# Terrestrial Ecosystem Science

**Summary of projects awarded in summer 2019 under the Terrestrial Ecosystem Science Funding Opportunity Announcement DE-FOA-0002043.**

## Program Overview

The goal of the Terrestrial Ecosystem Science (TES) activity in the U.S. Department of Energy's Office of Science, Office of Biological and Environmental Research (BER) is to advance a robust predictive understanding of terrestrial environments, extending from bedrock to the top of the vegetated canopy and from molecular to global scales in support of DOE's energy and environmental missions. Using an iterative approach to model-driven experimentation and observation, interdisciplinary teams of scientists work to unravel the coupled physical, chemical and biological processes that control the structure and functioning of terrestrial ecosystems across vast spatial and temporal scales. State-of-science understanding is captured in conceptual theories and models which can be translated into a hierarchy of computational components and used to predict system responses to perturbations caused, for example, by changes in climate, extreme events, etc. Basic understanding of the system structure and function is advanced through this iterative cycle of experimentation and observation by targeting key system components and processes that are suspected to most limit the predictive skill of the models. TES, along with the Subsurface Biogeochemical Research activity collectively form the Environmental System Science (ESS) program.

## Funding Opportunity Announcement Overview

The Funding Opportunity Announcement DE-FOA-0002043, was issued by the Terrestrial Ecosystem Science program and was released in the winter of 2018. The goal of this FOA was to improve the representation of terrestrial ecosystem processes, with a view towards advancing sophistication and accuracy of Earth system models (e.g, Energy Exascale Earth System Model, E3SM), thereby improving the quality of Earth and environmental model projections and providing the scientific foundation needed to support DOE's science and energy missions. Applications to this FOA were expected to take a systems approach to understand ecosystems over the multiple temporal and spatial scales that are represented in models (e.g., single process models, ecosystem models, and global models such as the E3SM). This emphasis on the capture of advanced empirical and theoretical understanding in models has two goals. First, it sought to improve the representation of these integrated processes in coupled models, thereby increasing the sophistication of the projections. Second, it encouraged the community to understand and use a diversity of existing models and to compare model results against observations or other data sets to identify knowledge gaps and future research directions. It also sought to encourage an iterative dialog between the empirical and modeling research communities such that research objectives are co-designed to address key model deficiencies and that modeling efforts are designed to inform empirical research. By connecting the modeling and experimental components, this approach maximizes the return on scientific investments by reducing duplication of efforts and encourages collaboration, thus generating a significant benefit to both the Department of Energy and the scientific community. Research in environmental system science also provides a public benefit through experiments, observations and modeling that acts to inform next-generation model projections of ecosystem processes and disturbances that can be used in decision support.

Overall, the FOA considered research applications that included and coupled measurements, experiments, modeling or synthesis to provide improved quantitative and predictive understanding of terrestrial ecosystem spanning the continuum from the bedrock through vegetation to the atmospheric interface. All projects were required to clearly delineate an integrative, hypothesis-driven approach and clearly describe the existing needs/gaps in state-of-the-art models. Applicants were required to provide details on how the results of the proposed research, if successful, would be incorporated into models and model frameworks of terrestrial ecosystems. While the TES program support a broad spectrum of fundamental research in environmental system science and considered research applications within this scope, this FOA particularly encouraged applications in the following two Science Areas:

<u>Science Area 1 – Interactions and Feedbacks between Above- and Belowground Processes</u>: Improved understanding of the interactions and feedbacks among key above- and below-ground ecological and biogeochemical components/ processes that span the functional soil-microbe-plant-atmosphere continuum, that in turn enables robust process level understanding and improved Earth system projections across scales, such as;

- An integrated systems approach that examines multi-scale processes across a soil-microbe-plant-atmosphere continuum is needed to better understand and project feedbacks of key processes at various temporal and spatial scales.
- This coupled systems approach that enables better understanding of uncertainties associated with interdependent processes that influence or control biogeochemical pools and fluxes, (e.g., aboveground plant-mediated transformations such as priming and hydraulic redistribution, plant-microbe interactions such as mycorrhizal interactions, regulation of biogeochemical fluxes, and nutrient redistribution, and belowground drivers/regulators of photosynthesis and evapotranspiration, including water availability (including precipitation);
- Provide new insights on the conceptualization and mechanistic model representation of coupled ecological and biogeochemical interactions and feedbacks between the above- and belowground system compartments/continuum in response to changing Earth and environmental systems;
- Utilize trait-based approaches, examine coupled biogeochemical cycles, system thresholds, and/or factors that create and sustain biogeochemical “hot spots” and “hot moments” within scope described above. Interactions and feedbacks across this continuum with a specific emphasis on critical biogeochemical transformations across spatial and temporal scales.

