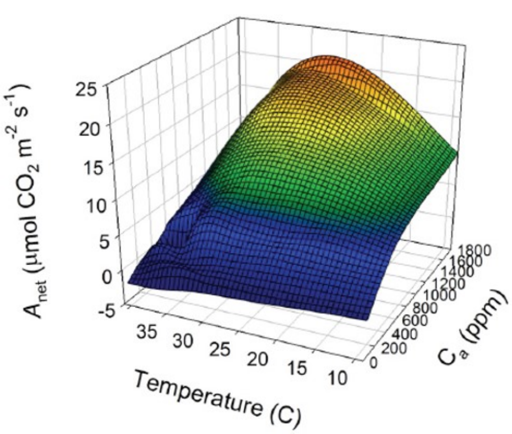


Fig 11. Mechanistic response surface for 1-year-old *Picea mariana* foliage grown under natural conditions at the S1-Bog. Photosynthesis (A_{net}) was measured at CO_2 concentrations ranging from 50-1600 ppm (C_a) at 5 °C temperature intervals from 10-40 °C.

<u>Sphagnum Physiology</u> – The vegetation of the S1 bog is dominated by peat mosses (*Sphagnum* spp.) that contribute substantially to bog NPP (~60%) and together with their associated microbiome contribute to ecosystem C and N cycling. Research in 2015 marks the end of pretreatment data collection and the start of treatment data collection. During the growing season, we continued measurement of net CO_2 with LiCOR 8100s. Eight automated clear-top chambers were installed from April to November. The chambers were all placed in hollow locations and species composition manipulated by transplanting *S. fallax* or *S. magellanicum* into the chambers with two bare-peat chambers (no live *Sphagnum*). These data were used to generate a *Sphagnum* GPP model (Fig. 12). Seasonality in GPP was driven primarily by water table height, most likely through resistance to CO_2 diffusion of standing water when the Sphagnum were submerged. Light and temperature were important in driving high-frequency (daily) variability in GPP, as indicated by the simulations which were able to capture some of this variability. The data show the GPP was overestimated by the simulations during periods of water submersion. Simulations using constant and variable CO_2 resistance functions (r_i) were used to investigate the effect of *Sphagnum* water content on CO_2 diffusion and GPP. The variable r_i functions were the closest to the observed *Sphagnum* GPP (Fig. 12), predicting a little higher GPP during late July and August compared with the constant r_i simulations. However, variable r_i was not able to account for the low GPP when Sphagnum were submerged or close to submerged (mid-April through May 2015 and all of June 2014).

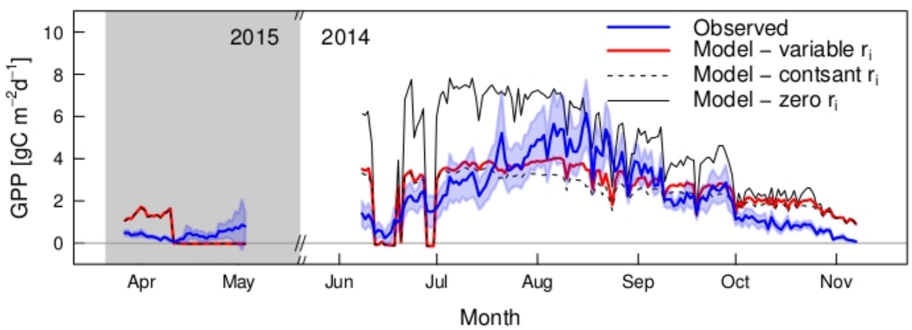


Fig. 12. Relationship among observed gross primary productivity (GPP) and modeled GPP. Observed GPP from clear-top chambers in blue with shadowed standard error (n=6), modeled GPP using a variation of the Flanagan & Williams model with original CO_2 resistance estimates (red line), a constant CO_2 resistance estimate (dotted line) and no CO_2 resistance value (gray line).

Experimental work for 2016 include the addition of two 8100 clear-top chambers each to the ambient +9 and ambient +2.25 experimental enclosures. Six additional 8100 chambers were established outside each enclosure that include two bare-peat (no live *Sphagnum*) chambers and four additional chambers within the hollows. In addition, a seasonal sampling design is being used to investigate seasonal patterns in *Sphagnum* - associated microbiome community composition and N_2 fixation. We anticipate linking N_2 fixation estimates with a *Sphagnum* - microbe physiology model (Weston et al. 2015).

Organized Workshop

11th New Phytologist Workshop: Scaling from genomes to ecosystem function in peat mosses (*Sphagnum*). 23-24 April 2016, Duke University. Organizers David Weston (ORNL), Jonathan Shaw (Duke U.), Merritt Turetsky (U. Guelph).

<u>Microbial Communities and Processes</u> - In June 2014, September 2014 and June 2015, and we examined microbial communities at eleven discrete depths across the peat profile to a depth of 200 cm using qPCR (Schadt/Kluber) as part of a collaborative effort with the Kostka/Chanton project (16S sequencing) and Bridgham/Keller project (Methane Biogeochemistry) that has recently been accepted for publication in Nature Communications (Wilson et al. 2016). After one year of warming under DPH, microbial community structure and abundance of bacterial, archaeal, fungal, and methanogenic populations showed strong vertical stratification across the peat depth profile, but there was no clear response of microbial communities to the temperature treatments (Fig. 13). Community shifts on a DNA level were not evident in the near surface peat either, however, incubations of peat for methanogenic

potential measurements suggested a moderate increase in activity over the course of this year-long experiment. This zone corresponds with our qPCR assessments as the depth with maximum methanogen populations.

Forty samples from 4 depth increments from the June 2015 cores have also recently completed metagenomic sequencing in collaboration with the Joint Genome Institute (JGI) and 40 additional samples from these same depths are in process at JGI for the June 2014 pre-DPH cores. These data will be combined as follow up to the *Nature Communications* paper or may be expanded to include additional comparison data from the first year of whole ecosystem warming from cores recently obtained in June 2016.

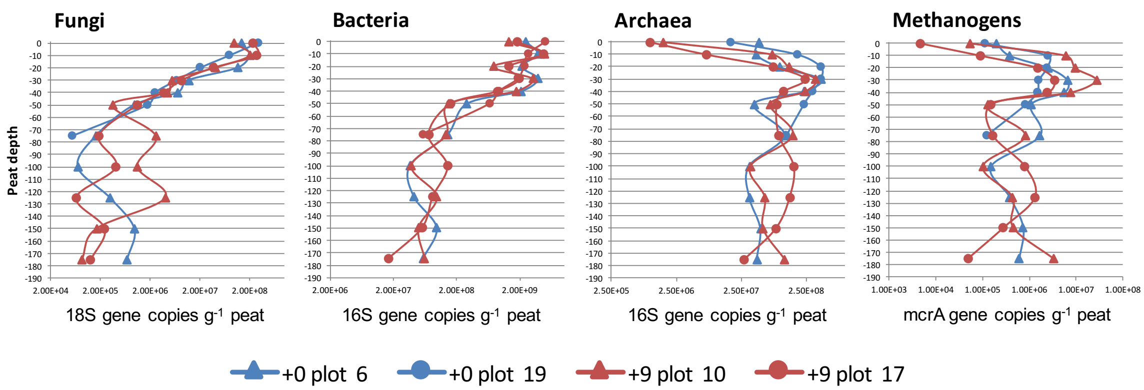


Fig. 13. QPCR assessment of fungal, bacterial, archaeal (rRNA gene) and methanogen (mcrA gene) populations with depth in June 2015 cores after one year of DPH experimental treatment were initiated.

Two additional data products are also expected from the DPH work. The first contains peat moisture fraction used to normalize microbial populations and functional activities, and temperature profiles to plot response variables against. These data are essential to all SPRUCE collaborators examining microbial communities and processes. The second data product is a microbial inventory of fungal, bacterial, and archeal communities present in samples collected in June 2014 and 2015, representing pre-treatment and one year after DPH initiation, and will include both phylogenetic (rRNA genes) and functional (metagenome) datasets. These sequences were produced in collaboration with JGI and can be used in future publications and serve as a benchmark for pre-WEW communities.

In an effort to identify factors that may be limiting decomposition and microbial community change, we conducted an *ex situ* microcosm incubation of deep peat (150 to 200 cm depth) at 6 and 15 °C designed to mimic ambient and +9 °C SPRUCE conditions at that depth under the DPH experiment. Additional treatments included elevated pH and the addition of N, P and N+P in a full factorial design. Three replicates of each condition were derived from peat obtained from each boardwalk transect across the S1 bog. Incubated microcosms were monitored for CO_2 and CH_4 production, and microbial community dynamics were assessed using qPCR and 16S rRNA gene amplicon sequencing. Results indicated that increasing temperature alone moderately elevated both CO_2 and CH_4 production while elevated pH only resulted in greater CH_4 production. The effects of elevating temperature and pH in combination with N, P, or N+P additions were more variable. Although temperature alone had little effect on the overall microbial community composition, there was a shift in the size of bacterial and archaeal populations evident from qPCR. In contrast, elevated pH and N additions seemed to have the largest influence on community structure and suggest that microbial community response in the deep peat may be limited by factors other than temperature (Fig. 14). Additionally, the location of peat collection within the three transects was reflected in community composition suggesting spatial variability across the S1 bog. A manuscript reporting findings from this experiment is currently under preparation for *Global Change Biology*.

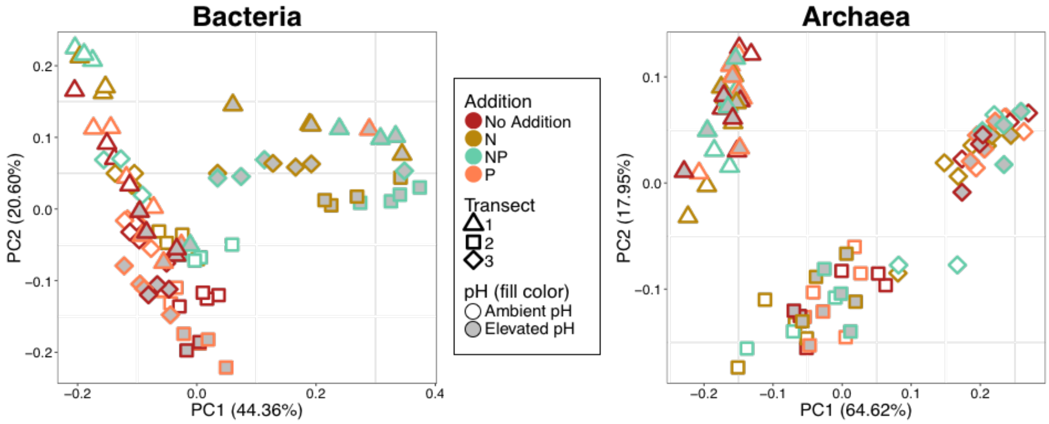


Fig. 14. NMDS ordinations of weighted Unifrac distances from 16S rRNA gene amplicon sequencing. Results show strong variation by transect in both Archaea and Bacteria. Bacterial communities also shifted by nitrogen addition either alone or in combination with phosphorus, while Archaeal communities responded more strongly to pH adjustment (increased from approx. 4.5 to 5.5)

Hydrology and Water Chemistry – In 2015-2016 lateral flow and solute fluxes were evaluated from each enclosed plot. Before initiating these measurements, the subsurface corrals and lateral outflow systems had to be installed and calibrated. The subsurface corrals were installed in winter 2015 and the lateral outflow systems were installed in summer 2015. In the following months, work focused on wiring, calibrating, and programming the autosampler and outflow system. Calibration curves (water level vs. water volume) were manually determined for each of the 10 collection basin systems. These calibration curves were used to calculate near-surface lateral runoff ("outflow" in L/s) from each enclosure by measuring the change in water level over time. In spring 2016, the outflow system was operational, and the autosamplers began collecting flow-weighed water samples for chemical analyses. Preliminary results from the first outflow samples (n=9) collected during snowmelt suggest that total organic carbon (TOC) concentrations were generally higher in water exiting the warmer plots, but there was considerable among-plot variation. Overall, the outflow system will allow us to examine how hydrology (i.e., lateral flow) and water chemistry, especially TOC, respond to warming and elevated CO_2.

Biweekly sampling of depth-specific porewater samplers continued in the ice-free periods of 2015 and 2016 to examine the porewater responses to DPH and whole-ecosystem warming (WEW). There were no substantial changes in deep (2 m) porewater chemistry in response to DPH, suggesting that porewater chemistry is initially resistant to warming. These results were included in the high-profile paper on DPH responses (Wilson et al. 2016).

After WEW began in August 2015, TOC and potassium concentrations increased in near-surface porewater (0 m); however, the responses were not always consistent across temperature treatments (Fig. 15). Little change was observed in deeper porewater (≥0.3 m). It is possible that the higher TOC and K concentrations resulted from increased mineralization of litter and surface peats and subsequent leaching of these solutes into water. It is also possible that these changes reflected concentration of solutes within the enclosures because the lateral outflow system was not operational until spring 2016. Now that the lateral outflow system is operational, the continued porewater sampling will determine if these elevated concentrations persist, or whether they were a transient response.

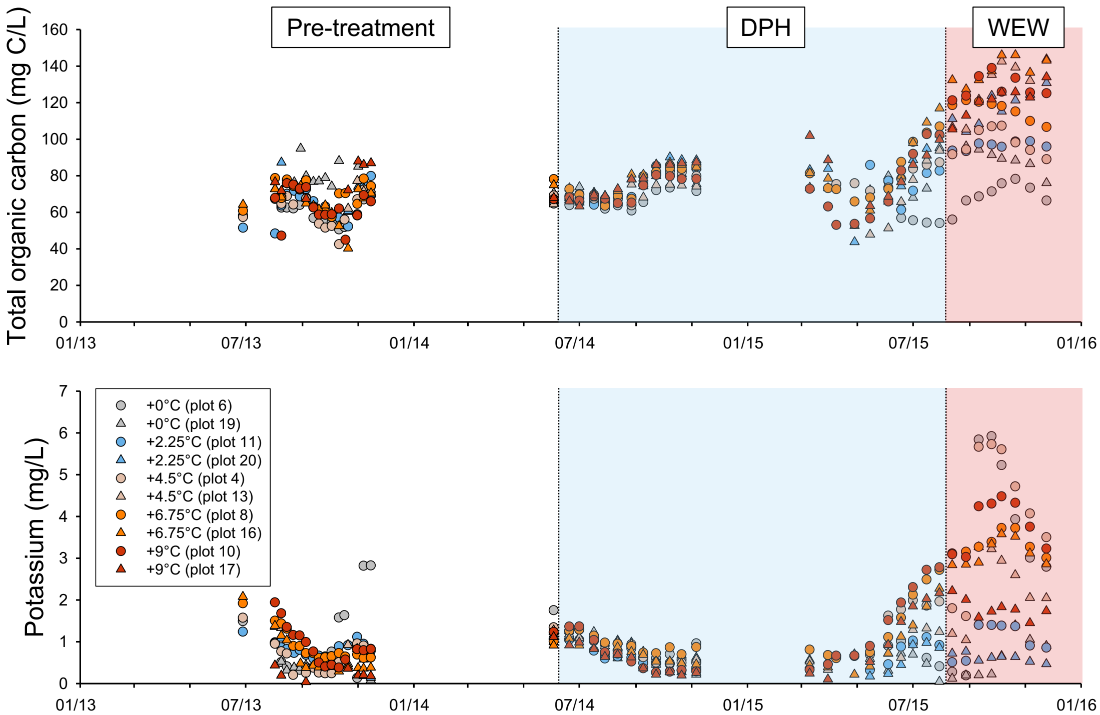


Fig. 15. Near surface porewater TOC (top) and potassium (bottom) concentrations during pre-treatment (white), DPH (blue), and WEW (pink). The 5 temperature treatments are shown in all years to illustrate temporal and spatial (among enclosure) variability.

Decomposition - Decomposition rates of above and belowground litter types [black spruce (*Picea mariana*) needles and fine roots, Labrador tea (*Ledum groenlandicum*) leaves and fine roots, *Sphagnum angustifolium*, and *S. magellanicum*] are being measured in the SPRUCE enclosures. A second experiment is examining the effect of litter mixtures (*S. angustifolium* with either black spruce needles or Labrador tea leaves) on breakdown rates. In 2015, litterbags (n=2640) were constructed and deployed in the enclosures (264 per enclosure) after the warming treatments were initiated (autumn). The initial (time zero) bags were brought back to the laboratory for analysis of dry mass and litter chemistry (C, N, P). In June 2016, the first set of incubated bags was retrieved from the enclosures (0.5 year pick up). The next pick up is scheduled for autumn 2016, and then in years 2, 5, and 10. In autumn 2015, meter-long cellulose (cotton) strips were deployed in each of the enclosures to assess the depth-specific and inter-annual variation in cellulose decomposition and response to warming and elevated CO_2. Each autumn, the strips will be picked up and analyzed, and a new set will be deployed.

CO_2/CH_4 *flux and model* – Simultaneous surface flux measurements of CO_2 and CH_4 have been made since 2011using open-path analyzers and custom-designed chambers that enclose the combined hummock-hollow topography of the bog. This measurement approach enables point-in-time observations of the combined shrub/forb/*Sphagnum*/microbial community for a1.13 m^2 area of the bog. A manuscript on the pretreatment seasonal and spatial patterns is being revised for final acceptance (Hanson et al. 2016). In addition, these data are highlighted in the multidisciplinary evaluation of DPH responses now being revised for final acceptance in *Nature Communications* (Wilson et al. 2016).

Under whole-ecosystem warming in October 2015, CH_4 flux was found to be much greater than under DPH in September - October 2014 (Fig. 16). The WEW late season CO_2/CH_4 ratios are fell dramatically from ambient expectations to between 10 to 20 down to near just 2. Winter conditions of 2015/2016 preclude CH_4 responses to deep warming as expected, but since these limitations were seen before the development of a frozen ice cap they may be reflective of a dormant season substrate limitation.

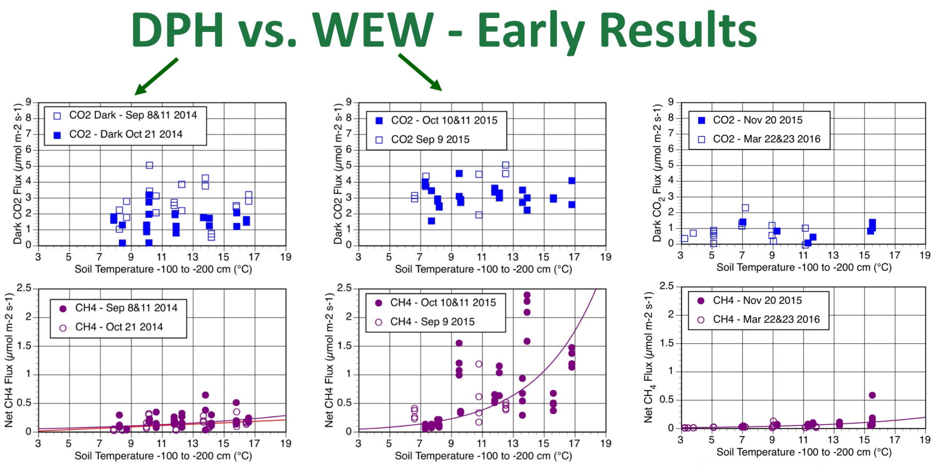


Fig. 16 Data for the large-collar net flux of CO_2 and CH_4 from the bog community during pretreatment (2014) and post-treatment (2015) periods.

Carbon Assessments for the S1-Bog – Stand level C budget components and estimates for the S1-Bog experimental plots were evaluated for pretreatment conditions using a number of approaches including: annual net primary production (NPP) assessments, C flux data interpolations or bottom up calculations for 2011 to 2014, and NPP assessments minus net community C losses estimated for 2015. S1-Bog annual NPP for 2015 is estimated to be 540 gC m^{-2} y^{-1} with 55, 25 and 20 percent of that total being contributed by the *Sphagnum spp., Picea/Larix* tree community, and the shrub layer vegetation, respectively. Fig. 17 suggests that net C input to the bog under pretreatment conditions could be as high as 262 to 366 gC m^{-2} y^{-1} when interpolated from C flux data, or lower at 53 gC m^{-2} y^{-1}. Both of these values may be supported by the available NPP. We are also pursuing direct measurements of plot level assessments of net carbon ecosystem exchange. The developing results from that effort are described in the next subsection.

