ORNL Terrestrial Ecosystem Sciences SFA Abstracts
for the 2022 ESS PI Meeting

Overview Poster Abstract

Hanson PJ and Ricciuto DM **ORNL's Terrestrial Ecosystem Science – Scientific Focus Area (TES SFA): a 2022 Overview**

Spark Presentation Abstracts (x10)

1. Salmon VG et al. – **Five Years of Experimental Manipulations at SPRUCE: Consequences for Nutrient cycling in Vegetation & Peat**
2. Weston DJ et al. – **An alternative to adapt, migrate or die: insights into microbial enhanced plants resilience to warming**
3. Roth S et al. – **Microbial Community Responses to Elevated Temperature and CO_2 in Peat Decomposition Ladders**
4. Mao J et al. – **Above- and Belowground Phenology Modeling of ELM Using the SPRUCE Observations**
5. Gu L et al. – **Coupling Photophysics, Photochemistry, and Biochemistry for a Complete Mechanistic Modeling and Remote Sensing of Photosynthesis**
6. Wood JD et al. – **From Below- to Aboveground, and Integrated Ecosystem Drought Responses**
7. Abramoff RZ et al. – **Modeling Climate Sensitivity of Above and Below Ground Processes at MOFLUX**
8. Warren J – **Dynamic Imaging of Root and Rhizosphere Processes**
9. Craig ME et al. – **Evaluating and Modeling the Alternative Hypotheses that Connect Organic Inputs to Soil Carbon**
10. Wang B et al. – **Taming fine-root systems complexity to reduce Earth System Model uncertainty**

ORNL's Terrestrial Ecosystem Science – Scientific Focus Area (TES SFA): a 2022 Overview

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

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

The proposed science includes manipulations, multi-disciplinary observations, database compilation, and fundamental process studies integrated and iterated with modeling activities. The centerpiece of our climate change manipulations is the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment that tests multiple levels of warming at ambient and elevated CO_2 on the vegetation response and biogeochemical feedbacks from a *Picea-Sphagnum* ecosystem. Other efforts aim to improve mechanistic representation of processes within terrestrial biosphere models by furthering our understanding of fundamental ecosystem functions and their response to environmental change. The TES SFA integrates experimental and observational studies with model building, parameter estimation, and evaluation to yield reliable model projections. This integrated model-experiment approach fosters an enhanced, interactive, and mutually beneficial engagement between models and experiments to further our predictive understanding of the terrestrial biosphere in the context of Earth system functions.

Five Years of Experimental Manipulations at SPRUCE: Consequences for Nutrient cycling in Vegetation & Peat

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Ombrotrophic peatlands store over a thousand gigatons of soil carbon (C) but primary productivity of these ecosystems is constrained by low availability nitrogen (N) and phosphorus (P; Bridgham et al., 1996; Nichols & Peteet, 2019). Elevated temperatures and an increase in atmospheric CO_2 may stimulate of peatland soil C, especially in northern peatlands (Crowther et al., 2016). Plant growth under climate change may offset some of these C losses but will depend on the balance of N and P availability versus to plant demand for these nutrients. At the SPRUCE experimental site, three years of warming increased losses of C from the ecosystem at a rate of 31.3 gC m^{-2} y^{-1} (Hanson et al., 2020) while availability of N and P in peatland soils increased dramatically (Iversen et al. *In Press*). This prompts the question: Are plants at SPRUCE utilizing the newly available N and P? We compiled comprehensive N and P budgets for bog vegetation following five years of experimental warming and elevated CO_2 to determine the answer. Annual tree surveys at SPRUCE were used to calculate aboveground tree biomass and net primary productivity (NPP) while understory aboveground biomass NPP were determined based on clip-plots. Ingrowth cores were used to quantify NPP of fine roots of all plant functional types (Malhotra et al., 2020). Biomass and NPP of *Sphagnum* moss was based on percent cover surveys and growth in mesh columns (Norby et al., 2019). Species-specific N and P content of plant tissues were measured and applied to vegetation pools and fluxes. Since peat stores approximately 99 and 98% of the ecosystem N and P pools at this site (Salmon et al., 2021), we decided to also assess whether there were detectable changes in peat N and P stocks or stoichiometry at SPRUCE based on peat profiles collected in 2012 and 2020. Preliminary results from this analysis indicate the decline of *Sphagnum* in warmed plots has greatly reduced the storage of N and P in moss biomass but the manipulative treatments have had little impact on tree biomass N and P stocks. Acrotelm peat within hollows at SPRUCE has altered N storage due to a significant interaction between warming and elevated CO_2 treatments. These results indicate that vegetation within an ombrotrophic bog experiencing 5 years of simulated climate is slow to take advantage of increased N and P availability, potentially leading to loss of nutrients from the ecosystem.