<u>Science Area 2 – Role of Disturbance at the Terrestrial-Aquatic Interface</u>: New or improved understanding of the vegetative and/or coupled biogeochemical processes at the coastal terrestrial-aquatic interface that are influenced by extreme or compounding disturbances which have the potential for direct feedbacks to the Earth system;

- Terrestrial-aquatic interfaces were limited to coastal ecosystems located adjacent to oceans, including salt and brackish wetlands, and estuaries with research focus limited to those processes that incorporate and connect directly to terrestrial ecosystems and processes;
- Improve the understanding and representation of vegetation and/or coupled biogeochemical processes at the TAI directly influenced by extreme or compounding disturbances (e.g., extreme events, such as hurricanes, droughts, fires and nor'easters, and/or less severe compounding events, such as sea level rise, rising atmospheric CO2, rain frequency, nutrient runoff, inundation, storm surge, etc.).

Overall, proposed research was intended to fill critical knowledge gaps, including the exploration of high-risk approaches. BER encouraged the submission of innovative riskier, exploratory applications with potential for future high impact on terrestrial ecosystem research.

Seven awards (two of which were exploratory awards) were made through this Funding Opportunity Announcement totaling $5,573,879 over three years.

## Funded Projects

**Water Foraging with Dynamic Roots in E3SM: The Role of Roots in Terrestrial Ecosystem Memory on Intermediate Time Scales**

- **Principle Investigator:** Max Berkelhammer (University of Illinois, Chicago)
- **Collaborators:** Miquel Gonzalez-Meler (University of Illinois, Chicago); Beth Drewniak (Argonne National Laboratory)
- **Total Award:** $299,554 over 2 years

Terrestrial ecosystems often display a sustained response to climate anomalies, such as drought, for multiple years after the event has occurred. This phenomenon - often referred to as "legacy" or "memory" - is poorly represented in earth system models. This observation highlights the presence of missing dynamics in these models and limits their capacity to provide skillful forecasting information for multiple years. While numerous hypotheses exist to explain the presence of intermediate-scale memory in terrestrial ecosystems, existing work on this topic has largely neglected the role that changes in root profiles play in generating legacy. We hypothesize that as root systems forage for water, the modified depth distribution of fine roots persists for multiple years. The root legacy, in turn, alters ecosystem primary productivity and net exchange of carbon with the atmosphere. These root dynamics are not standard components of current earth system models, which generally use simplifying assumptions about the passivity of root systems including static depth profiles and a fixed period of time for root mortality (i.e. turnover time). These assumptions are in contrast to observations, which have noted highly plastic profiles and turnover times for fine roots that vary between months and years. Theory and observations thus suggest that the addition of dynamic root profiles and both longer and more heterogeneous root turnover times in earth system models would enable multi-year legacy effects to emerge in model simulations.

This proposal will use a recently a developed dynamic root model within the Energy Exascale Earth System Model (E3SM) to explore the role that root dynamics play in multi-year ecosystem legacies for three long term forested AmeriFlux sites in the central United States. One of the challenges in developing and applying a dynamic root model for earth system models is the absence of datasets to validate temporal variability in root systems beyond 1 or 2 seasons. To address this challenge, we will generate a reconstruction of root dynamics for 4-5 decades using a recently developed approach to study root water uptake from high resolution isotopic analysis of tree ring cellulose. This data will provide an empirical constraint on the variability of root dynamics over decadal timescales in response to a wide spectrum of external forcing such as drought and heat waves. This unique observational dataset will then be used to find optimal model configurations for root turnover times and foraging dynamics within E3SM. Using an ensemble of model simulations that include and exclude optimal root dynamics, we will then quantify how modulating belowground roots enhances aboveground legacy effects. By improving the representation of legacy effects in earth system models, this project will improve the capacity for this model to provide near term (1-2 year) projections. The proposed work plan will also provide a general experimental and modeling framework that can be applied more broadly across other AmeriFlux and National Ecological Observatory Network (NEON) sites. Lastly, the multi-decadal validation dataset will be available to continue to test dynamic root models in other models such as the Functionally-Assembled Terrestrial Ecosystem Simulator (FATES) and Community Terrestrial System Model (CTSM).