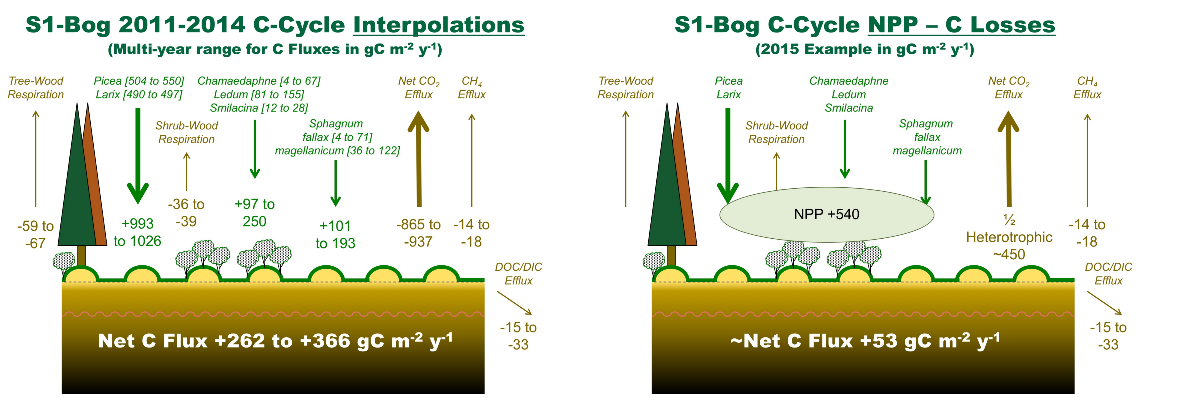
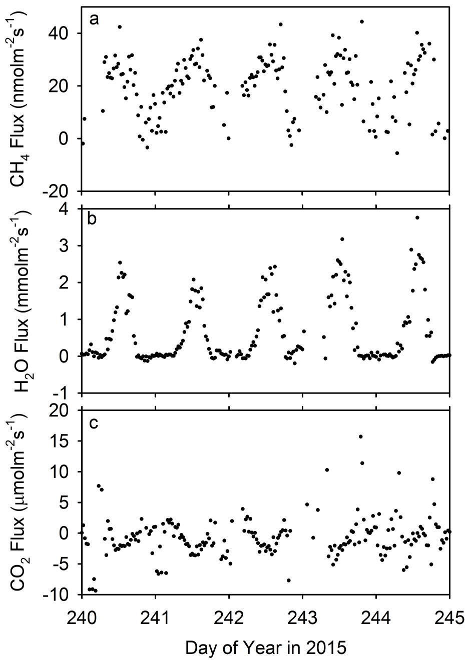


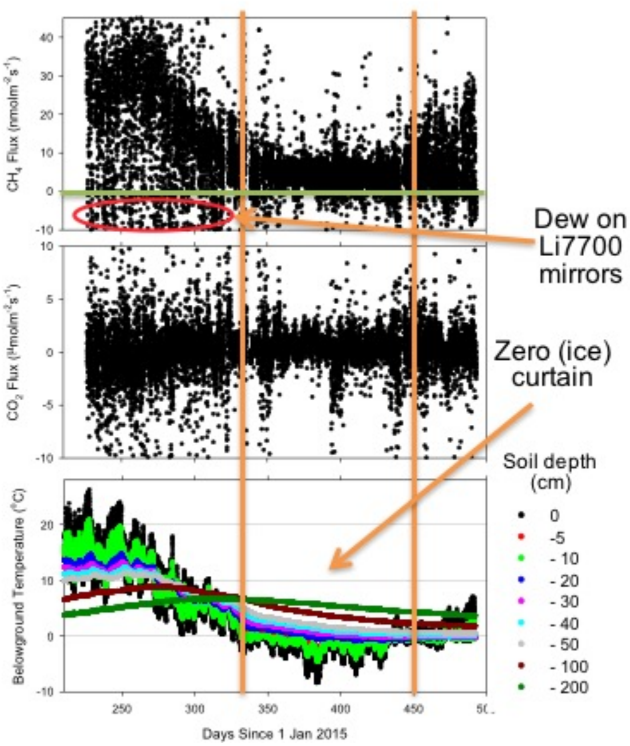
Fig. 17. Interpolated C budget for the S1-Bog for environmental conditions from 2011 to 2014 (left graph), and an alternate estimate based on NPP data and interpolated net C losses from the bog (right graph). Data presented are the multi-year range of data.

A corresponding annual N requirement for the S1-Bog before treatment addition was estimated from annual NPP and observed tissue N levels. That approach suggests annual N inputs from atmospheric deposition, mineralization of available N stocks, or N fixation to be around 14 gC m^{-2} y^{-1}. Continued work in this area will resolve the relative contributions of each.

Progress in SPRUCE Eddy Covariance Study (SPECS)- The objective of SPECS is to understand processes controlling exchanges of CH_4, CO_2, evapotranspiration, and sensible heat and relationships among them in wetland ecosystems, provide continuous ecosystem-level datasets to validate and improve wetland ecosystem models, and help scale up SPRUCE science beyond the S1-Bog. In August 2015, we installed a permanent shrub-level EC system in the ambient Plot #2. Measurements for this plot have shown that ambient emissions of CH_4 have a strong diurnal (Fig. 18) and seasonal (Fig. 19) pattern. This pattern is correlated with bog surface temperatures. The ambient S1-Bog is a continuous CH_4 source, even during winter time. We did not, however, observe the so-called zero curtain effect even though frozen conditions did occur in 2015 winter (Fig, 19).



Fig, 18. An example of diurnal pattern in fluxes of methane (a), water vapor (b) and carbon dioxide measured by eddy covariance system in Ring 2.



Fig, 19. Seasonal dynamics in the eddy covariance fluxes of methane (top) and carbon dioxide (middle) and bog temperatures at different depths (bottom).

SPRUCE Deliverable Progress

The SPRUCE project transitioned to whole ecosystem warming treatment applications in August 2015, and future activities and deliverables are associated with tracking the immediate and long-term responses to the warming treatments and elevated CO_2 exposures initiated in June 2016. The following deliverables cover SPRUCE activities for FY2015 and FY2016.

Task 1 – SPRUCE Deliverable Status

Date	Deliverable	Status
Remaining FY2015 Deliverables		
March 2015	Submission of manuscript describing vertical pore water profiles in the S1 bog.	Completed
March 2015	Submission of baseline SPRUCE water relations manuscripts	Completed Griffiths et al.
June 2015	Full deployment of remaining SPRUCE sensors in all treatment plots	Completed
Sep 2015	Manuscript on peat age and historical C accumulation from ^{14}C data.	Completed McFarlane *et al.*
Sep 2015	Initial whole-ecosystem response measurements for all tasks	Completed
Sep 2015	Submit High-profile paper(s) describing results from DPH	Completed Wilson et al.
Sep 2015	A manuscript on a 2-year preliminary investigation of fine-root dynamics in the S1 bog is currently being prepared	Completed Iversen et al. t
FY 2016 Deliverables		
Oct 2015	Recruit strong plant physiologist / ecophysiologist post docs	Completed x2
Jan 2016	Whole-Ecosystem Warming Technique Paper	Hanson et al. Complete pending submission
Jan 2016	Draft manuscript detailing spatial variation in porewater profiles in S1	Completed Griffiths and Sebestyen 2016
Oct 2016	Full season of task measurements under whole-ecosystem warming	Ongoing
Oct 2016	Manuscript on root-fungal interactions using AMR technology	In progress

Task 1 Publications

Griffiths NA, Sebestyen SD (2016) Temporal dynamics in the vertical profiles of peat porewater nutrients in a northern peatland. *Wetlands* (in review).

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. *Biogeochemistry* (provisionally accepted pending revisions).

Hanson PJ, Riggs JS, Nettles WR, Phillips JR, Krassovski MB, Hook LA, Richardson AD, Ricciuto DM, Warren JM, Barbier C (2016) achieving sustained whole-ecosystem warming for tall statured forest vegetation with constrained air and deep soil heating methods. G*lobal Change Biology* (submission pending one additional data set addition).

Hobbie EA, Hofmockel K, McFarlane KJ, Iversen CM, Hanson PJ, Thorp N, Chen J (2016) Long-term Carbon and Nitrogen Dynamics at SPRUCE Revealed through Stable Isotopes in Peat Profiles. *Biogeosciences* (in review).

Iversen CM, Childs J, Norby RJ, Ontl TA, Kolka RK, Brice DJ, McFarlane KJ, Hanson PJ (2016) The distribution and dynamics of fine roots in a forested bog. *Plant and Soil* (submitted).

Jensen, AM, JM Warren, PJ Hanson, J Childs, SD Wullschleger. (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

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* doi:10.1111/nph.13993.

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 CO2 experiment. *Geoscientific Instrumentation Methods and Data Systems* 4:203–213, doi:10.5194/gi-4-203-2015 Data doi: http://dx.doi.org/10.3334/CDIAC/spruce.013
McFarlane KJ, Iversen CM, Phillips JR, Brice DJ, Hanson PJ (2016) Temporal and spatial heterogeneity of carbon accumulation in an ombrotrophic bog in northern Minnesota over the Holocene. *The Holocene* (in review).
Shaw AJ, Schmutz J, Devos N, Shu S, Carrell AA, Weston DJ (2016) The Sphagnum genome project a new model for ecological and evolutionary genomics. *Advances in Botanical Research* 78:167-187.
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.
Weston DJ, Timm CM, Walker AP, Gu L, Muchero W, Schmutz J, Shaw AJ, Tuskan GA, Warren JM, Wullschleger SD (2015) *Sphagnum* physiology in the context of changing climate: Emergent influences of genomics, modeling and host-microbiome interactions on understanding ecosystem function. *Plant Cell & Environment* 38:1737-1751.
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 to rising temperatures. *Nature Communications* (accepted pending revisions).
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.

Task 1 Data Sets

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

Task 2: Walker Branch Watershed Long-Term Monitoring

Walker Branch Watershed research focused on finalizing publications and long-term datasets. A paper on litter decomposition responses to temperature was published in *Freshwater Science*, and the dataset and associated data guide were made available to the public (http://tes-sfa.ornl.gov/node/80). A paper on estimating uncertainty in stream nutrient uptake methods is in revision at *Limnology and Oceanography: Methods*, and a draft manuscript on dual nitrogen and phosphorus uptake dynamics was completed.

Collection of long-term hydrology (precipitation, stream flow), stream chemistry, and climate data in Walker Branch Watershed ended in 2013, and datasets have been available for public download via the Walker Branch website (walkerbranch.ornl.gov). In 2016, these datasets were revised (e.g., for consistent formatting, notation for missing datapoints, coding to denote detection limits, etc.) following standard data archiving protocols. More comprehensive data guides were completed from existing metadata and institutional knowledge. These updated datasets and data guides have been assigned DOIs.

Publications/Manuscripts

Griffiths NA, Tiegs SD (2016) Organic matter decomposition along a temperature gradient in a forested headwater stream. *Freshwater Science* 32:518-533.
Brooks SC, Brandt CC, Griffiths NA (2016) Estimating uncertainty in ambient and saturation nutrient uptake metrics from nutrient pulse releases in stream ecosystems. In Revision at *Limnology and Oceanography: Methods*.
Hill WR, Griffiths NA (2016) Nitrogen processing by grazers in a headwater stream: riparian connections. In Revision at *Freshwater Biology*.

Data Sets

One new data set from Task 2 work has been prepared and 4 historical data sets were posted (Appendix B).

Task 3: Mechanistic Carbon Cycle modeling

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

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

Point CLM, originally developed with TES SFA support in 2013, has now been extended to the ACME land model version 1 (ALM). A GitHub repository was established for CLM-SPRUCE (Shi et al., 2016) and serves as the central point for model development. CLM-SPRUCE improvements are on the ACME version 2 roadmap for integration in 2017 with joint TES SFA and ACME support. Point CLM was also used for a study at the PiTS experimental site, leading to new conceptual model of plant carbon allocation, for SFA-supported collaborative work on ^{13}C cycling and FLUXNET-China sites (Raczka et al., 2016; Zhang et al., 2016) and at the MOFlux site (Gu et al., in review). Uncertainty quantification has also been a key aspect of task 3: New model parameter optimization and sensitivity analysis algorithms are being applied to CLM and ALM, substantially improving model predictions (Shi et al., 2016; Mao et al., 2015), and for combinations of specific model sub-processes (see below). Both methods are being further developed and tested by Anthony Walker and new postdoctoral hire Dan Lu. Task 3a also supports a SPRUCE model intercomparison, initiated in January 2016. So far, 10 modeling teams have agreed to participate. Pre-treatment and meteorological driver data have been assembled and released to the modeling teams.

CLM and ALM SPRUCE modeling

Recent progress includes the incorporation of a mechanistic CH_4 model, a moss submodel and methods for model-data fusion and ecological forecasting using pre-treatment observations. To better understand the CH_4 model structure developed in this project, Xiaofeng Xu (San Diego State University subcontract) summarized 40 published CH_4 models (including CLM-Microbe) and compared these with the CLM-SPRUCE model. A cluster analysis was conducted to group 41 CH_4 models, considering model representation of acetoclastic methanogenesis, hydrogenotrophic methanogenesis, methanotrophy, different CH_4 transport pathways, multiple soil layers, and oxygen availability. Results show that both CLM-SPRUCE and CLM-Microbe used in this project are mechanistic CH_4 models that could be used to integrate observational datasets for mechanistic processes. In addition, we continue improving and applying the models to simulate CH_4 cycling in the S1-bog. A model parameter optimization algorithm significantly improves predictions of carbon cycling in these mechanistic models; Fig. 20 shows the model performance in simulating CH_4 concentration in soil pore water. The model optimization algorithm is currently being tested with a newly added vegetation component of moss in the ALM-SPRUCE model. The new *Sphagnum* submodel developed by Xiaoying Shi includes moss-specific representations of internal and external water, conductance and photosynthesis parameterized using site observations. The development of CH_4 model has been partially sponsored by NGEE-Arctic project. Preliminary results on these efforts were presented during the AGU fall meeting (December 2015) and SPRUCE all-hands meeting (May 2016).

We are also working to develop an ecological forecasting framework for the SPRUCE site with Yiqi Luo (Oklahoma University subcontract). The Terrestrial Ecosystem (TECO) model is being used in a prototype version of this framework for efficiency, which will be extended to CLM and ALM in 2017. This system uses a Markov Chain Monte Carlo data assimilation framework to estimate the relative contributions of predictive uncertainty from model drivers (e.g. meteorology) and model parameters. With the help of the SPRUCE team, the system is currently being integrated with real-time data acquisition software with the goal of providing automated, near real-time forecasts informed by current data.

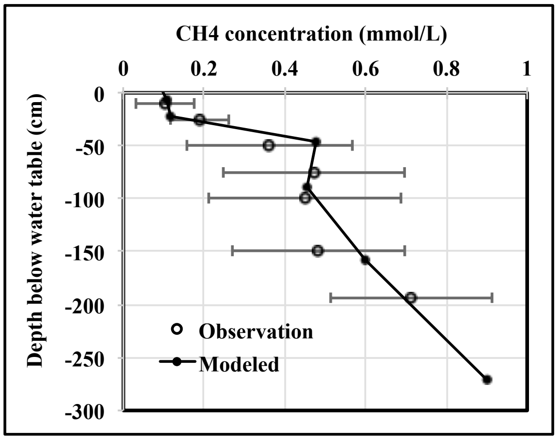


Fig. 20. Comparision of modeled and observed CH_4 concentraion in soil pore water in S1-Bog peatland

<u>Allocation modeling</u> - With the PiTS datasets, we systematically tested the performance of the Community Land Model version 4 (CLM4), in capturing short-term carbon and water dynamics in relation to manipulative shading treatments and the timing and magnitude of carbon fluxes through leaves, stems, roots, and soil. It was found that a combination of parameters measured on-site and calibrated targeting against observations of biomass, transpiration, and ^{13}C discrimination gave good agreement with pretreatment measurements, including independent evaluation metrics at the leaf scale. The calibrated model captured the tree-scale and monthly temporal dynamics of carbon and water fluxes observed in an experimental manipulation that reduced incoming radiation. The model persistently underestimated tree water use (transpiration) for the strongest shading treatment, suggesting the existence of a physiological response to deep shade that is neither included in the model nor described elsewhere in the literature. The lack of short-term carbohydrate storage pools in the model prevented it from simulating the observed timing of the carbon isotope labeling pulse as it moved from leaves through stems and roots and into the soil over a period of several days. A new conceptual model of short-term photosynthate storage and transport based on these experimental observations was proposed (Fig. 21). This work was supported by the TES SFA project and published in *Biogeosciences* (Mao et al., 2016).

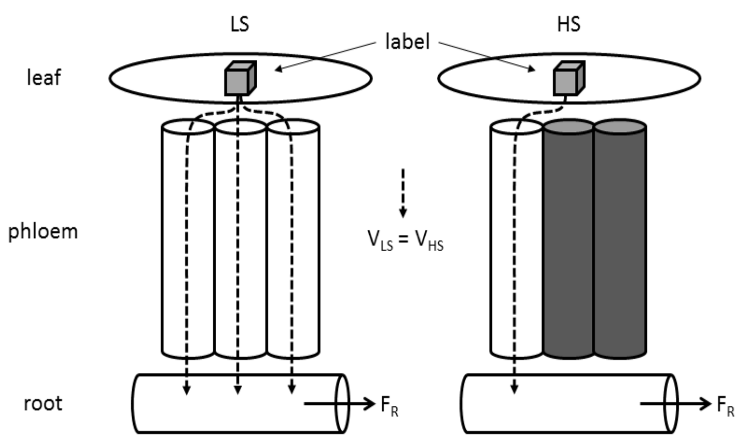


Fig. 21: Conceptual model of label transport, assuming a constant velocity (V) of phloem stream with a cross-sectional area for the phloem pathway that varies as a function of ongoing photosynthetic rate. Cross-sectional area is conceptualized here as a varying number of similar phloem elements, with white elements in an active state, and dark elements inactive. The experimental case with a higher photosynthetic rate for a low shade treatment and lower photosynthetic rate for a high shade treatment is illustrated. Flux from roots (F_R) includes root respiration, root exudation, and turnover of root tissue. The entire label is assumed to exit the leaf and enter the active phloem stream, at a rate that is independent of the ongoing rate of photosynthesis, as observed in the experiment.

Photosynthesis modeling -*Sphagnum* photosynthesis has been modelled and evaluated using the 8100 data as described in the SPRUCE *Sphagnum* task section. These efforts used the Multi-Assumption Architecture and Testbed (MAAT) developed as part of the broader photosynthesis modeling task. The MAAT software system, written in R, was developed in the early part of FY16 as a flexible and automated object oriented software framework to address process representation uncertainty in core models of leaf scale photosynthesis. The framework was also developed during FY16 to be a formalized flexible wrapper around modularized code that can simply switch between multiple representations of the same process, sometimes referred to as multi-physics. The MAAT allows full global process-representation and parametric uncertainty analysis. In collaboration with Ming Ye (Florida State University) and new ORNL postdoc Dan Lu, a method based on Sobol's method has been developed to formally analyses process-representation uncertainty and a manuscript is in development. This method and Sobol's method for parametric sensitivity analysis has been coded into the MAAT software framework and applied to leaf-scale photosynthesis modelling. This work was presented at the May TES-SBR PI meeting and a manuscript is in development. Future plans for this sub-task of the TES-SFA are to further develop the process-representation uncertainty analysis method to improve computational efficiency thus expanding the range of problems that can be addressed using this method. The MAAT leaf-scale and canopy-scale photosynthesis routines are supporting NGEE-Tropics RO2 model uncertainty analysis tasks and further development of these routines (i.e. the actual process) has been handed off to NGEE-Tropics. This SFA sub-task will focus on development of uncertainty analysis methods and application of these and the MAAT to answer TES-SFA science questions at SPRUCE and other sites.

Task 3.1 Deliverable status

Date	Deliverable	Status
2016	- Document CLM-SPRUCE with improved microbial model and simulations from multi-model SPRUCE ensemble - Prototype ecological forecasting system	*Underway* *Complete (MS in prep*)
2017	- Completion of CLM_SPRUCE model with improved Sphagnum photosynthesis - Complete 3D PFLOTRAN simulations	*Underway* Planned
2018	- Document ecological forecasting system - Deliver model to ACME	Planned Planned

Task 3.2 - Regional and global land ecosystem modeling

Progress in this task has focused on development of detection and attribution algorithms and applications. Significant land greening in the northern extratropical latitudes (NEL) has been documented through satellite observations during the past three decades. This enhanced vegetation growth has broad implications for surface energy, water and carbon budgets, and ecosystem services across multiple scales. Discernable human impacts on the Earth's climate system have been revealed by using statistical frameworks of detection and attribution. These impacts, however, were not previously identified on the NEL greening signal, due to the lack of long-term observational records, possible bias of satellite data, different algorithms used to calculate vegetation greenness, and the lack of suitable simulations from coupled Earth system models (ESMs). We have overcome these challenges in order to attribute recent changes in NEL vegetation activity. We used two 30-year-long remote-sensing-based LAI datasets, simulations from 19 coupled ESMs with interactive vegetation, and a formal detection and attribution (D&A) algorithm. Our findings reveal that the observed greening record is consistent with an assumption of anthropogenic forcings, where greenhouse gases play a dominant role, but is not consistent with simulations that include only natural forcings and internal climate variability (Fig. 22). This work was partially supported by the TES SFA project and published in *Nature Climate Change* (Mao et al., 2016).

