ORNL's Terrestrial Ecosystem Science – Scientific Focus Area (TES SFA): a 2021 Overview

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BER Program: ESS

Project: ORNL Terrestrial Ecosystem Science Scientific Focus Area (TES SFA)

Project Website: http://mnspruce.ornl.gov; http://tes-sfa.ornl.gov

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

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

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

Improving models of SPRUCE carbon cycling and phenology using observations

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Project Abstract:
Uncertainty about land surface processes contributes to a large spread in model predictions about the magnitude and timing of climate change within the 21st century. Global peatlands are an important reservoir of carbon that may be at risk due to climate change and have not traditionally been well-represented in models, contributing to this prediction uncertainty. The Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment is applying whole-ecosystem warming and elevated CO_2 concentrations to an ombrotrophic bog in northern Minnesota to represent a range of possible future conditions and study the ecosystem responses. A version of the E3SM land model, ELM-SPRUCE, is under continuing development to predict the experimental responses and provide a framework for integration of wetland processes to Earth System models. ELM-SPRUCE is a peatland-specific of ELM including hummock-hollow microtopography, bog-specific hydrology, CH_4 cycling and Sphagnum moss dynamics, which were previously absent from ELM. Observations in the enclosures with warming treatments using phenology cameras indicated strong phenological responses to warming, the magnitude of which varies with species. We calibrate ELM-SPRUCE with observed phenology data, carbon fluxes, biomass and hydrology. The calibrated model is then subjected to the experimental treatments over 15-year period. We assess the fate of carbon stocks given the assumptions in ELM-SPRUCE, how this impacted by phenology, and strategies for reducing prediction uncertainty in the future.

Probing structural differences in contemporary soil carbon models

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Project Abstract:
Hundreds of models have been developed to describe the formation and decomposition of soil organic carbon (SOC), representing different assumptions about the dominant processes governing SOC dynamics. Moreover, recent models employ even more complicated representations of microbial and mineral interactions, reflecting our evolving understanding of SOC. This has led to an explosion of potential SOC model configurations. Unsurprisingly, different process representations among existing models have led to divergent predictions about SOC responses to global change. As SOC models continue to evolve, there is a critical need to probe the drivers of this process-level uncertainty. Here, we investigate how alternative hypotheses affect predicted SOC responses to altered carbon inputs—which are changing due to multiple environmental and anthropogenic drivers. We developed a generalizable SOC model within the multi-assumption architecture and testbed (MAAT)—a modular modeling code that can easily vary model process representations. We evaluated how alternative hypotheses about microbial constraints and mineral saturation shape SOC responses to altered input rates. Then, we integrated contemporary microbially explicit SOC models (e.g. MIMICS, MEND, CORPSE) into MAAT to uncover the sources of process-level inter-model variability. Using a simple three-pool model, we find that model assumptions about microbial constraints and mineral saturation exert substantial control over the trajectory of SOC responses to altered input rates. Representing alternative hypotheses about constraints on microbial growth, lifespan, and mineral-associated SOC capacity led to linearly increasing, non-linearly increasing, or unresponsive SOC trajectories. More complicated, contemporary SOC models also predict substantially different SOC responses ranging from complete insensitivity of SOC to input rates to linear relationships. We find that unifying the representation of key processes brings model predictions into alignment. For example, representing microbial density-dependence in MEND leads to predictions that more closely mirror other models (e.g. MIMCS). We will discuss how these analyses are informing further developments of our multi-assumption SOC model and how this multi-assumption approach will be critical in efficiently directing future empirical studies and model development.