**Biophysical Processes and Feedback Mechanisms Controlling the Methane Budget of an Amazonian Peatland**

- **Principle Investigator:** Timothy Griffis (University of Minnesota)
- **Collaborators:** Erik Lilleskov (USDA Forest Service); Randall Kolka (USDA Forest Service); Daniel Roman (USDA Forest Service); Rod Chimner (Michigan Tech University); Jeffery Wood (University of Missouri); Dennis Del Castillo Torres (Instituto de Investigaciones de la Amazonia Peruana, Iquitos, Peru); Lizardo Fachin Malaverri (Instituto de Investigaciones de la Amazonia Peruana, Iquitos, Peru); Hinsby Cadillo-Quiroz (Arizona State University); Dan Ricciuto (Oak Ridge National Laboratory)
- **Total Award:** $999,998 over 3 years

Problem Statement: Tropical peatlands are a major methane ($CH_4$) source and represent an important biophysical feedback factor acting on Earth's radiative forcing. There is evidence in recent years for an increase in global $CH_4$ mixing ratios (> 6.7 ppb per year from 2009 to 2017) with a pronounced increase in equatorial zones. Global top-down and carbon-13 isotope analyses suggest that this increasing trend has largely been driven by changes in natural biogenic sources in response to warmer and wetter tropical conditions. However, large uncertainties in these source estimates persist because of a lack of $CH_4$ observations in the tropics, and it is difficult to rule out other factors such as increased anthropogenic emissions or reductions in $CH_4$ sink activity. Furthermore, the largest expanses of tropical peatlands are located in lowland areas of Southeast Asia, the Congo Basin, and the Amazon Basin where observations are sparse. The Loreto Province of Amazonian Peru is comprised of about 36,000 $km^2$ of peatlands, however, the extent of these low elevation peatlands has only recently been documented and little is known about their biogeochemistry and ecophysiology. Our proposed research, therefore, aims to address these knowledge gaps by providing much needed data regarding the biogeochemistry of $CH_4$ cycling in tropical Amazonian peatlands and developing and testing an Earth System Model that can be used to forecast how hydrometeorological variations and changes in peatland structure in tropical regions will influence the $CH_4$ budget of the atmosphere. Here, we propose to use the United States Department of Energy's Energy Exascale Earth System Model (E3SM) land surface component (ELM) in a synergistic fashion with field experiments and modeling activities mutually informing new scientific understanding.

Objectives:
A. Evaluate and modify algorithms within the ELM land surface model to improve its ability to simulate $CH_4$ production and consumption in tropical peatlands and assess potential feedbacks acting between hydrometeorological forcings and the carbon balance of these neotropical peatlands;

B. Determine the magnitude of the inter-annual variability of the $CH_4$ and $CO_2$ budgets and examine how hydrometeorological and ecophysiological factors influence these budgets;

C. Assess how much $CH_4$ is produced and transported to the atmosphere via living and dead trees compared to the diffusive flux from peat soil and ebullition events;

D. Examine the importance of anaerobic oxidation of methane (AOM) in determining the $CH_4$ budget and evaluate its representation in ELM;

E. Determine how photosynthetic and respiratory activity varies through time and space and how they influence the $CO_2$ and $CH_4$ budgets at short (hourly) to inter-annual timescales.

Potential Impact: The proposed field experiments and modeling activities will advance scientific understanding of biogeochemical cycling dynamics in Amazonian peatlands and the representation of these ecosystems within an Earth System Modeling framework. The experimental and modeling activities will be synergistic and inform one another to reduce the uncertainty regarding future $CH_4$ emissions and feedbacks to climate in a region where $CH_4$ cycling is hypothesized to be highly sensitive to climate. The modeling activities will provide new insights regarding $CH_4$ emissions for an ensemble of plausible climate change scenarios for the region over the time period 2020 to 2080.