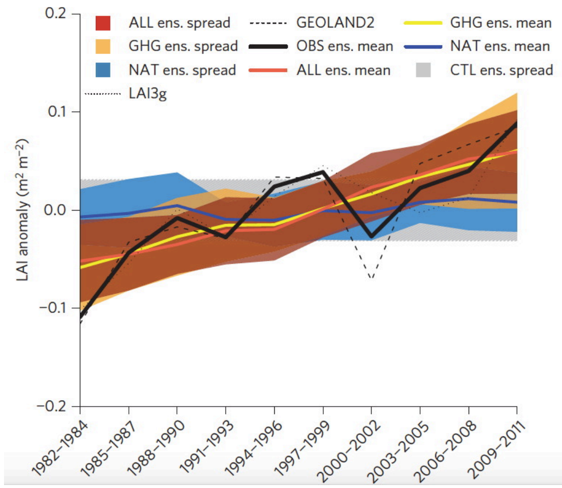


Fig. 22. Observed and simulated 1982–2011 time series of LAI anomalies. The 3-year mean growing season (April–October) LAI anomalies (m^2/m^2) over land of the northern-extratropical latitudes for both LAI3g and GEOLAND2 satellite-derived observations and CMIP5 simulations accounting for solely natural forcings (NAT) and greenhouse gas forcings (GHG) as well as CMIP5 simulations accounting for both anthropogenic and natural forcings (ALL). The ensemble mean for each set of forcings is given in blue, yellow, and red solid lines for NAT, GHG, and ALL, respectively. Individual satellite-derived observations are indicated with dashed black lines; the observational average is given with a bold solid black line. Blue, yellow, and red shading represent the 5%–95% confidence interval for NAT, GHG, and ALL ensembles, respectively (computed assuming a Gaussian distribution). The grey-hatched area represents the 5%–95% confidence interval for the range of variability for the centennial-long preindustrial unforced control simulations (CTL)

The Ridge Anomaly Index (RAI) was recently developed to characterize the size and extent of extreme heat events on the land surface by integrating key statistics (e.g. duration, spatial extent and frequency of events). Interannual variations and multiyear trends of the RAI could have significant effects on the terrestrial ecosystem, in terms of the vegetation growth and fluxes between the land and atmosphere. Besides the successful applications of the standard D&A methodology onto the study of NEL vegetation growth, we are trying to disentangle the natural and combined anthropogenic controls on the changes of RAI for the 1979-2013 period. We used four reanalysis products as the observations and the ensemble simulations (ALL and NAT) of the CAM5.1 from the International CLIVAR C20C+ Detection and Attribution Project. A linear regression framework for D&A was used with $y = \beta_{ANT}X_{ANT} + \beta_{NAT}X_{NAT}$. In the equation, y, β, and X represent the observations, scaling factors, and forcing data, respectively. A signal is detected if the scaling factor is significantly different from 0. After being detected, a forcing is attributed if its scaling factor and corresponding confidence interval include 1. The scaling factors for anthropogenic forcing (ANT = ALL –NAT) include 1 but not 0, and NAT includes 0. Therefore, the anthropogenic signal can be detected and attributed and the natural forcing cannot. This implies that RAI cannot be explained solely by natural forcings. The next step of this work would be testing the robustness of these results by using factorial simulations from other earth system models, and exploring the relationship between the human-induced changes of RAI and the terrestrial ecosystem dynamics. This work is supported by the TES SFA project and a potential paper is under discussion.

Task 3.2 Deliverable status

Date	Deliverable	Status
2016	- Collection and compilation of SIF, NDVI, SR and river flow data - Online and offline D&A methods development and testing	*Underway* *Underway*
2017	- CLM-SIF model validation; experimental design and model ensemble simulations - D&A study of the NDVI and river flow	Planned Planned

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

Task 3.3 – Functional testing

Using our functional testing framework, we continue to explore the functional representation of photosynthesis and Rd in CLM-SPRUCE and ALM. We have focused on the representation of foliar dark respiration (Rd) and pre-treatment (2010-2013) observations of the temperature response of Rd for black spruce (Picea mariana) at the SPRUCE site. In the functional unit testing framework, functional representations at the finest level of code granularity and the scale of observations are isolated as modular units, in this case Rd and its accompanying temperature response functions. We have found that the observed temperature response of black spruce foliar Rd is not duplicated by the foliar Rd module of CLM-SPRUCE. The model simulates a reduction in lnRd at temperatures > 30 °C not seen in the observations where ln Rd increases approximately linearly over the range 5-40 °C (Fig. 23). Substituting in a more conventional Q10 temperature response module improves the fit with observations. The “acclimation” of Rd coded into the model may not appear in the observations because historically, black spruce at the site experience the warmer temperatures infrequently and only briefly, and we are pursuing the investigation of this hypothesis with Jeff Warren (Task 1 physiology) and others. We are also utilizing the functional unit testing framework in the ^{13}C modeling for Task 7.

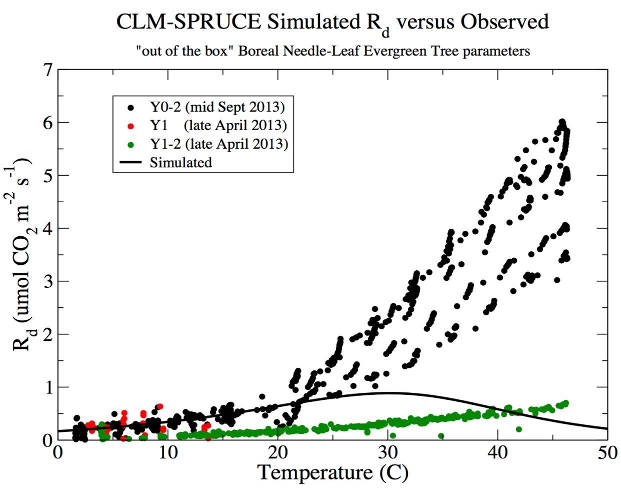


Fig. 23. Dark respiration as a function of temperature: modeled vs. observed responses at the SPRUCE site.

Task 3.3 Deliverable status

Date	Deliverable	Status
2016	Functional testing for “root” modules and integration with UQ methods	*Underway*
2017	Functional testing for ecosystem dynamics and hydrological components and model structure UQ development	Planned
2018	Regional CLM functional testing and multiscale UQ with observational datasets	Planned

Task 3 Publications

He H, Wang D, Tan J (2016) Data Synthesis in the Community Land Model for Ecosystem Simulation. *Journal of Computational Science* doi:10.1016/j.jocs.2016.01.005

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.

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, http://dx.doi.org/10.3402/tellusb.v68.28968.

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.

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 CO2 exchange with the atmosphere 1990-2009. *Biogeosciences* 12:399-414.

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.

Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016) Evaluating the Community Land Model in a pine stand with $^{13}CO_2$ and shading manipulations. *Biogeosciences* 13:641-657, doi:10.5194/bg-13-641-2016.

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 (2016) Human-induced greening of the northern high-latitude land surface. *Nature Climate Change* (Accepted)

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* (Accepted).

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

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.

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.

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 (2016) Uncertainty analysis of terrestrial net primary productivity and net biome productivity in China during 1901-2005. *Journal of Geophysical Research-Biogeosciences* 121, doi:10.1002/2015JG003062.

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.

Sun Y, Piao S, Huang M, Ciais P, Zeng Z, Cheng L, Li X, Zhang X, Mao J, Peng S, Poulter B, Shi X, Wang X, Wang YP, Zeng H (2016) Global patterns and climate drivers of water-use efficiency in terrestrial ecosystems deduced from satellite-based datasets and carbon cycle models. *Global Ecology and Biogeography* 25:311-323, doi: 10.1111/geb.12411.

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(6): 775-792.
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 CO2 enrichment: How and why do current ecosystem models differ? *Global Biogeochemical Cycles* 29:476-495.
Wang D, Janjusic T, Iversen C, Thornton PE, Krassovski M, Wu W, Xu Y (2015) 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*, 10.1109/SE4HPCS.2015.10.
Wang SS, Pan M, Mu QZ, Shi XY, Mao JF, Brummer C, Jassal RS, Krishnan P, Li JH, Black TA (2015) Comparing Evapotranspiration from Eddy Covariance Measurements, Water Budgets, Remote Sensing, and Land Surface Models over Canada. *Journal of Hydrometeorology* 16:1540-1560.
Xu XF, Elias DA, Graham DE, Phelps TJ, Carroll SL, Wullschleger SD, Thornton PE (2015). 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.
Xu XF, Hui DF, King AW, Song X, Thornton PE, Zhang LH (2015) Convergence of microbial assimilations of soil carbon, nitrogen, phosphorus, and sulfur in terrestrial ecosystems. *Scientific Reports* 5:17445, doi:10.1038/srep17445
Xu X, Yuan F, Hanson PJ, Wullschleger SD, Thornton PE, Riley WJ, Song X, Graham DE, Song CC, Tian H (2016) Review and Synthesis: Four decades of modeling methane cycling within terrestrial ecosystems, *Biogeosciences* (Accepted).
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* (Accepted).
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,* doi:10.1038/nclimate3004.

Model and Data Archiving

The recent publication of the first SPRUCE modeling study (Shi et al, 2015) with others in preparation highlights the need for a consistent archiving framework for model products. We are pursuing a strategy to arrive model code and datasets used for model validation. A model-data package for the CLM_SPRUCE manuscript is in the process being released and a DOI is being assigned. A repository has also been set up for code archiving, development and sharing (https://github.com/dmricciuto/CLM_SPRUCE/), enabling more efficient collaboration.

Task 4a: Synthesis of the Partitioning in trees and soils studies (PiTS; Goals 4 & 5).

The PiTS projects have been very successful in developing new relationships within the SFA group, and addressing a key limitation of carbon storage and timing of carbon flow in CLM and other terrestrial biosphere models. PiTS data analysis and modeling efforts continue in FY16 based on existing data from the three PiTS studies – the dogwood $^{13}CO_2$ labeling and shading dataset and manuscript is in development, and modeling activities are planned. Once the modeling runs are complete, we will reassess the utility of this MODEX, and in context of the primary goal (improved C partitioning model routines) if additional modeling or experimental studies are warranted in FY 17-18. Currently, the team plans to leverage the success of the PiTS collaboration to address a more comprehensive and integrative model-experiment program that focuses on measurement and modeling of the broader belowground plant-rhizosphere-soil system (described below in new task "Linking Root Traits to Function"). This effort will be coordinated with other proposed and ongoing SFA tasks (e.g., "Modeling of Microbial Processing of

Soil C”) to assess the belowground environment more broadly, and is anticipated to culminate in establishment of a “Rhizosphere Ecology Laboratory” (REL). The REL will be a focused, multi-scaled laboratory and small-scale field capacity to facilitate assessment of specific co-occurring mechanisms related to carbon uptake, partitioning, biogeochemical cycling, rhizosphere ecology and root function, and will be designed to provide pertinent data to the modeling group.

Task 4a. Deliverable status

Date	Deliverable	Status
Oct 2016	Submission of final PITS dogwood $^{13}CO_2$ labeling and shading data manuscript. Submit data to TES SFA data archive.	In progress
Oct 2017	Submission of final PITS dogwood $^{13}CO_2$ labeling and shading modeling manuscript	In progress

Publication

Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016) Evaluating the Community Land Model in a pine stand with shading manipulations and $^{13}CO_2$ labeling, *Biogeosciences* 13:641-657, doi:10.5194/bg-13-641-2016

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

Taking a MODEX approach, our strategy is three-pronged: (1) to develop a global root ecology database to improve the parameterization of root traits in existing plant functional types (PFTs) and to inform developing trait-enabled modeling approaches, (2) to facilitate the development of a ‘root module’ in CLM to perform analyses of model sensitivity to variation in root traits and to engage the broader community of root and rhizosphere ecologists, and (3) to improve CLM-CNP model structure to better reflect empirical knowledge gained from sensitivity analyses and the knowledge base of the broader community of root and rhizosphere ecologists. In contrast to the mechanistic observations and experiments proposed in Task 4c, this task is broadly focused at understanding the variation in root traits and function across the globe, which is the scale at which land surface models like CLM operate.

Variation and tradeoffs within and among plant traits are increasingly being harnessed by empiricists and modelers to predict ecosystem processes in response to current and future environmental conditions. While fine roots play an important role in ecosystem processes, most fine-root traits are extremely underrepresented in global trait databases. The lack of available and centralized data has hindered efforts to analyze fine-root trait variation at a global scale, and limited meaningful linkages among above- and belowground traits. Together, these limitations have contributed to the coarse representation of fine-root processes and associated parameters in terrestrial biosphere models. To address the need for a centralized fine-root trait database, we are compiling the Fine-Root Ecology Database (*FRED*) from published literature and datasets as well as unpublished sources; data collection is ongoing and will continue for the foreseeable future.

To date, *FRED* contains ~39,000 species-specific trait observations from 936 species, and ~15,000 trait observations collected from mixed plant communities. In total, these observations encompass approximately 170 root traits. The observations housed in *FRED* are from ecosystems spanning the globe, but the data compiled thus far highlight in stark relief the *observations that are missing*. This is particularly striking for polar and boreal regions underlain by permafrost or characterized by organic soils, as well as tropical regions. *FRED* will be available to the broader community of modelers, root and rhizosphere ecologists, and applied ecological communities with unrestricted access through a website hosted by ORNL (http://roots.ornl.gov); we are targeting a release date of late 2016. We recognize that a considerable number of discrete trait datasets still reside with individual researchers, and we are actively encouraging the broader scientific community to contribute published past and future datasets to FRED. The website will serve as a location for the broader community to contact us and provide input or additional sources of data, and will also be used for communication and updates. FRED Version 0 has been submitted to TRY version 4 as of June, 2016.

The version of CLM (CLM 4.5) upon which ALM is being built includes a number of root parameters that will benefit from being informed with empirical data from *FRED*. In turn, we will use sensitivity analyses to inform which observations and experiments are necessary to improve our understanding of roots and root processes. Our initial focus is on: (1) fine-root turnover rates, with are a fixed parameter in ALM, (2) fine-root phenology, which in CLM 4.5 is currently parameterized as a one-to-one relationship with leaf phenology, and (3) fine-root C/N ratios (currently equal to 42 for all plant functional types in CLM 4.5). We have added three new parameters to CLM 4.5, including a new parameter for fine-root longevity for evergreen plants that is independent of leaf longevity, and a simple modification of the root phenology algorithm to better capture differences in the timing of root growth that includes two new parameters: the time of the productivity-year that fine-root allocation peaks and the length of time during which fine-root allocation occurs (the width of the peak in allocation). Preliminary results indicate that fine-root C/N ratio, allocation, and turnover are important controls over site-level GPP, while rooting depth distribution and phenology are less important (and the width of the peak in allocation phenology was more important than the timing). Dan Ricciuto is leading sensitivity analyses of ten root-related traits in CLM 4.5, using *FRED*-informed distributions.

We have two subcontracts in place for work this work. A. Shafer Powell, a post-Baccalaureate student intern, has been adding data from published literature to *FRED*, to maintain and quality-assure the *FRED* database, and to maintain the associated data dictionary and user guidance document. Shafer recently filled his millionth data cell with root-related data. M. Luke McCormack, a research associate at the University of Minnesota, has been subcontracted to analyze global patterns in root traits compiled in the Fine-Root Ecology Database (*FRED*) and develop a manuscript on this topic, as well as participate in ORNL efforts to improve the conceptual representation of root traits and their associated functions in terrestrial biosphere models.

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Task 4b. Deliverable status

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

Publications/Manuscripts

None to date.

Data Sets

A root traits database has been initiated (Iversen et al. 20916; Appendix B).

Task 4c. Linking Root Traits to Function

Based on our recent review manuscript (Warren et al. 2015) we developed a framework to improve fine-root representation in large-scale models through new data compilation and collection efforts, scaling and modeling. The scope of this task will depend on results from FY15 and FY16 modeling and uncertainly analyses (i.e., if CLM or other relevant models are sensitive to root function, and if relevant data exist). Based on these analyses and initial results from Task 4b: Leveraging Root Traits to Inform Biosphere Models, including development of the FRED database, we will develop the appropriate experimental research plan in late FY16 to be deployed in FY 17-18. We anticipate the primary focus for this task will be on functional root nutrient and water uptake dynamics, as well as root hydraulics under drying conditions; however, appropriate linkages to root C sinks or C release will also be considered. We have recently constructed a pressure transducer-based hydraulic flow meter for use to characterize axial hydraulic conductivity in small roots (~1.5 to 3 mm), and will test it out with various species during the Fall. We are also beginning to apply our existing data on root function to mechanistic models at several scales. Using extensive knowledge of root morphology, distribution, and water extraction patterns for sweetgum trees at the ORNL FACE site, we have engaged ORNL reactive-transport modeler Scott Painter to develop an explicit model focused on root water extraction, and we are currently assembling the appropriate data sets for that effort. In addition, we have multiple neutron imaging datasets of root water extraction from prior and new experiments at the High Flux Isotope Reactor (HFIR). Scott is also developing a soil water extraction model that can utilize the high-spatial resolution data output from these imaging studies These initial focused efforts that apply root data to models will ultimately inform large-scale trait-based models that depend on large databases such as FRED and TRY. We plan to continue to collect relevant root data through the MODEX multi-scale framework based on sensitivity analysis and model iterations. New experiments will be focused to provide key data that can be applied to models and ultimately to parameterize and scale root functional knowledge into larger terrestrial biosphere models.

Task 4c. Deliverable status

Date	Deliverable	Status
Dec 2016	Leverage existing data sets (e.g., FACE water content, water use, root distribution) and apply root uptake models for uncertainty and sensitivity analyses	In progress
Oct 2017	Develop root nutrient or water uptake measurement protocols and tools to assess root function under dynamic conditions	In progress
Oct 2017	Begin directed laboratory and field-based experiments to quantify water and nutrient uptake kinetics by root functional classes in response to environmental conditions as justified by model uncertainty and sensitivity analyses	Planned
Dec 2017	Begin deployment of Rhizosphere Ecology Laboratory for integrative assessment of belowground dynamics	Planned

Publication

Warren, JM, Hanson PJ, Iversen CM, Kumar J, Walker AP, Wullschleger SD (2015) Tansley Review - Incorporation of root structure and function in models – evaluation and recommendations. *New Phytologist* 205:59-78.

Task 5: Microbial Processing of Soil C

Improvements to understanding the microbial processing of soil C and incorporating that understanding into the Microbial ENzyme Decomposition (MEND) model continued in FY15-16. A major focus continues to be the incubation study involving paired temperate forest and grassland on four soil types, adding ^{13}C-labeled glucose over short timeframes (~6 d) and ^{13}C-labeled cellulose over long timeframes (up to 2 y). We find that the forest and grassland soils responded similarly to the short-term glucose additions, with glucose dramatically increasing CO_2 fluxes (Fig. X-A, B). The majority of the ^{13}C-glucose is respired within 48 hours, although the ^{13}C signature persists until the end of the experiments at 6 days. We believe this response is because processing glucose does not require enzymes, and because glucose does not interact strongly with soil minerals that can inhibit microbial uptake. These short-term experiments will be used to calibrate the active microbial fraction in MEND; a recent improvement of MEND is to separate the active and dormant microbial fractions (Wang et al. 2014a,b). In contrast, respiration in soils labeled with ^{13}C cellulose is similar to controls, and in fact, cellulose additions suppress C mineralization in most forest and some grassland soils (Fig. X-C, D). These experiments will be used to test modeling the degradation of more complex plant polymer substrates with MEND, likely also involving increasing microbial dormancy over the longer timeframes. Isotopic analysis of soils from hour 114 (short term), and days 151 and 729 (long term, day 729 will occur in FY17) are being used to assess the fate of the ^{13}C additions. Microbial biomass measurements are measured at key points during the incubations since it is a key calibration target for the model (data not shown).

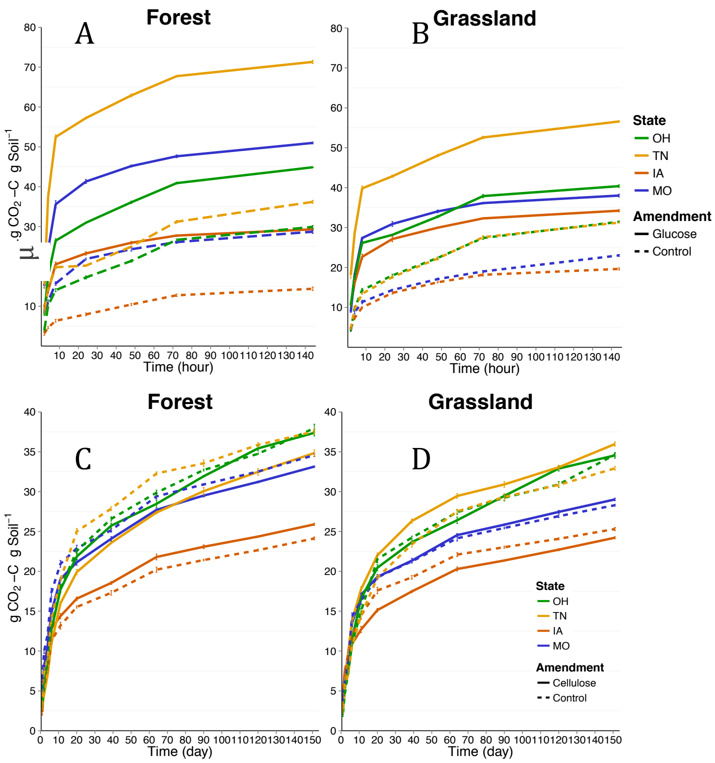

Fig. 24. CO_2 respiration from incubation experiments with four paired forest and grassland soils using (A, B) ^{13}C-labeled glucose additions and controls, and (C, D) ^{13}C-labeled cellulose additions and controls.