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An alternative to adapt, migrate or die: insights into microbial enhanced plants resilience to warming

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The onset of changing climatic conditions is eliciting research in the resilience of ecosystems to challenging environmental conditions. Initial results from such studies have led to the generalization that many plant species will have to either adapt or migrate in order to avoid extinction. However, species interactions, such as those mediated by microbes may provide an alternative approach. Here, we use a microbiome transfer approach to test if microbiome thermal origin influences host plant thermotolerance. We leveraged an experimental whole-ecosystem warming study to collect field grown *Sphagnum*, mechanically separate the associated microbiome and then transfer onto germ-free laboratory *Sphagnum* for temperature experiments. Host and microbiome dynamics were assessed with growth analysis, chlorophyll-*a* fluorescence imaging, metagenomics, metatranscriptomics, and 16S rDNA profiling. Microbiomes originating from warming field conditions imparted enhanced thermotolerance and growth recovery at elevated temperatures. Metagenome and metatranscriptome analyses revealed that warming altered microbial community structure in a manner that induced the plant heat shock response, especially the Hsp70 family and jasmonic acid production. The heat shock response was induced even without warming treatment in the laboratory, suggesting that the warm-microbiome isolated from the field provided the host plant with thermal preconditioning. Our results demonstrate that microbes, which respond rapidly to temperature alterations, can play key roles in host plant growth response to rapidly changing environments.

Microbial Community Responses to Elevated Temperature and CO_2 in Peat Decomposition Ladders

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Peatlands are ecosystems in which plant primary production has historically outpaced microbial decomposition and, as a result, peatlands store approximately one-third of the global terrestrial organic matter. As climate change accelerates, increased temperature and atmospheric CO_2 have the potential to alter the processes involved in organic matter accumulation and degradation. Specifically, warming may influence microbial communities involved in organic matter decomposition, leading to increased decomposition and further production of the greenhouse gases CO_2 and CH_4. To investigate how increased temperature and elevated CO_2 may impact microbial communities associated with organic matter decomposition, we utilized the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment in northern Minnesota. Peat decomposition ladders consisting of known quantities of peat in discrete mesh bags were placed into the SPRUCE treatment chambers at four depths below the surface of the peat in 10 cm increments (between 0-40 cm) allowing them to decompose *in situ* and were collected after three years. Peat mass loss and carbon:nitrogen (C:N) changes were quantified, and characterization of the microbial communities were accomplished through 16S rRNA (bacterial/archaeal) and ITS (fungal) amplicon sequencing. Our results show that microbial community composition is significantly impacted by depth, temperature, and CO_2 treatment. We found that bacterial/archaeal and fungal alpha-diversity were highest near the surface (0-10 cm) and in the plots with the highest warming treatment (+9° C). Numerous microbial phyla were significantly differentially abundant between temperature treatments, indicating selection of specific microbes with warming. We did not find a significant correlation between microbial community composition and peat mass loss or C:N. This may be due to a lag between community shift and decomposition process responses to warming and our planned outyear collections of peat decomposition ladders will be used to test this hypothesis. Collectively, our results indicate that increased temperature and CO_2 as a result of climate change can alter microbial communities in peatlands, potentially contributing to increased decomposition rates and greenhouse gas emissions.