**Exploring Halophyte Hydrodynamics and the Role of Vegetation Traits on Ecosystem Response to Disturbance at the Terrestrial-Aquatic Interface**

- **Principle Investigator:** Ashley Matheny (University of Texas, Austin)
- **Collaborators:** Chonggang Xu (Los Alamos National Laboratory); Matteo Detto (Princeton University/ Smithsonian Tropical Research Institute); Annalisa Molini (Masdar Institute at Khalifa University of Science and Technology); Timothy Shanahan (University of Texas, Austin)
- **Total Award:** $882,483 over 3 years

Mangroves grow along tropical and subtropical coastlines and intertidal zones, and are therefore very rarely limited by root-zone moisture availability. However, during the dry season, these ecosystems have been shown to behave more similarly to semi-arid ecosystems than well-watered forests. The process of salt exclusion from sea- and brackish waters during root-water uptake provides an additional energy and rate limiting step in water transport along the soil-plant-atmosphere continuum. This adaptation is responsible reductions in transpiration rates due to high tensions in the xylem system, in spite of adequate water availability. Reductions in transpiration cause increases in sensible heat flux rather than latent heat leading to an energy balance characteristic of a water-limited ecosystem. Current land-surface modeling technologies use a semi-empirical relationship to connect stomatal conductance directly to soil moisture, and are unable to replicate the behaviors of halophytes leading to errors in energy balance partitioning throughout tropical coastlines.

We propose to develop a salt-tolerant root-water uptake model for the FETCH2 advanced vegetation hydrodynamics model that will be capable of mechanistically simulating osmoregulation by halophytic plants such as mangroves. The FETCH2 model will then be integrated into the land-surface model component of the DOE's Energy Exascale Earth System Model (E3SM) as a replacement for the current direct link between soil moisture and stomatal conductance. FETCH2 approximates flow through the xylem of plants as a flow through porous media and accounts for dynamic changes to conductance and capacitance of plant tissues caused by changes in water content. Parameter sets within FETCH2 are based on measurable hydraulic traits including stomatal sensitivity, xylem and root vulnerability to hydraulic impairment (embolism), and rooting depth, among others. However, studies have shown that these above and belowground hydraulic traits can be highly plastic and vary both spatially and temporally. Therefore, we will couple our model development with an extensive field study of mangrove hydraulic traits, their variability, and their influence on plant and ecosystem level fluxes of carbon, water, and energy.

Atmospheric demand for water vapor and soil water availability are the primary determinants of vegetation water stress for terrestrial plants. Yet in the unique case of mangroves, salinity supersedes the control of soil water availability. Our study is designed to analyze mangrove forest function across both humidity and salinity gradients which are predicted to change in response to compounding disturbances such as sea level rise, enhanced variability in precipitation and overland runoff, inundation frequency, and increased atmospheric $CO_2$. We will combine ecosystem scale measurements of carbon, water, and energy flux with plant-level observations of sap flux, biomass water content, and leaf level gas exchange, and analysis of emergent above and below ground plant hydraulic traits in three field sites spanning a strong humidity gradient from Panama (humid), to the US Gulf Coast (subhumid), and Abu Dhabi (arid). Within each site, tidal influences, evaporation, and surface runoff create a salinity and water depth gradient from landward to ocean-ward edge. We propose to analyze trait plasticity along the axes of atmospheric response (across sites), salinity response (within sites), individual and species controls (individuals and species within and across sites), and temporal controls (across wet and dry seasons and years). This analysis of above and belowground trait plasticity will facilitate the development of a flexible parametric ‘trait-space’ for FETCH2. We hypothesize that such a trait-based plant hydrodynamics model will more accurately represent water, carbon, and energy exchange at the terrestrial-aquatic interface along tropical coastlines.

### Unraveling the Mechanisms of Below- and Aboveground Liana-Tree Competition in Tropical Forests

- **Principle Investigator:** David Medvigy (University of Notre Dame)
- **Collaborators:** Jennifer Powers (University of Minnesota); Peter Tiffin (University of Minnesota); Jerome Chave (CNRS Toulouse, France); Isabelle Marechaux (INRA Montpellier, France)
- **Total Award:** $999,869 over 3 years

Lianas, or woody vines, are abundant throughout forests worldwide. However, their effect on total forest biomass is puzzling from ecological and biogeochemical perspectives. Lianas are thought to directly contribute much less to total forest biomass than trees because lianas are typically more slender than trees. However, recent experiments have established an indirect effect of lianas on tropical forest biomass. In one case, tropical forest plots were intentionally cleared of lianas; tree growth rates in these cleared plots were monitored for several years, and then compared to tree growth rates in uncleared plots. The results were staggering: tree wood production was 75% greater in plots cleared of lianas than in the uncleared plots. To make this extra wood, the cleared plots absorbed 75% more carbon dioxide from the atmosphere than the uncleared plots. The exact reasons for this large indirect effect on biomass are still under debate.