This set of incubations began in FY15 and involved nearly 1,000 incubation microcosms and 5,000 individual samples for analysis. Over 1,500 gas and soil samples were submitted to Colorado State University for ^{13}C analyses. The analyses turned out to be quite slow, and in fact, we are still waiting on some key analyses of the $^{13/12}C$ ratio of the soils. Therefore, the deliverable date for completing the experiments and writing the manuscript (likely submit to *Biogeosciences)* has moved from the end of FY15 to early FY17. Samples from these experiments have been properly archived such that, if time permits, we will conduct molecular analysis to identify microbial taxa key to C turnover, and apply to EMSL for chemical analyses of the soil organic matter to examine the C transformations that contribute to stabilization.

We realize that modeling this set of experiments will be quite involved and time-consuming, so we add a new deliverable in FY18. We recruited a PhD student, Siyang Jian of Tennessee State University, to assist in the modeling activity and to perform additional incubation experiments as needed, beginning in August 2016. Mr. Jian will be supervised by Dr. Jianwei Li who has worked with the MEND model in the past (Li et al. 2014). Dr. Li is spending his second summer in a row with us at ORNL under DOE's Visiting Faculty Program; his proposal involves testing soil warming observations from the Harvard Forest with the MEND model.

After we wrote the renewal proposal in FY15, we began to test the MEND model against 3 years of field-scale heterotrophic respiration and microbial biomass data from the Dinghuashan Biosphere Reserve in subtropical southern China. Datasets from an old-growth broadleaf forest and a young pine forest are both available. The site exhibits a strong seasonal moisture pattern, so we added soil moisture sensitivity into the MEND model. The simulations result in a good match to the respiration data, with R^2 of 0.71 for the broadleaf forest (Fig. 25) and 0.47 for the pine forest (data not shown). Simulations of microbial biomass measurements are also impressive, with R^2 of 0.71 for the broadleaf forest and 0.84 for the pine forest (data not shown). We continue to refine the simulations and a draft manuscript has been prepared. The deliverable to include moisture sensitivity into MEND and test against experiments has therefore been moved forward in time. The scope changed from beginning a new set of lab-scale incubations to testing the model against pre-existing field-scale data. We find the field testing to be a huge step forward for the MEND model, in comparison to performing more lab-scale incubations.

In addition, we incorporated flexible C:N stoichiometry into MEND, which is partial progress on an FY18 deliverable.

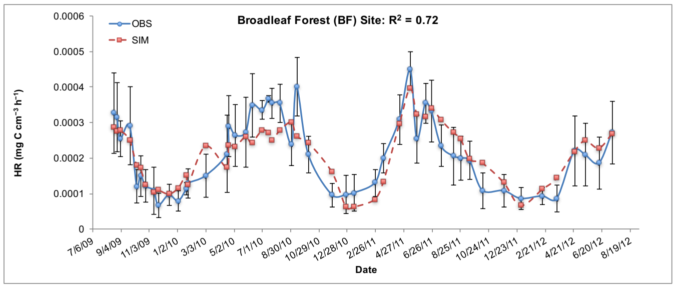

Fig. 25. Observed (obs) and model simulated (sim) heterotrophic respiration (HR) of the Dinghuashan old-growth broadleaf forest using the MEND model.

Task 5. Deliverable Status

Deliverable	Date
Complete temperate grassland v forest, short-term, long-term isotope study (revised, delayed)	10/16
Incorporate soil moisture effects into MEND model (note, this is complete) and test against field scale experimental data (revised, moved up)	12/16
Model temperate grassland v forest short-term, long-term isotope study (added)	12/17
Complete the proposed C:N ratio experiments	5/18
Incorporate flexible C:N ratio into MEND (completed) and test against experimental data	9/18

Publications/Manuscripts

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

Wang G, Mayes MA, Gu L, Schadt CW (2014) Representation of dormant and active microbial dynamics for ecosystem modeling. *PLOS ONE* 9:e89252.

Li J, Wang G, Allison SD, Mayes MA, Luo Y (2014) Soil carbon sensitivity to temperature, carbon use efficiency, and model complexity in two microbial-ecosystem models. *Biogeochemistry* doi:10.1007/s10533-013-9948-8.

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

During the current performance period (from Feb 2015 to the present), the research supported by Task 6 has resulted in 15 published papers in national and international scientific journals, two manuscripts under review, two invited oral presentations, and one dataset with assigned, citable DOI. Some of the key findings include the following:

- Using decade-long continuous observations of tree mortality and predawn leaf water potential at the Missouri Ozark AmeriFlux (MOFLUX) site, we studied how the mortality of important tree species varied and how such variations may be predicted. Water stress determined interannual variations in tree mortality with a time delay of 1 year or more, which was correlated fairly tightly with a number of quantitative predictors formulated based on predawn leaf water potential and precipitation regimes. Predictors based on temperature and vapor pressure deficit anomalies worked reasonably well, particularly for moderate droughts. The exceptional drought of the year 2012 drastically increased the mortality of all species, including drought-tolerant oaks, in the subsequent year. The drought-influenced tree mortality was related to the species position along the spectrum of leaf water potential regulation capacity with those in either ends of the spectrum being associated with elevated risk of death. Regardless of species and drought intensity, the predawn leaf water potential of all species recovered rapidly after sufficiently intense rain events in all droughts. This result, together with a lack of immediate leaf and branch desiccation, suggests an absence of catastrophic hydraulic disconnection in the xylem and that tree death was caused by significant but indirect effects. Species differences in the capacity of regulating leaf water potential and its temporal integral were magnified under moderate drought intensities but diminished towards wet and dry extremes. Severe droughts may overwhelm the capacity of even drought-tolerant species to maintain differential levels of water potential as the soil becomes exhausted of available water in the rooting zone, thus rendering them more susceptible to death if predisposed by other factors such as age. Long-term datasets of tree mortality and predawn leaf water potential are rarely. This study improves understanding tree mortality mechanisms and points to new directions for mortality research. It also identifies new ways to predicting tree death.

- Variations in precipitation regimes can shift ecosystem structure and function by altering frequency, severity and timing of plant water stress. There is a need for predictively understanding impacts of precipitation regimes on plant water stress in relation to species water use strategies. Here we first formulated two complementary, physiologically-linked measures of precipitation variability (PV) - Precipitation Variability Index (PVI) and Average Recurrence Interval of Effective Precipitation (ARIEP). We then used nine-year continuous measurements of Predawn Leaf Water Potential Integral (PLWPI) in a central US forest to relate PVI and ARIEP to actual plant water availability and comparative water stress responses of six species with different capacities to regulate their internal water status. We found that PVI and ARIEP explained nearly all inter-annual variations in PLWPI for all species as well as for the community scaled from species measurements. The six species investigated showed differential sensitivities to variations in precipitation regimes. Their sensitivities were reflected more in the responses to PVI and ARIEP than to the mean precipitation rate. Further, they exhibited tradeoffs between responses to low and high PV. Finally, PVI and ARIEP were closely correlated with temporal integrals of positive temperature anomalies and vapor pressure deficit. We suggest that the comparative responses of plant species to PV are part of species-specific water use strategies in a plant community facing the uncertainty of fluctuating precipitation regimes. PVI and ARIEP should be adopted as key indices to quantify physiological drought and the ecological impacts of precipitation regimes in a changing climate. Our study establishes a simple approach to quantifying physiological drought and the ecological impacts of precipitation regimes in a changing climate.

- Although drought events have limited duration, their impact on ecosystem structure and functioning can persist long after the events have gong. Due to a lack of long-term observations, it is not clear at present how ecosystem phenology is affected by the legacy of drought. The unique datasets obtained at the Missouri Ozark AmeriFlux (MOFLUX) site offer an opportunity to address this question. Since the establishment of the MOFLUX site in 2004, a wide range of precipitation regimes from abundant rain to extreme drought occurred at the MOFLUX site, resulting in large inter-annual fluctuations in plant water stress levels. In particular, several drought events with varying drought intensity occurred during the study period. The 2012 drought was the strongest category D4 (Exceptional Drought), according to the US Drought Monitor Classification Scheme and offered a contrast to earlier, less severe droughts. In this study, we used a suite of indices to characterize how MOFLUX forest functional phenology was affected by droughts with different severities. These indices included spring photosynthesis development velocity, fall photosynthesis recession velocity, growing season initiation day, growing season termination day, center day of the growing season, length of the growing season, effective length of the growing season, effective daily maximum canopy photosynthetic rate, and seasonal carbon dioxide assimilation potential index. We showed that legacy effects on these indices can still be detected years after a drought.

- Testing complex land surface models has often proceeded by asking the question: does the model prediction agree with the observation? Such an approach has yet led to high-performance terrestrial models that meet the challenges of climate and ecological studies. Here we test the Community Land Model (CLM) by asking the question: does the model behave like an ecosystem? We pursue its answer by testing CLM in the ecosystem functional space (EFS) at the Missouri Ozark AmeriFlux (MOFLUX) forest site in the central USA, focusing on carbon and water flux responses to precipitation regimes and associated stresses. In the observed EFS, precipitation regimes and associated water and heat stresses controlled seasonal and interannual variations of net ecosystem exchange (NEE) of CO_2 and evapotranspiration in this deciduous forest ecosystem. Such controls were exerted more strongly by precipitation variability than by the total precipitation amount per se. A few simply constructed climate variability indices captured these controls, suggesting a high degree of potential predictability. While the interannual fluctuation in NEE was large, a net carbon sink was maintained even during an extreme drought year. Although CLM predicted seasonal and interannual variations in evapotranspiration reasonably well, its predictions of net carbon uptake were too small across the observed range of climate variability. Also, the model systematically underestimated the sensitivities of NEE and evapotranspiration to climate variability and overestimated the coupling strength between carbon and water fluxes. We suspect that the modeled and observed trajectories of ecosystem fluxes did not overlap in the EFS and the model did not behave like the ecosystem it attempted to simulate. A definitive conclusion will require comprehensive parameter and structural sensitivity tests in a rigorous mathematical framework. We suggest that future model improvements should focus on better representation and parameterization of process responses to environmental stresses and on more complete and robust representations of carbon-specific processes so that adequate responses to climate variability and a proper degree of coupling between carbon and water exchanges are captured.

- Ongoing analysis of soil respiration and water relations showed that water, rather than temperature, is the dominant control of interannual variability in soil respiration.

- We are developing a solar-induced fluorescence (SIF) measurement system that is suitable for long-term, unattended installation at the MOFLUX site. The system is based on QEPro from Ocean Optics. It is controlled by a datalogger and can be easily integrated with the existing eddy covariance flux measurement system. The development of needed software has now been completed and is undergoing rigorous testing. The developed software is essentially a driver for QEPro (the original driver from the Ocean Optics is designed for lab use and difficult to be used as part of an integrated measurement system such as those at AmeriFlux sites). The design of the hardware system and its components has also been completed. We plan to test the whole hardware/software system at the MOFLUX site in August. Based on results of the SIF system tests, we plan to build another system for testing and potential future deployment within the SPRUCE treatment chambers. Such a unit would provide scaleable data on GPP and stress responses useful to modeling efforts.

Task 6. Deliverable status

Date	Deliverable	Status
FY2015	Complete and test the isoprene-modeling module for FAPIS. Conduct initial observational and modeling analyses on the correlation between CO_2 fluxes and isoprene emissions.	Completed
FY2015	1. Complete and submit the manuscript ‘The impacts of precipitation variability on species and community water stress in a central US forest’ 2. Complete and submit the manuscript ‘The impacts of precipitation variability and drought on ecosystem carbon uptake and water use in a central US forest’	Papers published
FY2016	Complete and submit the manuscript ‘The impacts of precipitation variability and drought on tree species and community mortality in a central US forest’	Published
March 2016	Submit 2015 MOFLUX data to AmeriFlux “Due to PI changes at University of Missouri, this work is in progress but is	In progress, expected by

	expected to complete by August 1"	August 1
FY 2016	Once the USFS completes the installation of the planned tower at the Bog Lake Fen Site in the Marcell Experimental Forest, we will instrument the eddy flux observation system for methane, carbon dioxide, sensible heat and latent heat. "Integration of this site with SPRUCE is in progress"	EC system installed.
August 2016	Test Installation of MOFLUX Solar Induced Fluorescence Measurement System	In progress
December 2016	Complete and submit the manuscript 'The impacts of precipitation variability and drought on leaf area display in a central US forest'	In progress
May 2017	Submit 2016 MOFLUX data to AmeriFlux	In progress
August 2017	MOFLUX SIF system operational	In progress

Publications/Manuscripts

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.

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

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.

Gu L, Pallardy SG, Hosman KP, Y Sun (2016) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. *Agricultural and Forest Meteorology* 217:120-136.

Gu L, Pallardy SG, Yang B, Hosman KP, Mao J, Ricciuto D, Shi X, Sun Y (2016) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a central USA forest. *Journal of Geophysical Research - Biogeosceinces* (In review).

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* doi:10.1002/2015JG00313

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.

Liu S, Zhuang Q, Chen M, Gu L (2015) Quantifying spatially explicit CO2 fertilization effects on global terrestrial ecosystem carbon dynamics. *Environmental Research Letters* (accepted).

Liu S, Zhuang Q, Chen J, Gu L, Noormets A (2016) Evaluating atmospheric CO2 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.

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.

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, et al. (2015) Biotic and climatic controls on interannual variability in carbon fluxes across terrestrial ecosystems. *Agricultural and Forest Meteorology* 205, 11-22.

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* (in press), *doi*:10.1002/2015JG003150

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* DOI: 10.1111/pce.12569.
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.
Wu X, Ju W, Zhou Y, He M, Law B, Black T, Margolis H, Cescatti A, Gu L, Montagnani L, et al. (2015) Performance of Linear and Nonlinear Two-Leaf Light Use Efficiency Models at Different Temporal Scales. *Remote Sensing* 7:2238-2278.
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 13C enrichment in heterotrophic organs relative to leaves in a landscape-building desert plant species. *Biogeosciences* 12:15-27.
Zhang JX, Gu LH, Zhang JB, Wu RN, Wang F, Lin GH, Wu B, Lu Q, Meng P (2016) The interaction between nitrogen and phosphorous is a strong predictor of intra-plant variation in nitrogen isotope composition in a desert species. *Biogeosciences* (In review).

Data Sets

In addition to the annual posting of MOFLUX site data to the AmeriFlux network data bases, a physiological data set was generated (Pallardy et al. 2015).

Task 7: Fossil emissions

The last ~16 months since our last report has seen continuing efforts within Task 7 toward maintaining and improving a publicly available data base on carbon dioxide emissions from fossil fuel consumption, examining and confronting the uncertainty in emissions estimates, and utilizing the carbon dioxide emissions database in terrestrial carbon budgets. Recent efforts include annual and monthly emissions data by country through 2013 which are available freely online; significant strides in characterizing the uncertainty associated with carbon dioxide emissions from fossil fuel consumption; and continuing efforts at more closely tying the fossil fuel data products to terrestrial biosphere understanding. A peer-reviewed manuscript describing the uncertainty with the gridded emissions product is in review with Atmospheric Chemistry and Physics (Fig. 26). A peer-reviewed manuscript updating estimates of Chinese emissions was published in Nature. Andres continues to play a prominent role in Global Carbon Project activities, including the Global Carbon Atlas (http://www.globalcarbonatlas.org). Andres is also contributing to the Carbon Model Intercomparison Project (CMIP6) activities which are underway. King is strengthening the link between fossil-fuel and other TES-SFA activities (SPRUCE modeling and experiments) through improved representation of ^{13}C in the SFA's CLM-SPRUCE model utilizing the SFA's functional unit testing framework.

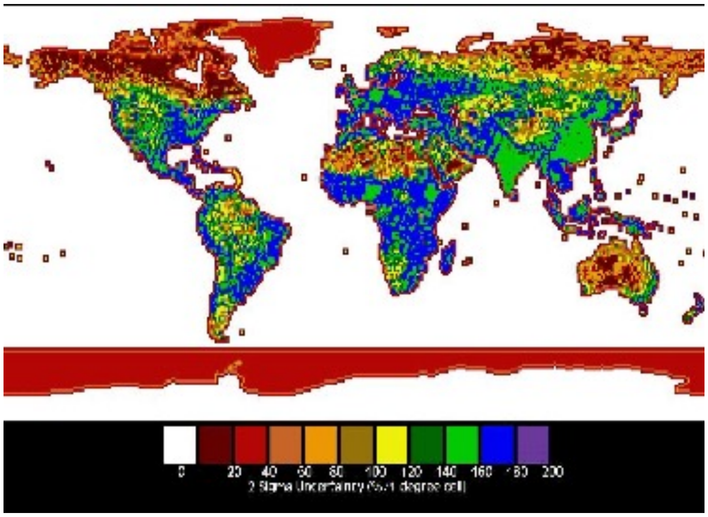

Fig. 26. The 2 sigma uncertainty expressed in percentage terms on a one-degree latitude by one degree longitude grid for fossil fuel carbon dioxide emissions. The population proxy used for within country emissions distribution is the largest contributor of the overall uncertainty. Other uncertainty components include the underlying geography map and the ungridded national emission estimates. Graphic from Andres et al. (2016, in review).

Activity directed toward the deliverables listed in the 27 February 2015 Description of Future Plans report is summarized in the following table.

Task 7. Deliverable status

Date	Deliverable	Status
FY 2016-18	Create monthly emission inventories at the scale of states and months at a global scale	Emission years 2011 and 2013 completed. Year 2012 skipped as U.N. released data close in time to 2013.
FY 2016-18	Create annual and monthly distributions of emissions	Emission years 2011 and 2013 completed. Year 2012 skipped as U.N. released data close in time to 2013.
FY 2016	Explore and publish uncertainty estimates associated with annual emissions	Annual completed with Tellus publication. Gridded undergoing peer-review now.
FY 2016-18	Create closer fossil fuel-terrestrial biosphere ties	Ongoing.

For items 1 and 2, data are made freely available to the public by CDIAC. Item 3 publications are open access and freely available. Item 4 is currently focused on better integrating stable carbon isotopic signatures of fossil fuel emissions and plant photosynthesis processes and resulting photosynthate directed toward investigation of fossil-fuel ^{13}C as a tracer of global terrestrial biosphere activity. Peer-reviewed publications on these four items are expected to continue.

For FY2017, we expect changes to the Task 7 plans, in part sparked by the announcement that Robert Andres will be leaving ORNL and he no longer will be directly involved in SFA activities. Discussions between DOE HQ and ORNL staff have led to a future division of responsibilities between SFA funding and other DOE funding where operational aspects of the fossil fuel work (items 1 and 2 above) will be conducted by other DOE funding and application aspects of the fossil fuel work, including analysis and understanding of the implications of fossil-fuel emissions for terrestrial ecosystems and the terrestrial biosphere (item 4 and application of item 3 above), will be conducted by SFA funding and led by Tony King at ORNL. The refocused subtasks are:

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

1. A synthesis of the implications of uncertainty in the global terrestrial biosphere flux estimated by closure of the global carbon budget for terrestrial biosphere research, modeling and observation.
2. Application of uncertainty methods developed within the TES-SFA to estimating uncertainty in total global and spatially distributed fossil fuel emissions. This item is something of a continuation of the current Item 3 in TES-SFA Task 7, but explores the use of tools of uncertainty analysis developed as part of the TES-SFA for terrestrial ecosystem application in estimating uncertainty in fossil fuel emissions.

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

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

Publications/Manuscripts

Andres RJ, Boden TA, Higdon DM (2016) Gridded uncertainty in fossil fuel carbon dioxide emission maps, a CDIAC example. *Atmospheric Chemistry and Physics* doi:10.5194/acp-2016-258. (in review).

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 Syst. Sci. Data* 7: 349-396. doi:10.5194/essd-7-349-2015.

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.

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.

Data Sets

Fifteen new data sets for fossil fuel task analyses have been generated (Appendix B).

Task 8: LeafWeb

LeafWeb is an internet service tool provided by ORNL TES SFA to global photosynthesis research community for analyzing and collecting photosynthetic data. It is free and automated. We have migrated LeafWeb from www.leafweb.ornl.gov to www.leafweb.org. The new LeafWeb has greatly expanded the services provided by the old LeafWeb. It can now analyze:

- CO_2 response curves (i.e., A/C_i curves, the only type of curves analyzed by the old LeafWeb),
- Light response curves,
- Temperature response curves,
- Pulse Amplitude Modulated (PAM) fluorescence measurements, and
- any combination of the curves listed above.