Nitrogen and Phosphorus Cycling at SPRUCE: Warming increases availability of crucial limiting nutrients

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Project Abstract:
Slow decomposition and isolation from groundwater mean that ombrotrophic peatlands store a large amount of soil carbon (C) but plant growth is constrained by the low availability of nitrogen (N) and phosphorus (P). To better understand the role these limiting nutrients play in determining the C balance of peatland ecosystems, we compiled comprehensive pretreatment N and P budgets for the S1 Bog (Salmon et al, 2021) and documented changes in N and P availability following the implementation of whole ecosystem warming treatments at SPRUCE. Pretreatment nutrient budgets showed that N accumulates in the bog ecosystem at 0.2 ± 0.1 g N m^{-2} y^{-1} while annual P inputs were generally balanced by losses from the bog ecosystem. Plant functional types (PFTs) varied in their degrees of N versus P limitation, allocation across tissues, and internal recycling of N and P. Building on these pre-treatment measurements, we used ion-exchange resins to investigate the seasonal and annual effects of warming and elevated [CO_2] on plant-available N and P in the SPRUCE enclosures. We found that warming increased resin-available NH_4-N and PO_4-P at similar rates, but the magnitude of the response increased over time and varied across the highly heterogeneous bog surface and with peat depth. In recent years, we observed a large increase in resin-available N and P in surface peat that was inversely related to the warming-induced decline of *Sphagnum* nutrient requirements. The ELM-SPRUCE terrestrial biosphere model captured N pools and fluxes better than P when simulating pre-treatment conditions. In response to warming, however, the model tended to underestimate the increase in plant-available nutrients, especially in deeper peat. ELM-SPRUCE predictions of peatland nutrient cycling under climate change scenarios must therefore account for the initial distribution of N and P across peatland soil and vegetation pools as well as the interplay between vegetation nutrient acquisition and microbial activity across microtopography and depth. Together, our pre- and post-treatment analyses highlight the role that N and P cycling play in: (1) determining ecosystem structure and function and (2) advancing our ability to predict the C balance of warming peatland ecosystems.

Belowground Plant Trait Strategies Across The World

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Project Abstract:
Land plants have developed diverse strategies to acquire soil resources for over 400 million years, but only recently have we started to comprehend the ecosystem-scale consequences of belowground plant trait strategies and their response to changing environmental conditions. In peatlands, one of the planet's most carbon-dense ecosystems, warming increases the length of ericaceous shrub roots by as much as 130% per °C. In turn, warmer peat temperatures are associated with increased abundance of fungal rhizomorphs and lengthening of the belowground active season. Taken together, these changes may affect peatland ability to store carbon into the future. Current investigations of plant-fungal interactions at the SPRUCE experiment show that plants rely on both their fine roots and symbionts for resource acquisition and that warming heighten their reliance on fine roots. These results will further our understanding of belowground acquisition strategies effects on carbon dynamics in peatlands. At the global scale, the Fine-Root Ecology Database (FRED) has been at the forefront of efforts to fill gaps in our understanding of belowground trait variation. Results from our team and international collaborations have revealed species-specific tradeoffs in mycorrhizal association and root traits as well as linkages within and among above- and belowground plant traits. In addition, we have released a third version of FRED that now includes a searchable interface so that scientists may filter more than 150,000 root trait observations according to their interests. Furthermore, we continue to harvest data from underrepresented tundra and tropical ecosystems. Site-specific observations of rooting distribution and dynamics in response to changing environmental conditions at SPRUCE, along with a global perspective provided by FRED, are serving as the foundation to improve the representation of fine-root form and function in the E3SM Land Model.

Plant Physiological Response to Whole Ecosystem Warming and Elevated CO_2

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Project Abstract:
Climate warming has an outsized impact on boreal and arctic biomes, with significant implications for ecosystem carbon uptake and atmospheric feedbacks. At the southern edge of the boreal forest large, open-topped enclosures are exposing a natural peatland to whole-ecosystem warming × CO_2 enrichment (https://mnspruce.ornl.gov/). After only a few years of warming and CO_2 treatments, the plant community in this bog ecosystem is showing signs of stress with crown damage, branch tip dieback and even mortality in the conifer species: the deciduous *Larix laricina* and evergreen *Picea mariana.* Similar results have been exhibited by the woody shrubs, *Chamaedaphne calyculata* and *Rhododendron groenlandicum*, which incidentally are also experiencing increased herbivory with warming. We examined the mechanisms of the hydraulic damage, hypothesizing that, even in this ecosystem characterized by saturated soils, evaporative demand created by elevated temperatures could exert critical tension on the hydraulic system, leading to dysfunction in the xylem.