Above- and Belowground Phenology Modeling of ELM Using the SPRUCE Observations

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Vegetation phenology controls the seasonal cycle of land surface properties and determines the exchange of energy, water, and carbon fluxes between the land and the atmosphere. To date, the phenology representations in land surface models rarely distinguish between the above- and belowground phenology; and this approach has been demonstrated to be unrealistic by many observational studies, especially for the boreal region, where the belowground growing season can be considerably longer and have different environmental cues than the aboveground season. This study continues previous phenology development effort of the land model of the US Department of Energy's Energy Exascale Earth System Model (ELM of E3SM) using the Spruce and Peatland Responses Under Changing Environments (SPRUCE). In addition to updating the leaf phenology of boreal evergreen needleleaf trees based on ground phenology observations, this study examined multiple formulas, fitted using minirhizotron-observed root growth data, for the belowground phenology of various plant functional types (e.g., boreal evergreen needleleaf and deciduous needleleaf trees, boreal deciduous shrubs). Different combinations of above- and belowground phenology algorithms were further intercompared by evaluating the simulations against selected SPRUCE observations (e.g., leaf area index, water outflow, soil carbon fluxes, and their temperature responses). The updated ELM, which contains the best set of phenology scheme, showed superior performances compared to the original ELM, demonstrating the importance of accurate presentations of above- and belowground phenology in land surface models.

Coupling Photophysics, Photochemistry, and Biochemistry for a Complete Mechanistic Modeling and Remote Sensing of Photosynthesis

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Photosynthesis consists of light and carbon reactions. The light reactions can be further divided into the photophysical and photochemical reactions because these two groups of reactions are spatially separated, follow different laws, and operate at vastly contrasting time scales. Recently, we have successfully developed steady-state, mechanistic models for the photophysical and photochemical reactions, respectively. The photophysical model predicts the partitioning of absorbed photon energy among different dissipation pathways. The photochemical model describes the photosynthetic electron transport controlled by the redox reactions between enzyme complexes and electron carriers along the electron transport chain between PSII and PSI. The developed photophysical and photochemical models can be directly coupled with the conventional Farquhar-von Caemmerer-Berry biochemical (carbon reaction) model. This coupling forms a complete model of photosynthesis to predict essentially all light and carbon reaction variables of interest at leaf and canopy scales, such as net and gross photosynthetic rates, actual electron transport rates, state transitions, ratio of cyclic electron transport in PSI, fluorescence emission, redox states of PSII, plastoquinone, and cytochrome b_6f complex, non-photochemical quenching, and constitutive heat dissipation. We have tested the coupled model

with pulse amplitude modulated (PAM) fluorometry and gas exchange measurements made on leaves of C_3 and C_4 species collected in the US, Canada, China, the Netherlands, and Finland. The species tested include lianas, shrubs, boreal deciduous trees, boreal evergreen needle-leaf tree, temperate deciduous trees, tropical deciduous trees, tropical evergreen trees, C_3 grasses, C_4 grasses, and different crop varieties.

The coupled photophysical-photochemical-biochemical model advances photosynthesis research in the following aspects:

- The PAM fluorometry and gas exchange measurements, which are the two most important data sources for studying photosynthesis at the leaf level, can now be used jointly in a unified framework for process understanding and carbon cycle model development.
- The relationship between sun-induced chlorophyll fluorescence and photosynthesis can now be simulated fully mechanistically for remote sensing applications.
- Different energy dissipation pathways can be simulated for better understanding land surface energy balance and temperature dynamics.
- Redox states of major enzymes and mobile electron carriers of the electron transport chain can be inferred directly from PAM fluorometry measurements to study state transition and regulation of electron transport and photosynthesis.
- For the first time, state transitions and ratio of cyclic electron transport are formally represented in photosynthesis modeling.
- The model also provides a logical explanation on why all land plants have a thylakoid with grana stacks.