Users from different countries have started to use www.leafweb.org although the interface is still undergoing improvement.

LeafWeb employs an innovative approach to gathering scattered but globally important dark datasets. Dark data are any data of value to society but not easily found or readily used by potential users. Dark data are typically those gathered by individual scientists in small independent projects, in contrast to visible data collected, in general, by large coordinated teams in organized projects with well-executed data management and sharing plans. Analogous to dark matter vs. visible matter in the universe, dark data may be more voluminous than visible data as majority of the scientists of the world work in small independent projects. Dark data can be easily lost to science. The scientific community has a collective responsibility to curb this wasteful loss of valuable research resources. We believe this responsibility can be carried out without adding an undue administrative burden to data contributors if an innovative information system implementing the Services in Exchange for Data Sharing (SEEDS) principle is available. LeafWeb demonstrates how this principle can be implemented. We introduced the SEEDS principle and LeafWeb in an invited presentation in the 2015 AGU Fall Meeting.

TES SFA Data Systems, Management, and Archiving Update

The open sharing of all data and results from SFA research and modeling tasks among researchers, the broader scientific community, and the public is critical to advancing the mission of DOE's Program of Terrestrial Ecosystem Science. Active data sharing facilitates delivery of SFA products to all of 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, access to web-based tools, links to external products (e.g., microbial metagenomes), and value-added products (http://tes-sfa.ornl.gov) enable these interactions.

The SPRUCE experiment is a key component of the SFA. SPRUCE has implemented an experimental platform for the long-term testing of the mechanisms controlling the vulnerability of organisms, ecosystems, and ecosystem functions to increases in temperature and exposure to elevated CO2 treatments within the northern peatland high-carbon ecosystem. All data collected at the SPRUCE facility, all results of analyses or synthesis of information, and all model algorithms and codes developed in support of SPRUCE will be submitted to the SPRUCE Data Archive in a timely manner such that data will be available for use by SPRUCE researchers and, following publication, the public via the recently updated SPRUCE website (http://mnspruce.ornl.gov).

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

In addition, ongoing SFA task data products continue to be archived at program-specific archives: new and updated Fossil Emissions at Carbon Dioxide Information Analysis Center (CDIAC); MOFLUX at AmeriFlux; and North American Carbon Program (NACP) data synthesis products at the ORNL Distributed Active Archive Center (ORNL DAAC). New SFA task data products are publically available on the ORNL TES-SFA web site: http://tes-sfa.ornl.gov.

Affiliated TES SFA Supported Publications

Staff supported by the TES SFA continue to collaborate and complete work funded by US DOE BER in prior fiscal years that may not explicitly be funded under Tasks 1 through 8. The following listing shows additional manuscripts completed since the February 2015 with limited TES SFA support.

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

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

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* doi: 10.1093/treephys/tpw031.

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.

McDowell N, **Hanson PJ**, Ibanez I, Phillips RP, Ryan MG (2016) Physiological Responses of Forests to Drought. pp. 49-58. In Vose JM, Clark JS, Luce CH, Patel-Weynand T eds. *Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis.* Gen. Tech. Rep. WO-93b. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office.

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

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.

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

4AII. SCIENCE HIGHLIGHTS SINCE FEBRUARY 2015

- ORNL TES SFA staff completed 73 articles and 2 book/proceedings chapters since February of 2015.
- TES SFA scientists initiated SPRUCE whole ecosystem warming (WEW) treatments in August 2015 and they have been operating essentially continuously ever since.
- Elevated CO_2 treatments on half of the SPRUCE WEW plots were initiated on 15 June 2016, and are being maintained during daylight hours for an extended growing season (essentially April through November).
- A major paper summarizing responses to DPH has been accepted for revision by *Nature Communications* (Wilson et al. 2016).
- Pretreatment analysis and characterization papers for SPRUCE continue to be produced and published (Jensen et al. 2015, Griffiths and Sebestyen 2016, Hanson et al.2016, McFarlane et al. 2016).
- Xu et al. (2016) published a major review on methane modeling through the years that should become a standard reference.
- For Walker Branch Watershed research the historical precipitation, climate, stream discharge, and stream chemistry datasets were finalized, and DOIs were assigned. One study on temperature effects on decomposition was published, and two on stream biogeochemistry are in review.
- We completed coordinated SPRUCE vegetation physiology and phenology measurement campaigns indicate warming treatments are inducing significant shifts in net plant C uptake, thermal and water stress, and timing of bud break, flowering and senescence.
- Initiation of the SPRUCE-MIP activity. 11 modeling groups have agreed to participate, model input data sets have been created and pre-treatment datasets are being assembled for initial intercomparisons.
- Colleen Iversen has initiated the Fine Root Ecology Database (FRED)
- Warren et al. (2015) published a Tansley review on the incorporation of root structure and function in models that is already noted as an ISI Web of Science highly cited paper.
- The MOFLUX effort funded under Task 6 resulted in 17 publications during this reporting period. Notable are the publications that characterize drought responses for this forest to prairie transition region (Gu et al. 2015 & 2016).
- The Gu et al (2016) article describes an ecosystem approach to evaluate model performance in ecosystem functional space (EFS). When applied to CLM predicted seasonal and interannual variations in evapotranspiration were found to be represented reasonably well, however, its predictions of net carbon uptake were too small across the observed range of climate variability. We suggest that future model improvements should focus on better representation and parameterization of process responses to environmental stresses and on more complete and robust representations of carbon-specific processes so that adequate responses to climate variability and a proper degree of coupling between carbon and water exchanges are captured.

4AIII. ANALYSIS OF PUBLICATIONS

Through senior and coauthored effort, TES SFA staff produced 75 publications or completed manuscripts since our last summary report. This total includes 65 published/in press/accepted journal articles, 2 technical reports, and 8 completed manuscripts that are working through the review process. This level of productivity over 1.33 years is 56 per year; a 33% increase over the average paper production rate from January 2012 through February 2015 (42 per year). A TES SFA cumulative publication summary is provided in Appendix A with the most recent publications from the current reporting period listed first. This listing duplicates the Task-specific summaries already provided.

The TES SFA group published in 42 different peer-reviewed. Publications in this reporting period include one paper in *Nature* (Liu et al. 2015) and several others in the *Nature* "family" of journals (*Nature Climate Change* x3; *Nature Communications* x1). Other journals with 3 or more TES SFA papers in the current reporting period include: *Biogeosciences* (x9), *Journal of Geophysical Research – Biogeosciences* (x6), Global Change Biology (x5), *Agricultural and Forest Meteorology* (x5), *New Phytologist* (x4) and *Biogeochemistry* (x3).

Journal selection for publication of TES SFA work is at the discretion of the senior author. Journals are typically selected to achieve maximum exposure of the research results for the science community. We focus on journals having high impact factors, but that is not necessarily the primary criteria for the selection of a journal for publication of a given research result. High-profile journals (e.g., *Science*, *Nature*, *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

Because we have just transitioned funding from the allocation effort (Task 4a) into two new efforts looking at root traits (Tasks 4b) and function (Task 4c), we are not anticipating near term redirection of process-level research beyond the plans described in the 2015 TES SFA renewal. As a part of the 2015 renewal we are, however, working towards extending eddy covariance efforts under Task 6 to include similar measurements at the S1-Bog. These observations will help us translate mechanistic work within the manipulations to landscape and regional areas, and ultimately help test models of temperate peatland function in a global context.

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

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

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

4C. NEW SCIENCE FOCUS AND IDENTIFIED KNOWLEDGE GAPS

Early results from the SPRUCE study have suggested that further investment in the biogeochemical cycling of phosphorus and the biological fixation of N_2 may be needed to adequately capture long-term nutrient feedbacks within the bog with warming. Models will be used to evaluate the potential feedback magnitudes from P limitations and N2 fixation inputs to better define the need for future measurements.

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

In addition to changes in the vegetation phenology, we have seen that the treatments are substantial enough to exacerbate impacts of extreme cold or heat waves on foliar function. Observations of foliar damage and loss indicate we achieved our initial goal to push the ecosystem over a tipping point, and allows identification of thermal thresholds as needed for the modeling effort. Differential vegetative responses to both the thermal events and the large increases in VPD suggest a need to intensify our MODEX effort and consider novel model components or applications to improve process representation.

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

4D. COLLABORATIVE RESEARCH

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

- Dr. Joel Kostka, Jeff Chanton and colleagues have received new support from DOE BER for a second 3-year to study microbial ecology within SPRUCE.
- Drs. Scott Bridgham and Jason Keller and colleagues are supported to conduct a DOE BER funded study of mechanisms underlying heterotrophic CO_2 and CH_4 fluxes in a peatland.
- Drs. Kirsten Hofmockel and Eric Hobbie are supported by DOE BER to address the question – Can microbial ecology inform ecosystem level C-N cycling response to climate change?
- Drs. Brandy Toner, Ed Nater and colleagues from the University of Minnesota, are conducting the Mercury and Sulfur Dynamics in the SPRUCE experiment using funding provided through the USDA Forest Service.
- Dr. Andrew Richardson has DOE BER funds for the acquisition and installation of phenology cameras at the SPRUCE site. Our electrical infrastructure and data transmission capabilities will facilitate this work once the experimental structures have been installed.
- Dr. Bruce McCune (Oregon State University) and Sarah Jovan (USDA Forest Service) have their own support to study lichen responses to warming and elevated CO_2 within the SPRUCE experimental infrastructure.
- Dr. Adrian Finzi obtained DOE BER support to add high temporal resolution measures of CO_2 and CH_4 flux from the experimental plots that will include ^{13}C isotopic capabilities.
- Dr. Karis McFarlane, Tom Guilderson, Jennifer Pett-Ridge and colleagues have obtained LLNL-CAMS internal laboratory directed funds to work with SPRUCE to characterize the ^{14}C isotopic composition of gases emanating from the S1-Bog surface. Such data will help interpret the relative balance between old and new C sources impacted by the SPRUCE warming and CO_2 treatments.
- The carbon cycle modeling team continues to participate in several model intercomparison studies, which provide valuable insight and standardized datasets used for SFA model development tasks. These projects enhance the visibility of TES SFA research and have resulted in numerous publications. TES SFA funds are being used to set up and perform the simulations. Projects include the NACP interim synthesis (Task 3a), NASA- funded MsTMIP (Task 3b), and PalEON (Task 3b)
- Dr. Nancy Glenn is now contracted through SPRUCE to provide ground-level LIDAR observations as a supplement to our destructive woody harvests and sphagnum production estimates.

- Dr. Yiqi Luo's group is attempting to utilize new high-temporal-resolution, model-data iterative analyses to better define measured ecosystem responses with the intention of helping the research group apply measurement efforts to critical processes.
- Dr. Xiaofeng Xu continues work with the modeling group on improved biogeochemical cycling models for methane flux.
- Dr. Danielle Way (University of Western Ontario) is an unfunded collaborator who has been providing expertise and two PhD students to assist with seasonal assessment of *Picea* and *Larix* photosynthetic and respiratory thermal and CO_2 acclimation.

CITED REFERENCES

BERAC (2010) *Grand Challenges for Biological and Environmental Research: A Long-Term Vision; A Report from the Biological and Environmental Research Advisory Committee March 2010 Workshop*, DOE/SC-0135, BERAC Steering Committee on Grand Research Challenges for Biological and Environmental Research (www.science.doe.gov/ober/berac/BER_LTVreport.pdf)

US DOE (2012) *Biological and Environmental Research Climate and Environmental Sciences Division Strategic Plan*, U.S. Department of Energy, Office of Science, July 2012, DOE/SC-0151, http://science.energy.gov/~/media/ber/pdf/CESD-StratPlan-2012.pdf.

5. STAFFING AND BUDGET SUMMARY

5A. FY2016 FUNDING ALLOCATION BY PROGRAM ELEMENT

FY2016 spending is summarized in the following table. The listed amounts represent costs and commitments incurred through 23 June 2016. Total expected available funding for ORNL's TES SFA includes $1,214K carryover from FY2015 and $8,255K of new budget authorization. As of 23 June 2016 we have not yet received $922K of the expected annual allocation.

FY2016 Budget expenditures by TES SFA Program Element through June 23, 2016.

Task	Cost Through June 23, 2016 ($K)	Commitments Through June 23, 2016 ($K)	Remaining Funds June 23, 2016 ($K)	**Expected Additional Allocation ($K)**
T1: SPRUCE Science	2,140	228	641	248
T3: Carbon Cycle Modeling	904	131	252	95
T6: MOFLUX	214	101	365	50
T4b: Process Study - Root traits	88	68	93	18
T4c: Process Study - Root Func.	17	0	144	12
T5: Soil C Studies	196	14	154	0*
T7: C Emissions	71	0	113	14
T8: LeafWeb	13	15	105	9
T1: SPRUCE – Operations	720	664	404	246
T1: SPRUCE – Materials	208	73	7	23
T1: SPRUCE – Reserve	9	5	184	159
ORNL Reserves	24	0	217	13
SFA Totals	**$4,604**	**$1,299**	**$2,679**	**$887**

- FY2016 funds are already fully allocated.

We are currently spending at rates consistent with the spending plans outlined in the February 2015 TES SFA renewal proposal budgets for FY2016. We anticipate unspent carry over funds to be less than $1000K.

Small amounts of new budget authorization provide to the TES SFA for closely related activities are managed as independent efforts and not included in this analysis ($85K as of 23 June 2016).

5B. FUNDING ALLOCATION TO EXTERNAL COLLABORATORS

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

The University of Missouri ($121K) 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 1 June 2016, Dr. Jeff Wood assumed the role of the University of Missouri on-site investigator for ORNL.

Yiqi Luo- The University of Oklahoma ($75K) – Dr. Luo and postdoc Jiang Jiang at OU are 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 manuscript is in preparation. This subcontract is planned to continue in FY17, developing a cyberinfrastructure for real-time data ingestion capabilities and extending the work to CLM and ALM modeling efforts.

Xiaofeng Xu - San Diego State University ($38K) - In a joint subcontract with NGEE-Arctic, Dr. Xu is developing and testing a CH_4 modeling capability for the CLM and ALM SPRUCE modeling efforts. This work has contributed to two manuscripts. Work to refine and optimize the model with SPRUCE observations is planned to continue in FY17.

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

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

John Latimer ($48K) – We have subcontracted John part-time through Excel Engineering since 2014 to collect weekly minirhizotron images from the SPRUCE experimental plots, and to collect and exchange ion-exchange resin capsules every 28 days from the SPRUCE experimental plots. John also hosts a weekly phenology show on the local NPR station in Grand Rapids, MN (http://www.kaxe.org/programs/phenology.aspx) and has been assisting with phenological observations in the SPRUCE experimental plots.

M. Luke McCormack ($50K) – We have subcontracted Luke beginning in May 2016 to analyze global patterns in root traits compiled in the Fine-Root Ecology Database (*FRED*) and develop a manuscript on this topic. In addition, Dr. McCormack will work with an interdisciplinary team of empiricists, modelers, and database managers to improve the conceptual representation of root traits and their associated functions in terrestrial biosphere models.

A. Shafer Powell ($25K) – We have contracted Shafer as a post-Bachelor intern to add data from published literature to *FRED*, to maintain and quality-assure the *FRED* database, and to maintain the associated data dictionary and user guidance document.

RhizoSystems, LLC ($30K) – 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.

Keith Oleheiser **($53K) -** The hydrology and porewater chemistry task greatly benefited from the subcontract for ORAU post-BS 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.

Northern Lights Land Surveying **($5K)** was subcontracted to perform a site survey and provide horizontal and vertical coordinates for selected locations. Survey points included central wells, elevation standards, central towers, 0 m piezometers, wood planks attached to the belowground corral, and 8 points around the octagonal boardwalks. Additional survey points included the EM1, EM2, and EM3 wells, the Forest Service bog well, and the Test 6 piezometer. These data have multiple uses, including setting the outflow drainage heights, determining the average hollow elevation in each enclosure, and expressing water table data as meters above sea level. The survey dataset and data guide were made available to the public on the SPRUCE website.

Infrastructure subcontracts in support of the SPRUCE project in FY2016 include funds and funding for site maintenance ***(Pokegama Electric $77K)***, electrical service ***(Lake Country Power $150K)***, propane supply ***(Lakes Gas Co. $200K)***, elevated CO_2 supply ***(PRAXAIR Inc. $200K)***, satellite internet connections ***(Hughes Net & Viasat $10K)***, and leased space in Minnesota **($45K**). The amounts required for each of these operational contracts will be reevaluated annually as actual usage rates and prices change.

5C. Personnel Actions and Procedures in FY2016

New Hires – Two new postdoctoral hires were made in FY2016. ***Avni Malhotra*** joined the TES SFA as a post-doc, beginning on August 8, 2016. She will be based at ORNL (supervised by Colleen Iversen), but will split her time in the field between the MOFLUX experimental site and the SPRUCE experimental site. Her main focus will be to link fine-root traits with ecosystem processes at each experimental site. ***Eric Ward*** joined the TES-SFA group as an ecophysiology post-doc, beginning May 31, 2016. He is based in Grand Rapids, MN, and will be contributing to SPRUCE ecophysiological measurements, including woody physiology and plant water relations tasks. ***David McLennan*** was hired on May 16, 2016 into the Laboratory Technology Program to support TES-SFA and related research, including plant ecophysiology and laboratory analyses such as non-structural carbohydrates. David's year-long post-BS internship program is designed to identify and evaluate potential new technicians.

Anticipated Future Hires – Looking ahead to FY2017, and as the budget allows, the TES SFA plans to pursue hiring an additional postdoctoral fellow to supplement full time staff positions in support of Carbon Cycle modeling, and another to replace Laurel Kluber as she completes her assignments at ORNL.

Retirements and Releases – No staff have retired or completed their postdoctoral appointment in FY2016, however, Kathy A. Huczko who provided technical project management expertise during the construction phases of the SPRUCE project has moved on to another position outside of ORNL. Her expertise is no longer needed for routine SPRUCE operations with Robert Nettles taking on those roles as a permanent ORNL staff member located in Grand Rapids, Minnesota.

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 FY2016

In past years, ORNL has demonstrated its commitment to climate and environmental change research through substantial investments in climate change modeling, the development of innovative large-scale experimental infrastructures through the Laboratory Directed Research and Development program (LDRD), the construction of a field support building (Building 1521), greenhouses, the Joint Institute for Biological Sciences, and renovations in support of molecular ecology. Concepts for the belowground warming technologies used for the SPRUCE Experiment (Task R1) were initiated with ORNL LDRD funds totaling $480K in FY2008 and FY2009, and current LDRD projects are leveraging the SPRUCE experiment to advance various fields of study. In FY2014, ORNL provided the equivalent of $1000K staff support from internal funds to allow completion of the SPRUCE warming aboveground infrastructure. No ORNL funds were requested or have been needed in FY2016.

The Climate Change Science Institute brings together all ORNL Climate Change staff including members of the TES SFA to foster day-to-day interactions among modelers, experimentalists and data management specialists.

The TES SFA is supported by world-class capabilities at ORNL. The National Leadership Computing Facility provides an open, unclassified resource that we will use to enable breakthrough discoveries in climate prediction. ORNL data centers (e.g., CDIAC and NASA Distributed Active Archive Center for Biogeochemical Dynamics (NASA-DAAC)) provide the infrastructure support for data and model integration, and information archival needs of the TES SFA.

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

5E. Capital Equipment

Capital equipment funds have previously been used to purchase open-path CO_2 and CH_4 monitoring systems for use and application in the SPRUCE experiment. Since that purchase the threshold amount of funds needed to define a capital expenditure has risen to the point that few other capital requests are anticipated. No ORNL TES SFA funds were used to acquire capital equipment in FY2016.

Significant funding for SPRUCE experimental infrastructure maintenance and future development at the S1-Bog are not classified as capital expenditures, but represent an analogous investment for the planned decadal duration of the long-term field experiment.

APPENDIX A: COMPLETE PUBLICATION LIST – ORNL TES SFA

Published, accepted and in review papers for the ORNL TES SFA since February 2015

1. Andres RJ, Boden TA, Higdon DM (2016) Gridded uncertainty in fossil fuel carbon dioxide emission maps, a CDIAC example. *Atmospheric Chemistry and Physics* doi:10.5194/acp-2016-258. (in review).
2. 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.
3. Brooks SC, Brandt CC, Griffiths NA (2016) Estimating uncertainty in ambient and saturation nutrient uptake metrics from nutrient pulse releases in stream ecosystems. In Revision at *Limnology and Oceanography: Methods* (being revised).
4. 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
5. 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.
6. 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
7. 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.
8. Griffiths NA, Sebestyen SD (2016) Temporal dynamics in the vertical profiles of peat porewater nutrients in a northern peatland. *Wetlands* (in review).
9. Griffiths NA, Tiegs SD (2016) Organic matter decomposition along a temperature gradient in a forested headwater stream. *Freshwater Science* 32:518-533.
10. 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.
11. 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.
12. Gu L, Pallardy SG, Hosman KP, Y Sun (2016) Impacts of precipitation variability on plant species and community water stress in a temperate deciduous forest in the central US. *Agricultural and Forest Meteorology* 217:120-136.
13. Gu L, Pallardy SG, Yang B, Hosman KP, Mao J, Ricciuto D, Shi X, Sun Y (2016) Testing a land model in ecosystem functional space via a comparison of observed and modeled ecosystem flux responses to precipitation regimes and associated stresses in a central USA forest. *Journal of Geophysical Research - Biogeosciences* (In review).
14. Hanson PJ, Riggs JS, Nettles WR, Phillips JR, Krassovski MB, Hook LA, Richardson AD, Ricciuto DM, Warren JM, Barbier C (2016) Achieving sustained whole-ecosystem warming for tall statured forest vegetation with constrained air and deep soil heating methods. G*lobal Change Biology* (submission pending one additional data set addition).
15. 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. *Biogeochemistry* (accepted pending major revisions).