A mechanistic, predictive model can, in principle, trace the essential lines of cause-and-effect and explain why lianas so strongly affect forests. Vexingly, however, lianas are not represented at all in current-day models, and so the modeling approach has not yet been leveraged. Indeed, current models cannot address how lianas affect the strength of the intact tropical forest carbon dioxide sink, which has helped buffer the Earth system against changes in climate, nor can they answer why liana infestation has been observed to have increased in intact tropical forests in recent decades. In order for these gaps to be filled and for accurate liana-predicting models to be developed, better knowledge of liana-specific morphology and allocation, both above- and belowground, is required. This project has three overarching objectives related to observations, modeling, and synthesis.

Observations: Field measurements will be made in tropical dry forests in Guanacaste, Costa Rica. First, excavations of entire trees and lianas will be carried out to enable measurement of belowground (coarse and fine root) and aboveground (woody stem, branch and leaf) biomass of co-occurring trees and lianas, as will coarse and fine root vertical distribution and lateral spread. Second, liana trait measurements will be made including xylem vessel diameter and length, turgor loss point, hydraulic conductivity, vulnerability to embolism, wood density, and specific leaf area. Third, above- and belowground productivity will be measured, and fine root productivity will be assigned to species using high-throughput DNA sequencing. Fourth, a throughfall exclusion experiment (designed to generate drier-than-usual soils) will be used to distinguish the responses of lianas and trees to drought. Fifth, additional measurements will be carried out in the latter part of the project to reduce model uncertainty and improve model quality.

Modeling: Lianas will be incorporated into a mechanistic, individual-based forest dynamics model that includes both trees and lianas. The model will simulate the unique features of lianas, accounting for their structural parasitism and their different (with respect to trees) allocation strategies and morphology. The simulated trees and lianas will compete aboveground for light and belowground for water. Thus, the model will integrate above- and belowground processes and couple the carbon and water cycles. Organism traits measured as part of this project will be used to parameterize the model, and parameter sensitivity will be assessed. Measurements of below- and aboveground productivity and liana colonization and shedding will be used to evaluate the model. Once model biases and trait sensitivities are identified, additional measurements will be planned to further improve model quality.

Synthesis: A working group will be established to plan for the incorporation of lianas into Earth system models (ESMs). About 25 participants are anticipated, with expertise thoroughly covering ESMs, modeling, lianas, roots, and tropical ecology.

In summary, this project includes tightly coupled, synergistic modeling and measurement campaigns. Novel measurements of liana below- and aboveground allocation, productivity, and function will allow the development of an unprecedented liana-simulating forest dynamics model. By tying the coupled model-measurement approach proposed here to the synthesis working groups, this project will achieve better representation of tropical forests in ESMs is essential for simulating global carbon cycle dynamics. Given the recent increases in liana abundance, inclusion of lianas in ESMs will be necessary to achieve a robust, predictive understanding of coupled biogeochemical processes and cycles. This project will also generate publicly-available (via ESS-DIVE) products, including ecological field measurements, DNA barcodes, model source code, and model simulations.

**Testing Mechanisms of How Mycorrhizal Associations Affect Forest Soil Carbon and Nitrogen Cycling**

- **Principle Investigator:** Caitlin Hicks Pries (Dartmouth College)
- **Collaborators:** Nina Wurzburger (University of Georgia); Richard Lankau (University of Wisconsin, Madison); Benjamin Sulman (Oak Ridge National Laboratory)
- **Total Award:** $999,995 over 3 years

Symbiotic mycorrhizal fungi are major drivers of forest soil biogeochemical processes. Mycorrhizal fungi provide trees with nutrients and in return, the trees provide the fungi with organic carbon. There are two main types of mycorrhizal associations—arbuscular mycorrhizae and ectomycorhizae—which differ in how they interact with plant roots and acquire nutrients. Most tree species associate with one of these mycorrhizal types. Generally, trees that associate with arbuscular mycorrhizae have faster-decomposing leaves than trees that associate with ectomycorrhizae. Tree mycorrhizal associations are thus a promising framework by which to study the effect of aboveground tree communities on belowground soil processes. However, most research on mycorrhizal associations has occurred across natural gradients and has not involved manipulative experiments that can address mechanisms and causation. There are two competing hypotheses to explain how mycorrhizal association affects soil carbon and nitrogen that have yet to be resolved: mycorrhizal nutrient acquisition strategies versus inherent differences in litter decomposability. Due to the widespread changes in the tree species composition of temperate forests due to climate-driven range shifts, oak decline, and invasive pests, a mechanistic understanding of mycorrhizal associations is key to accurately predicting the consequences of changing forest composition in biogeochemical models.