From Below- to Aboveground, and Integrated Ecosystem Drought Responses

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Drought, a pervasive threat to plant productivity across the globe, is projected to intensify under climate change. Accurate representations of plant and ecosystem drought responses are needed for carbon cycle/climate projections to support decision making for adaptation and risk management. While many aspects of plant drought responses are well-understood, there are gaps in mechanisms, methodologies, and data at the scale of whole ecosystems. Specifically, how the dynamics of processes throughout the entirety of the soil-plant-atmosphere continuum aggregate to control ecosystem-level responses and feedbacks to drought of varying intensities and frequencies. To address these gaps, we leverage the unique data sets collected at the Missouri Ozark AmeriFlux (MOFLUX) site, which is situated in a drought-prone *Quercus*-*Carya* (oak-hickory) forest in the transitional zone between the Eastern Deciduous Forest and the Great Plains. This site experiences frequent seasonal physiological drought, and a broad range of conditions ranging from years with no water stress to exceptional drought. MOFLUX is thus an ideal testbed for observing and modeling drought responses at a range of spatiotemporal scales, and our historical monitoring has emphasized the coordinated collection of ecosystem flux, soil, and ecophysiological data.

Our recent efforts have focused on developing understanding of the coupling of above- and below-ground processes to shed light on how forests respond to drought. Specifically, this has involved the addition of capacity for partitioning soil respiration into heterotrophic and autotrophic component fluxes, the observation of canopy sun-induced chlorophyll fluorescence (SIF) as a direct signal of photosynthesis and augmented measurements of leaf water potentials. Our overall scientific approach has focused on three areas: (i) studying the drought response of soil respiration and its components, (ii) how drought affects the coupling of photosynthesis with soil respiration fluxes, and (iii) developing the theory and testing ecosystem-level drought response traits that can be derived from flux and leaf water potential observations (e.g., a whole-ecosystem wilting point).

This "Spark" talk will provide an overview of these research activities and perspectives on how these empirical analyses can address deficiencies in modeling ecosystem drought responses. Specifically, we will emphasize what we see as the value of ecosystem functional traits for understanding drought responses and how they can be used to better evaluate the performance of models.

Modeling Climate Sensitivity of Above and Below Ground Processes at MOFLUX

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When considering belowground ecosystem responses to climate change, the soil is often treated as a monolith, i.e., considering root and soil microbial respiration together as the total soil respiration flux. However, plant roots and soil microorganisms represent fundamentally different components of belowground ecosystems with different potential sensitivities to drought, temperature extremes, and diurnal, seasonal, and inter-annual changes in productivity.

Together plant roots and soil microorganisms dominate ecosystem carbon (C) losses via respiration but are also responsible for soil C formation and stabilization. Therefore, the future balance of C that is allocated to and remains in soil depends on the relative climate sensitivity of plant productivity and belowground allocation, root respiration, and microbial respiration. We are exploring the climate sensitivity of belowground processes across multiple temporal scales (i.e., diurnal, seasonal, inter-annual), using long-term measurements from the Missouri Ozark AmeriFlux (MOFLUX) site. This heavily instrumented *Quercus-Carya* (oak-hickory) forest is located in the Ozark Border Region of Central Missouri, which experiences seasonal soil water deficits because of high precipitation variability, evapotranspiration, and vapor pressure deficit. The MOFLUX site has measured hourly soil respiration using 8 or 16 automated chambers since 2004, with a subset of chambers over plots where roots were excluded since 2017.

We are identifying quantitative frameworks to partition climate and plant allocation effects on autotrophic and heterotrophic respiration across temporal scales, including statistical and process-based models. The main objective is to decompose the real-time and time-lagged effects of photosynthesis, temperature, and soil moisture on belowground activity. We particularly aim to understand effects of seasonal drought on plant root and microbial activity by exploring mathematical relationships that reflect different hypotheses about the roles of matric potential, diffusion, and oxygen limitation. Modeling frameworks where the structure and key parameters are constrained using long-term measurements can be used to project C responses and their uncertainty to future climate.