16. He H, Wang D, Tan J (2016) Data Synthesis in the Community Land Model for Ecosystem Simulation. *Journal of Computational Science* doi:10.1016/j.jocs.2016.01.005
17. 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* 121, doi:10.1002/2015JG00313
18. Hill WR, Griffiths NA (2016) Nitrogen processing by grazers in a headwater stream: riparian connections. *Freshwater Biology* (being revised).
19. Hobbie EA, Hofmockel K, McFarlane KJ, Iversen CM, Hanson PJ, Thorp N, Chen J (2016) Long-term Carbon and Nitrogen Dynamics at SPRUCE Revealed through Stable Isotopes in Peat Profiles. *Biogeosciences* (in review).
20. 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.
21. 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.
22. Iversen CM, Childs J, Norby RJ, Ontl TA, Kolka RK, Brice DJ, McFarlane KJ, Hanson PJ. (2016) The distribution and dynamics of fine roots in a forested bog. *Plant and Soil* (submitted).
23. 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, http://dx.doi.org/10.3402/tellusb.v68.28968.
24. 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
25. 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* doi:10.1093/treephys/tpw031.
26. 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.
27. 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 CO2 exchange with the atmosphere 1990-2009. *Biogeosciences* 12:399-414.
28. 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.
29. 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
30. 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 CO2 experiment. *Geoscientific Instrumentation Methods and Data Systems* 4:203–213, doi:10.5194/gi-4-203-2015, Data doi: http://dx.doi.org/10.3334/CDIAC/spruce.013
31. 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.

32. Li J, Wang G, Allison SD, Mayes MA, Luo Y (2014) Soil carbon sensitivity to temperature, carbon use efficiency, and model complexity in two microbial-ecosystem models. *Biogeochemistry*. doi:10.1007/s10533-013-9948-8.
33. Liu S, Zhuang Q, Chen M, Gu L (2015) Quantifying spatially explicit CO2 fertilization effects on global terrestrial ecosystem carbon dynamics. *Environmental Research Letters* (accepted).
34. Liu S, Zhuang Q, Chen J, Gu L, Noormets A (2016) Evaluating atmospheric CO2 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.
35. 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.
36. 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* (accepted).
37. 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.
38. Mao J, Ricciuto DM, Thornton PE, Warren JM, King AW, Shi X, Iversen CM, Norby RJ (2016) Evaluating the Community Land Model in a pine stand with $^{13}CO_2$ and shading manipulations. *Biogeosciences* 13:641-657, doi:10.5194/bg-13-641-2016.
39. 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 (2016) Human-induced greening of the northern high-latitude land surface. *Nature Climate Change* (accepted)
40. 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.
41. 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.
42. McFarlane KJ, Iversen CM, Phillips JR, Brice DJ, Hanson PJ (2016) Temporal and spatial heterogeneity of carbon accumulation in an ombrotrophic bog in northern Minnesota over the Holocene. *The Holocene* (in review).
43. 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

44. 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
45. 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.
46. 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.
47. 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
48. 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.
49. 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 (2016), Uncertainty analysis of terrestrial net primary productivity and net biome productivity in China during 1901-2005. *Journal of Geophysical Research-Biogeosciences,* 121, doi:10.1002/2015JG003062.
50. Shaw AJ, Schmutz J, Devos N, Shu S, Carrell AA, Weston DJ (2016) The Sphagnum genome project a new model for ecological and evolutionary genomics. *Advances in Botanical Research* 78:167-187
51. 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.
52. 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
53. Sun Y, Piao S, Huang M, Ciais P, Zeng Z, Cheng L, Li X, Zhang X, Mao J, Peng S, Poulter B, Shi X, Wang X, Wang YP, Zeng H (2016) Global patterns and climate drivers of water-use efficiency in terrestrial ecosystems deduced from satellite-based datasets and carbon cycle models. *Global Ecology and Biogeography* 25:311-323, doi: 10.1111/geb.12411.
54. 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.
55. 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.
56. 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 CO2 enrichment: How and why do current ecosystem models differ? *Global Biogeochemical Cycles* 29:476-495.
57. Wang D, Janjusic T, Iversen C, Thornton PE, Krassovski M, Wu W, Xu Y (2015) 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*, 10.1109/SE4HPCS.2015.10.
58. Wang G, Jagadamma S, Mayes MA, Schadt C, Steinweg JM, Gu L, Post WM (2015) Microbial dormancy improves development and experimental validation of ecosystem model. *The ISME Journal* 9:226-237, doi:10.1038/ismej.2014.120.
59. Wang G, Mayes MA, Gu L, Schadt CW (2014) Representation of dormant and active microbial dynamics for ecosystem modeling. *PLOS ONE* 9:e89252.
60. Wang SS, Pan M, Mu QZ, Shi XY, Mao JF, Brummer C, Jassal RS, Krishnan P, Li JH, Black TA (2015) Comparing Evapotranspiration from Eddy Covariance Measurements, Water Budgets, Remote Sensing, and Land Surface Models over Canada. *Journal of Hydrometeorology* 16:1540-1560.
61. Warren JM, Hanson PJ, Iversen CM, Kumar J, Walker AP, Wullschleger SD (2015) Tansley Review - Incorporation of root structure and function in models – evaluation and recommendations. *New Phytologist* 205:59-78.
62. 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.
63. Weston, DJ, Timm CM, Walker AP, Gu L, Muchero W, Schmutz J, Shaw JA, Tuskan GA, Warren JM, Wullschleger SD (2014) *Sphagnum* physiology in the context of changing climate: emergent influences of genomics, modeling and host-microbiome interactions on understanding ecosystem function. *Plant Cell and Environment* 38:1737-1751, doi: 10.1111/pce.12458.
64. 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* (accepted pending revisions).
65. 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.
66. 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.
67. 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.
68. Wullschleger SD, Warren JM, Thornton PE (2015) Leaf respiration (GlobResp) – global trait database supports Earth System Models – Commentary. *New Phytologist* 206: 483-485.
69. Xu XF, Elias DA, Graham DE, Phelps TJ, Carroll SL, Wullschleger SD, Thornton PE (2015) 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.
70. Xu XF, Hui DF, King AW, Song X, Thornton PE, Zhang LH (2015) Convergence of microbial assimilations of soil carbon, nitrogen, phosphorus, and sulfur in terrestrial ecosystems. *Scientific Reports* 5:17445, doi:10.1038/srep17445
71. Xu X, Yuan F, Hanson PJ, Wullschleger SD, Thornton PE, Riley WJ, Song X, Graham DE, Song CC, Tian H (2016) Review and Synthesis: Four decades of modeling methane cycling within terrestrial ecosystems, *Biogeosciences* 13:3735-3755, doi:10.5194/bg-13-3735-2016.
72. 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, Meng P (2015) Nitrogen control of 13C enrichment in heterotrophic organs relative to leaves in a landscape-building desert plant species. *Biogeosciences* 12:15-27.

73. Zhang JX, Gu LH, Zhang JB, Wu RN, Wang F, Lin GH, Wu B, Lu Q, Meng P (2016) The interaction between nitrogen and phosphorous is a strong predictor of intra-plant variation in nitrogen isotope composition in a desert species. *Biogeosciences* (in review).
74. 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 (*accepted).
75. 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,* doi:10.1038/nclimate3004.

ORNL TES SFA Publications January 2012 through February 2015

1. Andres RJ, Boden TA, Bréon F-M, Ciais P, Davis S, Erickson D, Gregg JS, Jacobson A, Marland G, Miller J, Oda T, Olivier JGJ, Raupach MR, Rayner P, Treanton K (2012) A synthesis of carbon dioxide emissions from fossil fuel combustion. *Biogeosciences* 9:1845-1871, doi:10.5194/bg-9-1845-2012.
2. Andres RJ, Boden TA, Higdon D (2014) A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission. *Tellus B*. 66:23616, doi:10.3402/tellusb.v66.23616.
3. Bailey V, Hanson PJ, Jastrow J, Torn M, Stover D (2014) *Data-model needs for belowground ecology. A summary report from the Terrestrial Ecosystem Science (TES) Mini-Workshop,* http://science.energy.gov/~/media/ber/pdf/workshop%20reports/Belowground-Workshop-Report-Nov2014.pdf
4. Bandaru B, West TO, Ricciuto DM, Izaurralde C (2013) Estimating crop net primary production using inventory data and MODIS-derived parameters. *ISPRS Journal of Photogrammetry and Remote Sensing* 80:61-71, doi:10.1016/j.isprsjprs.2013.03.005.
5. Barbier C, Hanson PJ, Todd DE Jr, Belcher D, Jekabson EW, Thomas WK, Riggs JS (2012) Air Flow and Heat Transfer in a Temperature Controlled Open Top Enclosure, *ASME International Mechanical Engineering Congress and Exposition*, 2012, Houston, TX, Paper #IMECE2012-86352.
6. Barr AG, Richardson AD, Hollinger DY, Papale D, Arain MA, Black TA, Bohrer G, Dragoni D, Fischer M, Gu L, Law BE, Margolis HM, McCaughey JH, Munger J, Oechel W, Schaeffer K (2013) Use of change-point detection for friction-velocity threshold evaluation in eddy-covariance studies. *Agricultural and Forest Meteorology* 171:31-45, doi:10.1016/j.agrformet.2012.11.023.
7. Bauerle WL, Oren R, Way A, Qian SS, Stoy PC, Thornton PE, Bowden JD, Hoffman FM, Reynolds RF (2012) Photoperiodic regulation of the seasonal pattern of photosynthetic capacity and the implications for carbon cycling. *Proceedings of the National Academy of Sciences of the United States of America* 109(22):8612-8617, doi:10.1073/pnas.1119131109.
8. Blanco G, Gerlagh R, Suh S, Barrett J, de Coninck H, Felix Diaz Morejon C, Mathur R, Nakicenovic N, Ofosu Ahenkorah A, Pan J, Pathak H, Rice J, Richels R, Smith SJ, Stern D, Toth FL, Zhou P, Andres R, Baiocchi G, Hanemann M, Jakob M, Kolp P, la Rovere E, Michielsen T, Nansai K, Rogner M, Rose S, Santalla E, Wiedmann T, Wilson T, Ürge-Vorsatz D (2014) Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, [Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC (eds.)] Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Released online 17 Dec 2013.
9. Cheng CL, Kang M, Perfect E, Bilheux HZ, Horita J, Voisin S, Warren JM, Hussey D (2012) Average soil water retention curves measured by neutron radiography. *Soil Science Society of America Journal* 76:1184–1191, doi:10.2136/sssaj2011.0313.

10. Chinnasamy P and Hubbart JA (2014a) Stream and shallow groundwater nutrient concentrations in an Ozark forested riparian zone of the central USA. *Environmental Earth Sciences*, doi:10.1007/s12665-014-3880-7.
11. Chinnasamy P and Hubbart JA (2014b) Potential of MODFLOW to model hydrological interactions in a semikarst floodplain of the Ozark border forest in the central United States. *Earth Interactions* 18:1–24, doi: http://dx.doi.org/10.1175/EI-D-14-0015.1.
12. Chinnasamy P and Hubbart JA (2014c) Measuring and modeling shallow groundwater flow between a semi-karst border stream and Ozark forested riparian zone in the central USA. *Journal of Scientific Research and Reports* 3(6):844-865, doi:10.9734/JSRR/2014/7711#sthash.hc3dzq8i.dpuf.
13. Ciais P, Dolman AJ, Bombelli A, Duren R, Peregon A, Rayner PJ, Miller C, Gobron N, Kinderman G, Marland G, Gruber N, Chevallier F, Andres RJ, Balsamo G, Bopp L, Bréon F-M, Broquet G, Dargaville R, Battin TJ, Borges A, Bovensmann H, Buchwitz M, Butler J, Canadell JG, Cook RB, DeFries R, Engelen R, Gurney KR, Heinze C, Heimann M, Held A, Henry M, Law B, Luyssaert S, Miller J, Moriyama T, Moulin C, Myneni RB, Nussli C, Obersteiner M, Ojima D, Pan Y, Paris J-D, Piao SL, Poulter B, Plummer S, Quegan S, Raymond P, Reichstein M, Rivier L, Sabine C, Schimel D, Tarasova O, Valentini R, van der Werf G, Wickland D, Williams M, Zehner C (2014) Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system. *Biogeosciences* 11:3547-3602, doi:10.5194/bg-11-3547-2014.
14. De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze M C, Hickler T, Jain AK, Luo YQ, Parton WJ, Prentice IC, Smith B, Thornton P E, Wang SS, Wang YP, Wårlind D, Weng ES, Crous KY, Ellsworth DS, Hanson PJ, Seok Kim H, Warren JM, Oren R. Norby RJ (2013) Forest water use and water use efficiency at elevated CO2: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology* 19:1759-1779, doi:10.1111/gcb.12164.
15. De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze M, Wang Y-P, Luo Y, Jain AK, El-Masri B, Hickler T, Wårlind D, Weng E, Parton WJ, Thornton PE, Wang S, Prentice IC, Asao S, Smith B, McCarthy HR, Iversen CM, Hanson PJ, Warren JM, Oren R, Norby RJ (2014) Where does the carbon go? A model-data intercomparison of vegetation carbon allocation and turnover processes at two temperate forest free-air CO_2 enrichment sites. *New Phytologist* 203:883-899, doi:10.1111/nph.12847.
16. Dodds WK, Collins SM, Hamilton SK, Tank JL, Johnson S, Webster JR, Simon KS, Whiles MR, Rantala HM, McDowell WH, Peterson SD, Riis T, Crenshaw CL, Thomas SA, Kristensen PB, Cheever BM, Flecker AS, Griffiths NA, Crowl T, Rosi-Marshall EJ, El-Sabaawi R, Martí E (2014) You are not always what we think you eat: selective assimilation across multiple whole-stream isotopic tracer studies. *Ecology* 95:2757-2767. http://dx.doi.org/10.1890/13-2276.1
17. Dong X, Patton J, Gu L, Wang J, Patton B (2014) Leaf photosynthesis and plant competitive success in a mixed-grass prairie: With reference to exotic grasses invasion. *Journal of Ecosystem and Ecography* 4:9, doi: 10.4172/2157-7625.1000152.
18. Fisher JB, Sikka M, Oechel WC, Huntzinger DN, Melton JR, Koven CD, Ahlstrom A, Arain MA, Baker I, Chen JM, Ciais P, Davidson C, Dietze M, El-Masri B, Hayes D, Huntingford C, Jain AK, Levy PE, Lomas MR, Poulter B, Price D, Sahoo AK, Schaefer K, Tian H, Tomelleri E, Verbeeck H, Viovy N, Wania R, Zeng N, Miller CE (2014) Carbon cycle uncertainty in the Alaskan Arctic. *Biogeosciences* 11:4271-4288, doi: 10.5194/bg-11-4271-2014
19. Francey RJ, Trudinger CM, van der Schoot M, Law RM, Krummel PB, Langenfelds RL, Steele LP, CE Allison, AR Stavert, RJ Andres, C Rödenbeck (2013a) Atmospheric verification of anthropogenic CO_2 emission trends. *Nature Climate Change* 3:520-524, doi:10.1038/NCLIMATE1817.
20. Francey RJ, CM Trudinger, M van der Schoot, RM Law, PB Krummel, RL Langenfelds, LP Steele, Allison CE, Stavert AR, Andres RJ, Rödenbeck C (2013b) Reply to comment on atmospheric verification of anthropogenic CO_2 emission trends. *Nature Climate Change* 3:604, doi:10.1038/NCLIMATE1925.
21. Ganshin A, Oda T, Saito M, Maksyutov S, Valsala V, Andres RJ, Fischer RE, Lowry D, Lukyanov A, Matsueda H, Nisbet EG, Rigby M, Sawa Y, Toumi R, Tsuboi K, Varlagin A, Zhuravlev R (2012) A global coupled Eulerian-Lagrangian model and 1 × 1 km CO_2 surface flux dataset for high-resolution

atmospheric CO_2 transport simulations. *Geoscientific Model Development* 5:231-243, doi:10.5194/gmd-5-231-2012.
22. Griffiths NA, Hill WR (2014) Temporal variation in the importance of a dominant consumer to stream nutrient cycling. *Ecosystems* 17:1169-1185, doi: 10.1007/s10021-014-9785-1.
23. Gu LH (2013) An eddy covariance theory of using O_2 to CO_2 exchange ratio to constrain measurements of net ecosystem exchange of any gas species. *Agricultural and Forest Meteorology* 176:104-110, doi:10.1016/j.agrformet.2013.03.012.
24. 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.
25. Gu LH, Sun Y (2014) Artefactual responses of mesophyll conductance to CO_2 and irradiance estimated with the variable J and online isotope discrimination methods. *Plant Cell & Environment* 37:1231-1249, doi:10.1111/pce.12232.
26. Hayes DJ, Turner DP, Stinson G, McGuire AD, Wei YX, West TO, Heath LS, Dejong B, McConkey BG, Birdsey RA, Kurz WA, Jacobson AR, Huntzinger DN, Pan YD, Post WM, Cook RB (2012) Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data. *Global Change Biology* 18:1282-1299, doi:10.1111/j.1365-2486.2011.02627.x.
27. Hou ZS, Huang MY, Leung LR, Lin G, Ricciuto DM (2012) Sensitivity of surface flux simulations to hydrologic parameters based on an uncertainty quantification framework applied to the Community Land Model. *Journal of Geophysical Research-Atmospheres* 117: D15108, doi:10.1029/2012JD017521.
28. Huang N, Gu L, Niu Z (2014) Estimating soil respiration using spatial data products: A case study in a deciduous broadleaf forest in the Midwest USA. *Journal of Geophysical Research - Atmosphere* 119:6393-6408, doi:10.1002/2013JD020515.
29. Hudiburg TW, Luyssaert S, Thornton PE, Law BE (2013) Interactive effects of environmental change and management strategies on regional forest carbon emissions. *Environmental Science & Technology* 47:13132-13140, doi:10.1021/es402903u.
30. Huimin L, Huang M, Leung LR, Yang D, Shi X, Mao J, Hayes DJ, Schwalm CR, Wei Y, Liu S (2014) Impacts of hydrologic parameterizations on global terrestrial carbon cycle dynamics in the Community Land Model. *Journal of Advances in Modeling Earth Systems* (Accepted).
31. Huntzinger D N, Schwalm C, Michalak AM, Schaefer K, King AW, Wei Y, Jacobson A, Liu S, Cook RB, Post WM, Berthier G, Hayes D, Huang M, Ito A, Lei H, Lu C, Mao J, Peng CH, Peng S, Poulter B, Ricciuto D, Shi X, Tian H, Wang W, Zeng N, Zhao F, Zhu Q (2013) The North American Carbon Program Multi-Scale Synthesis and Terrestrial Model Intercomparison Project – Part 1: Overview and experimental design. *Geoscientific Model Development Discussion* 6:2121-2133, doi:10.5194/gmd-6-2121-2013.
32. Iversen CM (2014) Using root form to improve our understanding of root function. *New Phytologist* 203:707-709
33. Iversen CM, Murphy MT, Allen MF, Childs J, Eissenstat DM, Lilleskov EA, Sarjala TM, Sloan VL, Sullivan PF (2012) Advancing the use of minirhizotrons in wetlands. *Plant and Soil* 352:23–39, doi:10.1007/s11104-011-0953-1.
34. Iversen CM, Norby RJ (2014) Terrestrial plant productivity and carbon allocation in a changing climate. In *Handbook of Global Environmental Pollution: Global Environmental Change*, [Freedman B, ed.] New York, NY: Springer, pp. 297-316.
35. Jagadamma S, Mayes MA (2013a) The role of sorption on mineralization of carbon in soils. *JSM Environmental Science & Ecology* 1:1005.
36. Jagadamma S, Steinweg JM, Mayes MA, Wang G, Post WM (2013b) Mineral control on decomposition of added and native organic carbon in soils from diverse eco-regions. *Biology and Fertility of Soils* 49, doi:10.1007/s00374-013-0879-2.
37. Jagadamma S, Mayes MA, Steinweg JM, Wang G, Post WM (2014a) Organic carbon sorption and decomposition in selected global soils. Carbon Dioxide Information Analysis Center, Oak Ridge