We found increased vapor pressure deficient, driven by air temperature, translated into greater plant water stress. Interestingly, diurnal water potential patterns revealed contrasting hydraulic strategies in the two tree species, with *Picea* operating conservatively, below its turgor loss point, while *Larix* operated at or above its turgor loss point, increasing water use with warming. Despite the divergence in water stress patterns, both species experienced a significant increase in hydraulic dysfunction with warming, measured as an increase in native xylem embolism. Using microscopy, we also assessed xylem area, ring width, lumen area and density – characteristics linked to hydraulic function. While there was large variability in growth ring width response to warming, elevated CO_2 + warming resulted in a significant increase in xylem wood production in branches, which can facilitate greater water movement though the stem.

Together our results show that elevated evaporative demand can strain plant hydraulic systems even in regions not at risk of severe soil water limitation. But there is some evidence that warming stress may be offset by increased CO_2, which can both increase availability of non-structural carbohydrates and reduce water stress. Now in our sixth year of treatments, we continue to track changes in hydraulic responses to understand what acclimation mechanisms plants may leverage to overcome the severe heat/water stress imposed by the treatments.

Root Function - Process-Level Studies Focused on Mycorrhizae, Drought, Temperature and Neutron Imaging

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Project Abstract:
Assessment of root function is extremely difficult, but new field techniques and advances in imaging technology are allowing unprecedented insight into root dynamics. Neutron imaging is highly sensitive to hydrogen ions, thus biological material and water are readily visible, which allows for *in situ* assessment of root structure, root growth, root water uptake & internal root water transport. 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 root water extraction rates by cottonwood ranged from 0.003 to 0.02 g cm^{-2} h^{-1}, with lower rates for larger roots. Across species, root rhizosphere development increases with root size, stabilizing as roots reach ~2 mm in diameter, likely linked to their suberization. Neutron radiography has also indicated significant root and mycorrhizal impacts on soil hydraulic parameters, including hydraulic conductivity and residual water content. Presence of mycorrhizae led to more even water extraction rates in soil areas with and without roots, as well as increased shoot:root ratio. Results are important for testing and improving models of root water uptake and its linkages to root traits – one easy model improvement is to use root biomass as a modifier of hydraulic parameters. Other key root processes that models are sensitive to include dynamics of root carbon allocation, relationships between roots and mycorrhizal fungi, root nutrient uptake, and root respiration and acclimation to temperature. In poplar exposed to two levels of warming, photosynthetic acclimation and biomass increased for both treatments, whereas belowground, peak biomass was achieved by the intermediate treatment, and root respiration suppressed at the highest temperature. Respiration rates of intact root systems of mature trees increased their contribution to total soil CO_2 efflux with warming, particularly for acquisitive root strategies, as represented by root functional trait space axes related to high specific root length, high root tip abundance, and low root tissue density Here, we leverage field and chamber-based neutron imaging techniques to assess root functional dynamics *in situ*, particularly patterns of water uptake and respiration linked to species and root traits. We also

discuss current and future improvements in neutron imaging analysis and application to belowground systems.

The Missouri Ozark AmeriFlux Site: An Ecosystem Observatory Enabling Improved Understanding of Drought Impacts on Deciduous Forests