Dynamic Imaging of Root and Rhizosphere Processes

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Attenuation-based neutron radiography and computed tomography are currently utilized for the study of plant-soil interactions *in situ*. Results with various woody plants, maize and switchgrass indicate significant variability in water dynamics across the soil-rhizosphere-root pathway, including root water uptake and hydraulic redistribution, hysteresis in water release curves and soil wettability. Measured water extraction rates by cottonwood roots ranged from 0.003 to 0.02 g cm^{-2} root surface h^{-1}, with rates declining for larger roots. Across species, root rhizosphere development increases with root size, stabilizing as roots reach ~2 mm in diameter. Analysis leveraged development of a novel image analysis software to identify and segment roots, and analyze root, rhizosphere, and soil water dynamics. Neutron radiography and paired laboratory measurements have also indicated significant root and mycorrhizal impacts to the soil hydraulic parameters, including hydraulic conductivity and residual water content, and the impacts were more pronounced in sandy soil as compared with silt-loam. While bulk water dynamics are readily visible using neutron radiography, alternate or novel techniques are needed to assess higher resolution water dynamics (e.g., <50 um), symbiotic root-microbial relationships, development of gaps across the rhizosphere that can isolate the root from the soil, and critically, nutrient, ion or exudate uptake or release dynamics.

Evaluating and Modeling the Alternative Hypotheses that Connect Organic Inputs to Soil Carbon

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The rate and quality of carbon inputs to soil are a primary control on belowground carbon storage, and carbon inputs are being altered by environmental changes—e.g., those that alter productivity or shift plant communities. Yet, the ability of soil carbon models to simulate the effects of altered inputs has been repeatedly challenged in recent years. Conventional models predict that soil carbon should increase linearly with input rates, and most dramatically with low-quality inputs. But modern biogeochemical theory emphasizes that microbial and mineral interactions can lead to counterintuitive relationships between inputs and soil carbon. For example, priming effects could offset increased inputs, or fast-decomposing plant products could promote greater mineral stabilization of soil carbon. The newest generation of soil carbon models attempt to capture these phenomena by including more sophisticated representations of mineral and microbial dynamics, yet these models make vastly different predictions because immense uncertainty still exists about the processes connecting inputs to soil carbon.

Here, we discuss our progress on a key question: How do alterations to the rate and quality of organic inputs drive changes in soil carbon storage? We have implemented several microbially explicit models in the multi-assumption architecture and testbed (MAAT)—a modular modeling code that can easily vary model process representations—with the goal of identifying the sources of process-level uncertainty among contemporary soil carbon models. We find that models simulate markedly different responses of soil carbon to alterations in inputs, ranging from highly sensitive to complete insensitivity. Alternative hypotheses about the turnover of mineral-associated and microbial biomass pools account for a large portion of this uncertainty. Whereas both processes are often modeled as a linear first-order process, results from a literature synthesis and from microcosm experiments support the hypothesis that both processes depend on the size of the microbial biomass pool. Standardizing models to include this assumption leads to a convergence of model predictions. We will discuss how using MAAT, or similar tools, to probe process-level uncertainty can inform empirical studies to efficiently progress our predictive understanding of ecosystem carbon cycling.

Taming fine-root systems complexity to reduce Earth System Model uncertainty

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Terrestrial biosphere models are confronted with huge structural and parameter uncertainty. Improving leaf and canopy processes has been the focus since the 1980s. However, the rudimentary representation of fine-root systems forms another large model-data discrepancy. Theoretical and empirical advances in the last two decades have revealed structural and functional differentiation and cooperation within fine-root systems underlying their functioning of nutrients and water acquisition and transport. To close this model-data gap, we propose a 3-pool structure of TAM (Transport, Absorptive, and Mycorrhizal fungi) to model vertically resolved explicit fine-root systems. We hypothesize that TAM will contribute to reducing uncertainty in terrestrial biosphere models. We discuss realization of this TAM structure using an APD scheme (Allocation, Partitioning, and Distribution) in the context of Energy Exascale Earth System Model (E3SM) Land Model (ELM). ELM is representative of existing land surface models grouping heterogeneous fine roots into a single homogeneous pool. Accounting for parametric and structural uncertainty, a demonstration of TAM at two temperate forests (evergreen and deciduous) shows robust impacts of dampening GPP, heterotrophic respiration, and soil carbon stock but of increasing fine-root biomass. TAM captures structural and functional heterogeneity within fine-root systems and provides a framework that can best leverage increasingly explicit root and fungal traits data (e.g., FRED: Fine Root Ecology Database). Though with challenges for a full test of the uncertainty reduction hypothesis, TAM holds promise to guide empirical root ecology, advance understanding of ecosystem functioning, and improve ESMs accuracy. We advocate for its embrace by both modelers and empiricists.