National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A, doi:10.3334/CDIAC/ornlsfa.002
38. Jagadamma, S, Steinweg, M, and Mayes, MA (2014b) Substrate quality alters microbial mineralization of added substrate and soil organic carbon. *Biogeosciences* 11:4665-4678. doi:10.5194/bg-11-4665-2014.
39. Joiner J, Yoshida Y, Vasilkov AP, Schaefer K, Jung M, Guanter L, Zhang Y, Garrity S, Middleton EM, Huemmrich KF, Gu LH, Marchesini LB (2014) The seasonal cycle of satellite chlorophyll fluorescence observations and its relationship to vegetation phenology and ecosystem-atmosphere carbon exchange. *Remote Sensing of Environment* 152:375-391, doi:10.1016/j.rse.2014.06.022.
40. Kang M, Bilheux HZ, Voisin S, Cheng CL, Perfect E, Horita J, Warren JM (2013) Water calibration measurements for neutron radiography: application to water content quantification in porous media. *Nuclear Instruments and Methods in Physics Research* 708:24-31, doi:10.1016/j.nima.2012.12.112.
41. Kang M, Perfect E, Cheng CL, Bilheux HZ, Gragg M, Wright DM, Lamanna JM, Horita J, Warren JM (2013) Diffusivity and sorptivity of Berea sandstone determined using neutron radiography. *Vadose Zone Journal* 12, doi:10.2136/vzj2012.0135.
42. Kang M, Perfect E, Cheng CL, Bilheux HZ, Lee J, Horita J, Warren JM (2014) Multiple pixel-scale water retention curves quantified by neutron radiography. *Advances in Water Resources* 65:1-8, doi:10.1016/j.advwatres.2013.12.004.
43. Keppel-Aleks G, Wennberg PO, Washenfelder RA, Wunch D, Schneider T, Toon GC, Andres RJ, Blavier J-F, Connor B, Davis KJ, Desai AR, Messerschmidt J, Notholt J, Roehl CM, Sherlock V, Stephens BB, Vay SA, Wofsy SC (2012) The imprint of surface fluxes and transport on variations in total column carbon dioxide. *Biogeosciences* 9:875-891, doi:10.5194/bg-9-875-2012.
44. 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.
45. 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).
46. King AW, Hayes DJ, Huntzinger DN, West TO, Post WM (2012) North American carbon dioxide sources and sinks: magnitude, attribution, and uncertainty. *Frontiers in Ecology and the Environment* 10:512-519, doi:10.1890/120066.
47. Kominoski JS, Follstad Shah JJ, Canhoto C, Fischer DG, Gilling DP, González E, Griffiths NA, Larrañaga A, LeRoy CJ, Mineau MM, McElarney YR, Shirley SM, Swan CM, Tiegs SD (2013) Forecasting functional implications of global changes in riparian plant communities. *Frontiers in Ecology and the Environment* 11:423-432. http://dx.doi.org/10.1890/120056
48. Le Quére C, Andres RJ, Boden T, Conway T, Houghton RA, House JI, Marland G, Peters GP, van der Werf GR, Ahlström A, Andrew RM, Bopp L, Canadell JG, Ciais P, Doney SC, Enright C, Friedlingstein P, Huntingford C, Jain AK, Jourdain C, Kato E, Keeling RF, Klein Goldewijk K, Levis S, Levy P, Lomas M, Poulter B, Raupach MR, Schwinger J, Sitch S, Stocker BD, Viovy N, Zaehle S, Zeng N (2013) The global carbon budget, 1959-2011. *Earth System Science Data* 5:165-185, doi:10.5194/essd-5-165-2013.
49. Le Quére C, Peters GP, Andres RJ, Andrew RM, Boden TA, Ciais P, Friedlingstein P, Houghton RA, Marland G, Moriarty R, Sitch S, Tans P, Arneth A, Arvanitis A, Bakker DCE, Bopp L, Canadell JG, Chini LP, Doney SC, Harper A, Harris I, House JI, Jain AK, Jones SD, Kato E, Keeling RF, Klein Goldewijk K, Körtzinger A, Koven C, Lefèvre N, Maignan F, Omar A, Ono T, Park G-H, Pfeil B, Poulter B, Raupach MR, Regnier P, Rödenbeck C, Saito S, Schwinger J, Segschneider J, Stocker BD, Takahashi T, Tilbrook T, van Heuven S, Viovy N, Wanninkhof R, Wiltshire A, Zaehle S (2014) Global carbon budget 2013. *Earth System Science Data* 6:235-263 doi:10.5194/essd-6-235-2014.
50. Lei HM, Huang MY, Leung LR, Yang DW, Shi XY, Mao JF, Hayes DJ, Schwalm CR, Wei YX, Liu SS (2014) Sensitivity of global terrestrial gross primary production to hydrologic states simulated by the Community Land Model using two runoff parameterizations. *Journal of Advances in Modeling Earth Systems* 6:658-679, doi:10.1002/2013MS000252.

51. Li J, Wang G, Allison SD, Mayes MA, Luo Y (2014) Soil carbon sensitivity to temperature and carbon use efficiency compared across microbial-ecosystem models of varying complexity. *Biogeochemistry* 119:67-84, doi:10.1007/s10533-013-9948-8.
52. Lin X, Tfaily MM, Steinweg JM, Chanton P, Esson K, Yang ZK, Chanton JP, Cooper W, Schadt CW, Kostka JE (2014a) 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.
53. Lin X, Tfaily MM, Green SJ, Steinweg JM, Chanton P, Imvittaya A, Chanton JP, Cooper W, Schadt CW, Kostka JE (2014b) Microbial community stratification linked to utilization of carbohydrates and phosphorus limitation in a boreal peatland at Marcell Experimental Forest, Minnesota, USA. *Applied and Environmental Microbiology* 80:3518-3530, doi:10.1128/AEM.00205-14.
54. 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.
55. Luyssaert S, Abril G, Andres R, Bastviken D, Bellassen V, Bergamaschi P, Bousquet P, Chevallier F, Ciais P, Corazza M, Dechow R, Erb K-H, Etiope G, Fortems-Cheiney A, Grassi G, Hartman J, Jung M, Lathière J, Lohila A, Mayorga E, Moosdorf N, Njakou DS, Otto J, Papale D, Peters W, Peylin P, Raymond P, Rödenbeck C, Saarnio S, Schulze E-D, Szopa S, Thompson R, Verkerk PJ, Vuichard N, Wang R, Wattenbach M, Zaehle S (2012) The European land and inland water CO_2, CO, CH_4 and N_2O balance between 2001 and 2005. *Biogeosciences* 9:3357-3380. doi:10.5194/bg-9-3357-2012.
56. Lynch DJ, Matamala R, Iversen CM, Norby RJ, Gonzalez-Meler MA (2013) Stored carbon partly fuels fine-root respiration but is not used for production of new fine roots. *New Phytologist* 199:420-430, doi:10.1111/nph.12290.
57. Maksyutov S, Takagi H, Valsala VK, Saito M, Oda T, Saeki T, Belikov DA, Saito R, Ito A, Yoshida Y, Morino I, Uchino O, Andres RJ, Yokota T (2013) Regional CO_2 flux estimates for 2009–2010 based on GOSAT and ground-based CO_2 observations. *Atmospheric Chemistry and Physics* 13:9351-9373, doi:10.5194/acp-13-9351-2013.
58. Mao JF, Shi XY, Thornton PE, Hoffman FM, Zhu ZC, Myneni RB (2013) Global latitudinal-asymmetric vegetation growth trends and their driving mechanisms: 1982-2009. *Remote Sensing* 5:1484-1497, doi:10.3390/rs5031484.
59. Mao JF, Shi XY, Thornton PE, Piao SL, Wang XH (2012) Causes of spring vegetation growth trends in the northern mid-high latitudes from 1982 to 2004. *Environmental Research Letters* 7(1), doi:10.1088/1748-9326/7/1/014010.
60. Mao JF, Thornton PE, Shi XY, Zhao MS, Post WM (2012) Remote sensing evaluation of CLM4 GPP for the period 2000-09. *Journal of Climate* 25:5327-5342, doi:10.1175/JCLI-D-11-00401.1.
61. McFarlane KJ, Torn MS, Hanson PJ, Porras RC, Swanston CW, Callaham MA Jr., Guilderson TP (2013) Comparison of soil organic matter dynamics at five temperate deciduous forests with physical fractionation and radiocarbon measurements. *Biogeochemistry* 112:457-476, DOI: 10.1007/s10533-0212-9740-1 10.1007/s10533-012-9740-1
62. Nassar R, Napier-Linton L, Gurney KR, Andres RJ, Oda T, Vogel FR, Deng F (2013) Improving the temporal and spatial distribution of CO_2 emissions from global fossil fuel emission data sets. *Journal of Geophysical Research - Atmospheres* 118:917-933, doi:10.1029/2012JD018196.
63. Niu SL, Luo YQ, Fei SF, Yuan WP, Schimel D, Law BE, Ammann C, Arain MA, Arneth A, Aubinet M, Barr A, Beringer J, Bernhofer C, Black TA, Buchmann N, Cescatti A, Chen JQ, Davis KJ, Dellwik E, Desai AR, Etzold S, Francois L, Gianelle D, Gielen B, Goldstein A, Groenendijk M, Gu LH, Hanan N, Helfter C, Hirano T, Hollinger DY, Jones MB, Kiely G, Kolb TE, Kutsch WL, Lafleur P, Lawrence KM, Li LH, Lindroth A, Litvak M, Loustau D Lund M, Marek M, Martin TA, Matteucci G, Migliavacca M, Montagnani L, Moors E, Munger JW, Moormets A, Oechel W, Olejnik J, Kyaw TPU, Pilegaard K, Rambal S, Raschi A Scott RL, Seufert G, Spano D, Stoy P, Sutton MA, Varlagin A, Vesala T, Weng ES, Wohlfahrt G, Yang B, Zhang ZD, Zhou XH (2012) Thermal optimality of net ecosystem exchange of carbon dioxide and underlying mechanisms. *New Phytologist* 194:775-783, doi:10.1111/j.1469-8137.2012.04095.

64. Niu S, Fu Y, Gu L, Luo Y (2013) Temperature sensitivity of canopy photosynthesis phenology in northern ecosystems. Ch. 27 in *Phenology: An Integrated Environmental Science*, [Schwartz MD (ed)] © Springer Science+Business Media B.V. 2013, doi:10.1007/978-94-007-6925-0_27
65. Oda T, Ganshin A, Saito M, Andres RJ, Zhuravlev R, Sawa Y, Fisher RE, Rigby M, Lowry D, Tsuboi K, Matsueda H, Nisbet EG, Toumi R, Lukyanov A, Maksyutov S (2013) The use of a high-resolution emission dataset in a Global Eulerian-Lagrangian coupled model, in *Lagrangian Modeling of the Atmosphere* [Lin J, Brunner D, Gerbig C, Stohl A, Luhar A, Webley P (eds)]. Washington, D.C.: American Geophysical Union, doi: 10.1029/2012GM001263.
66. Oleson, KW, Lawrence DM, Bonan GB, Drewniak B, Huang M, Koven CD, Levis S, Li F, Riley WJ, Subin ZM, Swenson SC, Thornton PE, Bozbiyik A, Fisher R, Heald CL, Kluzek E, Lamarque J-F, Lawrence PJ, Leung LR, Lipscomb W, Muszala S, Ricciuto DM, Sacks W, Sun Y, Tang J, Yang Z-L (2013) Technical description of version 4.5 of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-503+STR, 434 pp.
67. Piao SL, Ito A, Li SG, Huang Y, Ciais P, Wang XH, Peng SS, Nan HJ, Zhao C, Ahlstrom A, Andres RJ, Chevallier F, Fang JY, Hartmann J, Huntingford C, Jeong S, Levis S, Levy PE, Li JS, Lomas MR, Mao JF, Mayorga E, Mohammat A, Muraoka H, Peng CH, Peylin P, Poulter B, Shen ZH, Shi X, Sitch S, Tao S, Tian HQ, Wu XP, Xu M, Yu GR, Viovy N, Zaehle S, Zeng N, Zhu B (2012) The carbon budget of terrestrial ecosystems in East Asia over the last two decades. *Biogeosciences* 9:3571-3586, doi:10.5194/bg-9-3571-2012.
68. Piao S, Nan H, Huntingford C, Ciais P, Friedlingstein P, Sitch S, Peng S, Ahlstrom A, Canadell JG, Levis S, Levy PE, Liu L, Lomas MR, Mao J, Myneni RB, Peylin P, Poulter B, Shi X, Ying G, Viovy N, Wang T, Wang X, Zaehle S, Zeng N, Zeng Z, Chen A (2014) Evidence for a weakening relationship between temperature variability and northern vegetation activity. *Nature Communications* 5:5018, doi:10.1038/ncomms6018.
69. Potosnak MJ, LeStourgeon L, Pallardy SG, Hosman KP, Gu LH, Karl T, Gerone C, Guenther AB (2014) Observed and modeled ecosystem isoprene fluxes from an oak-dominated temperate forest and the influence of drought stress. *Atmospheric Environment* 84:314-322, doi:10.1016/j.atmosenv.2013.11.055.
70. Raczka BM, Davis KJ, Huntzinger D, Neilson RP, Poulter B, Richardson AD, Xiao JF, Baker I, Ciais P, Keenan TF, Law B, Post WM, Ricciuto D, Schaefer K, Tian HQ, Tomelleri E, Verbeeck H, Viovy N (2013) Evaluation of continental carbon cycle simulations with North American flux tower observations. *Ecological Monographs* 83:531-556, doi:10.3334/ORNLDAAC/1183.
71. Richardson AD, Anderson RS, Arain MA, Barr AG, Bohrer G, Chen GS, Chen JM, Ciais P, Davis KJ, Desai AR, Dietze MC, Dragoni D, Garrity SR, Gough CM, Grant R, Hollinger DY, Margolis HA, McCaughey H, Migliavacca M, Monson RK, Munger JW, Poulter B, Raczka BM, Ricciuto DM, Sahoo AK, Schaefer K, Tian HQ, Vargas R, Verbeeck H, Xiao JF, Xue YK (2012) Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. *Global Change Biology* 18:566-584, doi:10.1111/j.1365-2486.2011.02562.x.
72. Roley SS, Tank JL, Griffiths NA, Hall RO Jr., Davis RT (2014*)* The influence of floodplain restoration on whole-stream metabolism in an agricultural stream: insights from a 5-year continuous data set. *Freshwater Science* 33:1043-1059. http://dx.doi.org/10.1086/677767
73. Ryan MG, Vose JM, Ayres MP, Band LE, Ford CR, Hanson PJ, Hicke JA, Iversen BK, Kerns BK, Klein SL, Littell JS, Luce CH, McKenzie D, Wear DN, Weed AS (2013) Chapter 2 Effects of Climate Variability and Change, pp. 7-95 In: SL, Vose JM, Peterson DL, Patel-Weynand T, Eds. *Effects of Climate Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector*, Gen. Tech. Rep. PNW-GTR-870, Portland, Oregon.
74. Ryan MG, Vose JM, Hanson PJ, Iverson LR, Miniat CF, Luce CH, Band LE, Klein SL, McKenzie D, Wear DN (2014) Chapter 3 Forest Processes, pp. 25-54, In Peterson DL, Vose JM, Patel-Weynand T, Eds., Climate Change and United States Forests, Springer Book Series: *Advances in Global Change Research* 57:25-54.
75. Ryu Y, Baldocchi DD, Black TA, Detto M, Law BE, Leuning R, Miyata A, Reichstein M, Vargas R, Ammann C, Beringer J, Flanagan LB, Gu LH, Hutley LB, Kim J, McCaughey H, Moors EJ, Rambal

S, Vesala T (2012) On the temporal upscaling of evapotranspiration from instantaneous remote sensing measurements to 8-day mean daily-sums. *Agricultural and Forest Meteorology* 152:212-222, doi:10.1016/j.agrformet.2011.09.010.

76. Saeki T, Maksyutov S, Saito M, Valsala V, Oda T, Andres RJ, Belikov D, Tans P, Dlugokencky E, Yoshida Y, Morino I, Uchino O, Yokota T (2013a) Inverse modeling of CO_2 fluxes using GOSAT data and multi-year ground-based observations. *Scientific Online Letters on the Atmosphere (SOLA)* 9:45-50, doi:10.2151/sola.2013-011.
77. Saeki T, Maksyutov S, Sasakawa M, Machida T, Arshinov M, Tans P, Conway TJ, Saito M, Valsala V, Oda T, Andres RJ (2013b) Carbon flux estimation for Siberia by inverse modeling constrained by aircraft and tower CO_2 measurements. *Journal of Geophysical Research- Atmospheres* 118:1-23, doi:10.1002/jgrd.50127.
78. Sargsyan K, Safta C, Najm HN, Debusschere BJ, Ricciuto D, Thornton P.(2014) Dimensionality reduction for complex models via bayesian compressive sensing. *International Journal for Uncertainty Quantification* 4:63-93, doi:10.1615/Int.J.UncertaintyQuantification.2013006821.
79. Schaefer K, Schwalm C, Williams C, Arain M, Barr A, Chen JM, Davis K, Dimitrov D, Hilton T, Hollinger D, Humphreys E, Poulter B, Raczka B, Richardson A, Sahoo1 A, Thornton P, Vargas R, Verbeeck H, Anderson R, Baker I, Black T, Bolstad P, Chen J, Curtis P, Desai A, Dietze M, Dragoni D, Gough C, Grant R, Gu LH, Jain A, Kucharik C, Law B, Liu SG, Lokipitiya E, Margolis HA, Matamala R, McCaughey JH, Monson R, Munger JW, Oechel W, Peng CH, Price DT, Ricciuto D, Riley WJ, Roulet N, Tian HQ, Tonitto C, Torn M, Weng ES Zhou XL (2012) A model-data comparison of gross primary productivity: Results from the North American Carbon Program Site Synthesis. *Journal of Geophysical Research – Biogeosciences* 117:G03010, doi:10.1029/2012JG001960.
80. Shao J, Zhou X, He H, Yu G, Wang H, Luo Y, Chen J, Gu L, Li B (2014) Partitioning climatic and biotic effects on interannual variability of ecosystem carbon exchange in three ecosystems. *Ecosystems* 17:1186-1201 doi:10.1007/s10021-014-9786-0.
81. Shi XY, Mao JF, Thornton PE, Huang MY (2013) Spatiotemporal patterns of evapotranspiration in response to multiple environmental factors simulated by the Community Land Model. *Environmental Research Letters* 8(2): 024012, doi:10.1088/1748-9326/8/2/024012.
82. Shi X, Wang D (2014) Processing NOAA observation data over hybrid computer systems for comparative climate change analysis, The 2014 International Conference on Parallel and Distributed Processing Techniques and Applications, July 21-24, 2014, Las Vegas, Nevada, USA http://worldcomp-proceedings.com/proc/p2014/PDP2896.pdf.
83. Smith SJ, van Aardenne J, Klimont Z, Andres RJ, Volke A, Delgado Arias S (2011) Anthropogenic sulfur dioxide emissions: 1850-2005. *Atmospheric Chemistry and Physics* 11:1101-1116, doi:10.5194/acp-11-1101-2011.
84. Sulman BN, Desai AR, Schroeder NM, Ricciuto D, Barr A, Richardson AD, Flanagan LB, Lafleur PM, Tian HQ, Chen GS, Grant RF, Poulter B, Verbeeck H, Ciais P, Ringeval B, Baker IT, Schaefer K, Luo YQ, Weng ES (2012) Impact of hydrological variations on modeling of peatland CO_2 fluxes: Results from the North American Carbon Program site synthesis. *Journal of Geophysical Research-Biogeosciences* 117: G01031, doi:10.1029/2011JG001862.
85. Sun Y, Gu L, Dickinson RE, Pallardy SG, Baker J, Cao Y, DaMatta FM, Dong X, Ellsworth D, Goethem DV, Jensen AM, Law BE, Loos R, Martins SCV, Norby RJ, Warren J, Weston D, Winter K (2014a) Asymmetrical effects of mesophyll conductance on fundamental photosynthetic parameters and their relationships estimated from leaf gas exchange measurements. *Plant Cell and Environment* 37:978-994, doi:10.1111/pce.12213.
86. Sun Y, Gu L, Dickinson RE, Norby RJ, Pallardy SG, Hoffman FM (2014b) 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.
87. Sun Y, Gu L, Dickinson R, Zhou B (2012) Forest greenness after the massive 2008 Chinese ice storm: integrated effects of natural processes and human intervention. *Environmental Research Letters* 7:035702, doi:10.1088/1748-9326/7/3/035702.