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The Missouri Ozark AmeriFlux (MOFLUX) site was established in 2004 in the Ozark Border Region of Central Missouri. The site is located in a *Quercus-Carya* forest, and high precipitation variability induces frequent physiological drought stress, a situation that is often is exacerbated by the comparatively thin soils. MOFLUX (AmeriFlux ID, US-MOz) is instrumented to monitor processes from roots-to-shoots and leaf-to-landscape. It is based around a tower that is equipped for observing ecosystem fluxes using the eddy covariance technique, and more recently, canopy scale sun-induced chlorophyll fluorescence (SIF). In addition to the extensive suite of automated instrumentation, routine biometric and ecophysiological data, including weekly to biweekly measurements of community predawn leaf water potential (Ψ_{leaf}) are collected. MOFLUX has evolving scientific objectives driven by ever-deepening understandings of ecosystem processes. However, the core ecosystem flux and supporting datasets provide an invaluable long-term perspective on how drought dynamics and extreme events shape the function and structure of temperate deciduous forests and are essential for developing and testing ecosystem models. Here, we provide an overview of the MOFLUX site and highlight the science enabled by novel long-term observations and current ongoing science activities. Specifically, we will report the following:

- We conducted novel analyses leveraging coordinated Ψ_{leaf} and ecosystem gas exchange observations. First, we synthesized Ψ_{leaf} (predawn and mid-day) with ecosystem gas exchange to estimate the ecosystem scale hydraulic conductance (K_{eco}). K_{eco} represents a significant constraint on ecosystem transpiration and gross primary productivity that increases during drought. In a separate analysis, we used community predawn Ψ_{leaf} and evapotranspiration observations during a major drought to deduce an ecosystem scale wilting point. The ecosystem wilting point is an ecosystem property tightly related to drought responses, and results imply canopy traits governing wilting are coordinated with root system traits and soil characteristics.
- We developed a three-way carbon dioxide flux-partitioning algorithm that separates net ecosystem exchange into above-ground plant respiration, below-ground root and soil

respiration, and gross primary production. We found that on annual time scale, belowground soil respiration dominates over aboveground plant respiration in total ecosystem respiration but the relative contributions of different sources vary seasonally.

- Current research activities include an increased emphasis on connections between above and belowground processes, on observing and interpreting canopy SIF to enable improved scientific understanding of ecosystem physiology, and on developing an integrated model of photophysics, photochemistry and biochemistry of photosynthesis for applications in ecosystem models.

Changes in Soil Microbial Community and Function with Changes in Soil Moisture and Texture

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Project Abstract:
Soil microbes are very sensitive to soil moisture, but there are many reasons to explain observed changes in CO_2 fluxes. Generally, at lower soil moisture, CO_2 emissions decrease, which could be attributed to changes in substrate availability, soil microbial biomass and community composition, microbial dormancy, and enzyme activity. Under transient (wetting-drying) conditions, breaking of soil aggregates can alter substrate availability, microbial community composition can change, and microbes can protect themselves from death through osmolyte (metabolite) production. Here, a set of lab incubations involving 3 different soil textures (sandy, loamy, and clayey soils) were conducted over a range of soil moistures and over steady-state and transient conditions. The steady state moisture manipulation showed different moisture optima for highest microbial respiration for different textured soils. Extractable organic carbon was greatest under dry conditions, and carbon degrading enzyme activity was lowest, indicating lower microbial activities for all soil textures. The transient incubation experiment sought to understand mechanisms fueling the "Birch effect", by comparing soils that were air-dried and at water holding capacity, under both steady-state (55% water holding capacity) and transient conditions. We found higher cumulative soil organic carbon loss under transient moisture state compared to steady state, and that different mechanisms contributed to the Birch effect in different textured soils. In sandy soil, metabolite accumulation and changes in bacterial community structure were the most important Birch effect responses; while in loamy and clayey soils, metabolite accumulation and release of aggregate protected carbon were more important. Therefore, the response of microbial respiration to changing soil moisture will strongly depend on the sensitivity to textural differences. Finally, a field-scale moisture manipulation experiment – drought, rainfed, and irrigated – in a soybean field in western Tennessee showed decreases in CO_2 emissions and enzyme activity concomitant with increases in microbial biomass and extractable organic carbon under the imposed drought compared to rainfed and irrigated conditions. This likely suggests increased microbial dormancy and substrate accumulation under drought conditions, which may fuel CO_2 emissions upon rewetting. This comprehensive set of

analyses provides key information on how microbes respond to changes in moisture as a function of soil texture, under both steady state and transient conditions, and ranging from lab to field scales.