88. Sun Y, Gu L, Dickinson R (2012) A numerical issue in calculating the coupled carbon and water fluxes in a climate model. *Journal of Geophysical Research – Atmospheres* 117:D22103, doi:10.1029/2012JD018059.
89. Takagi H, Houweling S, Andres RJ, Belikov D, Bril A, Boesch H, Butz A, Guerlet S, Hasekamp O, Maksyutov S, Morino I, Oda T, O'Dell CW, Oshchepkov S, Parker R, Saito M, Uchino O, Yokota T, Yoshids Y, Valsala V (2014) Influence of differences in current GOSAT X_{CO2} retrievals on surface flux estimation. *Geophysical Research Letters* 41:2598-2605, doi:10.1002/2013GL059174.
90. Tfaily MM, Cooper WT, Kostka JE, Chanton PR, Schadt CW, Hanson PJ, Iversen CM, Chanton JP (2014). Organic matter transformation in the peat column at Marcell Experimental forest: Humification and vertical stratification. *Journal of Geophysical Research: Biogeosciences* 119:661-675, doi:10.1002/2013JG002492.
91. Van Goethem D, Potters G, De Smedt S, Gu LH, Samson R (2014) Seasonal, diurnal and vertical variation in photosynthetic parameters in *Phyllostachys humilis* bamboo plants. *Photosynthesis Research* 120:331-346, doi:10.1007/s11120-014-9992-9
92. Vicca S, Bahn M, Estiarte M, van Loon EE, Vargas R, Alberti G, Ambus P, Arain MA, Beier C, Bentley LP, Borken W, Buchmann N, Collins SL, de Dato G, Dukes JS, Escolar C, Fay P, Guidolotti G, Hanson PJ, Kahmen A, Kröel-Dulay G, Ladreiter-Knauss T, Larsen KS, Lellei-Kovacs E, Lebrija-Trejos E, Maestre FT, Marhan S, Marshall M, Meir P, Miao Y, Muhr J, Niklaus PA, Ogaya R, Peñuelas J, Poll C, Rustad LE, Savage K, Schindlbacher A, Schmidt IK, Smith AR, Sotta ED, Suseela V, Tietema A, van Gestel N, van Straaten O, Wan S, Weber U, Janssens IA (2014) Can current moisture responses predict soil respiration under altered precipitation regimes? A synthesis of manipulation experiments. *Biogeosciences* 11:2991-3013, doi:10.5194/bg-11-2991-2014.
93. Walker A, Beckerman A, Gu L, Kattge J, Cernusak L, Domingues T, Scales J, Wohlfahrt G, Wullschleger S, Woodward F (2014) The relationship of leaf photosynthetic traits–V-cmax and J(max)–to leaf nitrogen, leaf phosphorus, and specific leaf area: a meta-analysis and modeling study. *Ecology and Evolution* 4:3218-3235, doi:10.1002/ece3.1173.
94. Walker AP, Hanson PJ, De Kauwe MG, Medlyn BE, Zaehle S, Asao S, Dietze M, Hickler T, Huntingford C, Iversen CM, Jain A, Lomas M, Luo Y, McCarthy H, Parton W, Prentice IC, Thornton PE, Wang S, Wang Y-P, Wårlind D, Weng E, Warren JM, Woodward FI, Oren R, Norby RJ (2014) Comprehensive ecosystem model-data synthesis using multiple data sets at two temperate forest free-air CO_2 enrichment experiments: Model performance at ambient CO_2 concentration. *Journal of Geophysical Research-Biogeosciences* 119:937-964, doi:10.1002/2013JG002553.
95. Wang D, Xu Y, Thornton P, King A, Steed C (2013) A pilot study on functional testing for the community land model, *Proceedings of Computational Data Analytics Workshop*, Oak Ridge National Laboratory, October 8-9, 2013, Oak Ridge TN, http://cda.ornl.gov/workshops/2013/cdaw/WangetalCDAW13.pdf.
96. Wang D, Xu Y (2014b) Software engineering for scientific application: effort report on the Community Land Model within the Earth System Modeling framework. In: *Proceedings of the 7th International Congress on Environmental Modeling and Software*, [Ames DP, Quinn NWT, Rizzoli AE (Eds.)] June 15-19, San Diego, California, USA. ISBN: 978-88-9035-744-2.
97. Wang D, Schuchart J, Janjusic T, Winkler F, Xu Y (2014c) Toward better understanding of the community land model within the earth system modeling framework, In: *2014 International Conference on Computational Science* [Abramson D, Lees M, Krzhizhanovskaya VV, Dongarra J, Sloot PMA (eds.)], June 10-12, Cairns, Australia, Amsterdam, Netherlands: Elsevier Science BV, doi:10.1016/j.procs.2014.05.137.
98. Wang D, Wu W, Janjusic T, Xu Y, Iversen C, Thornton P, Krassovisk M, (2015) Scientific Functional Testing Platform for Environmental Models: An Application to Community Land Model, 37th International Conference on Software Engineering, May 16-24, 2015, Florence, Italy (accepted)
99. Wang D, Xu Y, Thornton P, King A, Steed C, Gu LH, Schuchart J (2014d) A functional testing platform for the Community Land Model. *Environmental Modeling and Software* 55:25-31, doi:10.1016/j.envsoft.2014.01.015.

100. Wang G, Jagadamma S, Mayes MA, Schadt CW, Steinweg JM, Gu LH, Post WM (2014a) Microbial dormancy improves development and experimental validation of ecosystem model. *The ISME Journal*, doi:10.1038/ismej.2014.120.
101. Wang G, Mayes MA, Gu L, Schadt CW (2014b) Representation of dormant and active microbial dynamics for ecosystem modeling. *PLOS One* 9:e89252, doi:10.1371/journal.pone.0089252.
102. Wang G, Post WM (2012) A theoretical reassessment of microbial maintenance and implications for microbial ecology modeling. *FEMS Microbiology Ecology* 81:610-617, doi:10.1111/j.1574-6941.2012.01389.x.
103. Wang G, Post WM, Mayes MA (2013) Development of microbial-enzyme-mediated decomposition model parameters through steady-state and dynamic analyses. *Ecological Applications* 23:255-272, ISSN: 1051-0761.
104. Wang K, Mao JF, Dickinson RE, Shi XY, Post WM, Zhu ZC, Myneni RB (2013) Evaluation of CLM4 solar radiation partitioning scheme using remote sensing and site level FPAR datasets. *Remote Sensing* 5:2857-2882, doi:10.3390/rs5062857.
105. Warren JM, Bilheux H, Kang M, Voisin S, Cheng C, Horita J, Perfect E (2013) Neutron imaging reveals internal plant water dynamics. *Plant and Soil* 366:683-693, doi:10.1007/s11104-012-1579-7.
106. Warren JM, Bilheux H, Cheng CL, Perfect E (2013) Reply to: Comment on ‘neutron imaging reveals internal plant water dynamics. *Plant and Soil* 371:15–17, doi:10.1007/s11104-013-1858-y.
107. Warren J, Iversen C, Garten C, Norby R, Childs J, Brice D, Evans RM, Gu L, Thornton P, Weston D (2012) Timing and magnitude of C partitioning through a young loblolly pine (Pinus taeda L.) stand using C-13 labeling and shade treatments *Tree Physiology* 32:799-813, doi:10.1093/treephys/tpr129.
108. Warren, JM, Hanson PJ, Iversen CM, Kumar J, Walker AP, Wullschleger SD (2015) Root structural and functional dynamics in terrestrial biosphere models – Evaluation and recommendations (Tansley Review). *New Phytologist* 205:59-78, doi:10.1111/nph.13034.
109. Warren JM, Jensen AM, Medlyn BE, Norby RJ, Tissue DT (2015) 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.
110. Wei Y, Liu S, Huntzinger D, Michalak AM, Viovy N, Post WM, Schwalm C, Schaefer K, Jacobson A, Lu C, Ricciuto DM, Cook RB, Mao J, Shi X (2014) The North American Carbon Program multi-scale synthesis and terrestrial model intercomparison project: Part II – environmental driver data. *Geoscientific Model Development* 7:2875-2893, doi:10.5194/gmd-7-2875-2014.
111. Williams RS, Marbert BS, Fisk MC, Hanson PJ (2013) Ground-dwelling beetle responses to long-term precipitation alterations in a hardwood forest. *Southeastern Naturalist* 13:138-155.
112. 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.
113. Xiao J, Ollinger S, Frolking S, Hurtt G, Hollinger D, Davis K, Pan Y, Zhang X, Deng F, Chen J, Baldocchi D, Law B, Arain M, Desai A, Richardson A, Sun G, Amiro B, Margolis H, Gu L, Scott R, Blanken P, Suyker A (2014) Data-driven diagnostics of terrestrial carbon dynamics over North America. *Agricultural and Forest Meteorology* 197:142-157, doi:10.1016/j.agrformet.2014.06.013.
114. Xu X, Schimel JP, Thornton PE, Song X, Yuan F, Goswami S (2014) Substrate and environmental controls on microbial assimilation of soil organic carbon: a framework for Earth system models, *Ecology Letters*, 17:547-555, doi:10.1111/ele.12254.
115. Xu X, Thornton PE, Post WM (2013) A global analysis of soil microbial biomass carbon, nitrogen, and phosphorus in terrestrial ecosystems. *Global Ecology and Biogeography* 22:737-749, doi:10.1111/geb.12029.
116. Yang X, Wang D, Janjusic T, Xu X (2014a) A web-based visual analytic system for understanding the structure of Community Land Model. The 2014 International Conference on Software Engineering Research and Practice, July 21-24, 2014, Las Vegas, Nevada, USA, http://worldcomp-proceedings.com/proc/p2014/SER2350.pdf

117. Yang X, Thornton P, Ricciuto D, Post W (2014b) The role of phosphorus dynamics in tropical forests – a modeling study using CLM-CNP. *Biogeosciences* 11:1667-1681, doi:10.5194/bg-11-1667-2014.
118. Yang X, Post WM, Thornton PE, Jain A (2013) The distribution of soil phosphorus for global biogeochemical modeling. *Biogeosciences* 10:2525-2537, doi:10.5194/bg-10-2525-2013.
119. Yi CX, Rustic G, Xu XY, Wang JX, Dookie A, Wei SH, Hendrey G, Ricciuto D, Meyers T, Nagy Z, Pinter K (2012) Climate extremes and grassland potential productivity. *Environmental Research Letters* 7(3):035703, doi:10.1088/1748-9326/7/3/035703.
120. Yu H, Orteg J, Smith JN, Guenther AB, Kanawade VP, You Y, Liu Y, Hosman K, Karl T, Seco R, Geron C, Pallardy SG, Gu L, Mikkilä J, Lee SH (2014) New particle formation and growth in an isoprene-dominated Ozark forest: From sub-5 nm to CCN-active sizes. *Aerosol Science and Technology* 48:1285-1298, doi:10.1080/02786826.2014.984801.
121. Zaehle S, Medlyn BE, De Kauwe MG, Walker AP, Dietze MC, Hickler T, Luo Y, Wang Y-P, El-Masri B, Thornton P, Jain A, Wang S, Wårlind D, Weng E, Parton W, Iversen CM, Gallet-Budynek A, Mccarthy H, Finzi A, Hanson PJ, Prentice IC, Oren R, Norby RJ (2014) Evaluation of 11 terrestrial carbon–nitrogen cycle models against observations from two temperate Free-Air CO_2 Enrichment studies. *New Phytologist* 202:803–822, doi:10.1111/nph.12697
122. Zeng Z, Wang T, Zhou F, Ciais P, Mao J, Shi X, Piao S (2014) A worldwide analysis of spatiotemporal changes in water balance based evapotranspiration from 1982 to 2009. *Journal of Geophysical Research-Atmospheres* 119:1186-1202, doi:10.1002/2013JD020941.
123. 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.
124. Zhao Z, Shaw S-L, Wang D (2014) A space-time raster GIS data model for spatiotemporal Analysis of vegetation responses to a freeze event. *Transaction in GIS*, published online 27 May 2014, doi:10.1111/tgis.12088.
125. Zhen L, Bambha RP, Pinto J, Zeng T, Boylan J, Huang M, Lei H, Zhao C, Liu S, Mao J, Schwalm CR, Shi X, Wei Y, Michelsen HA, (2014) Toward verifying fossil fuel CO_2 emissions with the Community Multi-scale Air Quality (CMAQ) model: motivation, model description and initial simulation. Journal of the Air & Waste Management Association 64:419-435, DOI:10.1090/10962247.2013.816642.
126. Zscheischler J, Michalak AM, Schwalm C, Mahecha MD, Huntzinger DN, Reichstein M, Bertheir G, Ciais P, Cook RB, El-Masri B, Huang M, Ito A, Jain A, King A, Lei H, Lu C, Mao J, Peng S, Poulter B, Ricciuto D, Shi X, Tao B, Tian H, Viovy N, Wang W, Wei Y, Yang J, Zeng N (2014) Impact of large-scale climate extremes on biospheric carbon fluxes: An intercomparison based on MsTMIP data. *Global Biogeochemical Cycles* 28:585-600, doi:10.1002/2014GB004826.

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APPENDIX B: COMPLETE LIST OF TES SFA DATA SETS

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

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

Archived data products are freely available to the public. Users should acknowledge the contribution of the data provider with the citation (with DOI) as provided in the documentation and acknowledge the U.S. DOE Program for Terrestrial Ecosystem Science.

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

Data sets marked with a triple asterisk (***) have been added since February 2015.

SPRUCE Public Data Sets:

1. *** Griffiths NA, Hook LA, Hanson PJ (2016) **SPRUCE S1 Bog and SPRUCE Experiment Location Survey Results, (2015)** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.015
2. Hanson, PJ, U.S. Forest Service Staff, and SPRUCE Team (2012) **SPRUCE S1-Bog Vegetation Survey and Peat Depth Data: 2009.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.003.
3. Hanson PJ, Riggs JS, Dorrance C, Nettles WR, Hook LA (2015) **SPRUCE Environmental Monitoring Data: 2010-2014.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.001. (Includes recent additions of annual data files.)
4. *** Hanson PJ (2015) **SPRUCE S1 Bog and SPRUCE Experiment Aerial Photographs.** 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.012
5. *** Jensen, AM, JM Warren, PJ Hanson, J Childs and SD Wullschleger. (2015) 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
6. Lin X, Tfaily MM, Steinweg JM, Chanton P, Esson K, Yang ZK, Chanton JP, Cooper W, Schadt CW, Kostka JE (2014) **Microbial metabolic potential in carbon degradation and nutrient (nitrogen and phosphorus) acquisition in an ombrotrophic peatland.** Applied and Environmental Microbiology 80:3531-3540, doi:10.1128/AEM.00206-14. [**Access SPRUCE Microbial Community Metagenome** (SPRUCE Metagenome Lin *et al.* 2014)]
7. Slater L, Hanson PJ, Hook LA (2012) **SPRUCE S1-Bog Peat Depth Determined by Push Probe and GPR: 2009-2010.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. doi: http://dx.doi.org/10.3334/CDIAC/spruce.002.

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

1. Hanson PJ, Brice D, Garten CT, Hook LA, Phillips J, Todd DE (2012) **SPRUCE S1-Bog Vegetation Allometric and Biomass Data: 2010-2011**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.004.
2. Hanson PJ, Phillips JR, Riggs JS, Nettles WR, Todd DE (2014) **SPRUCE Large-Collar In Situ CO_2 and CH_4 Flux Data for the SPRUCE Experimental Plots**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.006.
3. Hanson PJ, Riggs JS, Hook LA, Nettles WR, Dorrance C (2015) **SPRUCE S1-Bog Phenology Movies, 2010-2104.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.011.
4. *** Hanson PJ, Riggs JS, Nettles WR, Krassovski MB, Hook LA (2015) **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
5. Iversen CM, Hanson PJ, Brice DJ, Phillips JR, McFarlane KJ, Hobbie EA, Kolka RK (2014) **SPRUCE Peat Physical and Chemical Characteristics from Experimental Plot Cores, 2012**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.005.
6. *** Finzi AF, Giasson MA, Gill AL (2016) **SPRUCE Autochamber CO2 and CH4 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

Other TES SFA Public Data Sets and Tools:

1. *** Griffiths NA, Tiegs SD (2016) **Walker Branch Watershed: Temperature Response of Organic-Matter Decomposition in a Headwater Stream.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.003
2. *** Iversen CM, Powell AS, McCormack ML, Blackwood CB, Freschet GT, Kattge J, Roumet C, Stover DB, Soudzilovskaia NA, Valverde-Barrantes OJ, van Bodegom PM, Violle C. (2016) **Fine-Root Ecology Database (FRED): A Global Collection of Root Trait Data with Coincident Site, Vegetation, Edaphic, and Climatic Data, Version 1.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. Access on-line at: http://dx.doi.org/10.3334/CDIAC/ornlsfa.005.
3. Jagadamma S, Mayes MA, Steinweg JM, Wang G, Post WM (2014) **Organic Carbon Sorption and Decomposition in Selected Global Soils.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.002.
4. **LeafWeb.** LeafWeb is a TES SFA-funded web-based tool for the automated numerical analyses of leaf gas exchange measurements. LeafWeb is a Service-in-Exchange-for-Data-Sharing (SEEDS) Project. With the approval of the user, the data LeafWeb receives are preserved and added to a global database of biochemical, physiological, and biophysical properties of single leaves to support studies of plant functions and terrestrial carbon cycle modeling. Access LeafWeb at http://leafweb.ornl.gov/.
5. **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.
6. *** Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Hourly, Daily, and Annual Precipitation**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.006

7. *** Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: 15-minute and Daily Stream Discharge and Annual Runoff**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.007
8. *** Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Daily Climate and Soil Temperature Data**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.008
9. *** Mulholland PJ, Griffiths NA (2016) **Walker Branch Watershed: Weekly Stream Water Chemistry**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.009
10. *** Pallardy SG, Gu L, Hosman KP, Sun Y (2015) **Predawn Leaf Water Potential of Oak-Hickory Forest at Missouri Ozark (MOFLUX) Site: 2004-2014.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.004
11. Shi X, Wang D (2014) **GSOD Based Daily Global Mean Surface Temperature and Mean Sea Level Air Pressure** (1982-2011)", doi: 10.15149/1130373. (Landing page under development).
12. **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.
13. **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/.
14. Warren JM, Iversen CM, Garten Jr CT, Norby RJ, Childs J, Brice D, Evans RM, Gu L, Thornton P, Weston DJ (2013) PiTS-1: **Carbon Partitioning in Loblolly Pine after ^{13}C Labeling and Shade Treatments**. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/ornlsfa.001.

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

1. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.ndp058.2013.
2. Andres RJ, Boden TA, Marland G (2013) **Monthly Fossil-Fuel CO_2 Emissions: Mass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1950-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.MonthlyMass.2013.
3. Andres RJ, Boden TA, Marland G (2013) **Annual Fossil-Fuel CO_2 Emissions: Isomass of Emissions Gridded by One Degree Latitude by One Degree Longitude, 1751-2010**. ORNL/CDIAC, electronic database. doi 10.3334/CDIAC/ffe.AnnualIsomass.2013.
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.

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

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

[http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/ORNLDAAC/1220.

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

Data Sets in Development for Publication with Manuscripts

1. *** Griffiths NA, Sebestyen SD (2016) **SPRUCE S1 Bog Porewater, Groundwater, and Stream Chemistry Data: 2011-2013.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.018
2. *** Iversen CM, Childs J, Norby RJ, Garrett A, Martin A, Spence J, Ontl TA, Burnham A, Latimer J (2016) **SPRUCE S1 Bog Fine-root Standing Crop, Production, and Mortality Assessed Using Minirhizotrons.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.019
3. *** Iversen CM, Brice DJ, Childs J, Vander Stel HM (2016) **SPRUCE S1 Bog Production and Chemistry of Newly-Grown Fine Roots Assessed Using Root Ingrowth Cores.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.020
4. *** Iversen CM, Childs J (2016) **SPRUCE S1-Bog Fine-Root Morphology and Chemistry Across Root Orders and Root Functional Classes for the Dominant Woody Species.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.021
5. *** Iversen CM, Latimer J, Ontl TA, Burnham A, Brice DJ, Childs J, Vander Stel HM (2016) **SPRUCE S1-Bog and SPRUCE Experiment Plant-Available Nutrients Assessed Using Ion-Exchange Resins from 2011-2013, Version 1.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.022
6. *** Iversen CM, Garrett A, Martin A, Turetsky M, Norby RJ, Childs J, Ontl TA (2016) **SPRUCE S1 Bog Tree Basal Area and Understory Vascular Plant Community Composition.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.024
7. *** Hofmockel KS, Chen, J, Hobbie EA (2016) **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. Accessed on-line at: http://dx.doi.org/10.3334/CDIAC/spruce.025
8. *** Ontl TA, Iversen CM (2016) **SPRUCE S1 Bog Areal Coverage of Hummock and Hollow Microtopography.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. http://dx.doi.org/10.3334/CDIAC/spruce.023
9. *** Wilson RM, Hopple AM, Tfaily MM, Sebestyen SD, Schadt CW, Pfeifer-Meister L, Medvedeff C, McFarlane KJ, Kostka JE, Kolton M, Kolka R, Kluber LA, Keller JK, Guilderson TP, Griffiths NA, Chanton JP, Bridgham SD, Hanson PJ (2016) **SPRUCE Stability of Peatland Carbon to Rising Temperatures: Supporting Data.** Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/10.3334/CDIAC/spruce.026