Our main objective is to understand the degree to which the observed differences in soil carbon and nitrogen dynamics in ectomycorrhizal (EcM) and arbuscular mycorrhizal (AM) dominated forests are driven by litter decomposability versus mycorrhizal fungal function using targeted experiments, and to incorporate this knowledge into a process-based soil organic matter model. Previous model simulations based on litter decomposability suggest there is a larger proportion of mineral-associated organic matter in AM forest stands relative to EcM forest stands. However, preliminary data suggest that mycorrhizal fungal abundance is a stronger driver of soil organic matter patterns than litter. To achieve our objective, we will test the mechanisms by which soil carbon and nitrogen are affected by mycorrhizal dominance via two novel experiments: 1) a growth chamber experiment across four EcM and five AM tree species using a $^{13}C$-labeled atmosphere to trace seedling-derived carbon into hyphae, the rhizosphere, and various soil fractions; and 2) an in situ decomposition experiment of six different $^{13}C$ and $^{15}N$ labeled litters that range in decomposability incubated across a gradient of EcM dominance at three sites that capture important variation in climate, soils, and forest species composition. Our experiments are motivated by uncertainties in model structural representation of plant-mycorrhizae-soil interactions, and the results of our experiments will inform a mycorrhizal community-explicit version of the soil organic matter model named FUN-CORPSE. This new version of FUN-CORPSE will be developed simultaneously with the experiments, tested or parameterized using the experimental data, and used to project the consequences of several global change scenarios.

Key outcomes of this work will include (1) a mechanistic understanding of how mycorrhizal associations affect soil carbon and nitrogen cycling; (2) a parameterized and tested soil organic matter model incorporating mechanistic differences between major mycorrhizal types using a model framework that has already been successfully coupled into global land surface models; (3) experimental constraints on mycorrhizal model parameters that have been previously identified as key sources of predictive uncertainty; (4) empirical tests of whether incorporating mycorrhizal function into models leads to more accurate estimates of forest soil carbon and nitrogen cycling. The improved model will enhance our ability to predict how soil carbon and nitrogen across the Eastern U.S. will be affected by global change.

**Coupled Long-Term Experiment and Model Investigation of the Differential Response of Plants and Soil Microbes in a Changing Permafrost Tundra Ecosystem**

- **Principle Investigator:** Edward (Ted) Schuur (Northern Arizona University)
- **Collaborators:** Yiqi Luo (Northern Arizona University)
- **Total Award:** $999,972 over 3 years

We established a new type of multifactor ecosystem experiment in 2008 at the Eight Mile Lake watershed in the foothills of the Alaska Range that was designed to significantly warm deep soil and degrade permafrost (perennially-frozen) ground. Within this framework, we also manipulate the seasonal water table within the soil profile. For ten years, this manipulation has degraded an increasing amount of permafrost each year, more than doubling the growing-season depth of ground thaw. Warming alone has resulted in wetter soils as a result of ground subsidence, and the drying treatment counteracts that effect by significantly reducing the soil water table. This warming and drying experiment represents a one-of-a-kind system that that influences air and deep soil temperatures, permafrost, and creates wetter and drier soil moisture conditions that are primary drivers of changing tundra ecosystems across the entire Arctic landscape. This unique long-termexperimental framework allows us to study the coupled responses of plant and soil microbial communities to environmental change. The vastly different timescales that shape the aboveground plant community and the belowground soil microbes impacts the trajectory and timing of carbon release and uptake across high latitude regions with critical implications for global climate. Soil microbial communities have the potential to respond relatively quickly to a changing environment, converting thawed organic matter into carbon dioxide and methane. In contrast, the slow growth rates and successional dynamics typical of these long-lived perennial plants means that change in the plant community in response to disturbance and a changing environment can play out over decades to a century, and are unlikely to match short-term responses.

The goal of this proposal is to address the following overarching question: How does the response of plants and soil microbes to changing environmental conditions affect permafrost ecosystem carbon balance over decadal timescales? We hypothesize that soil microbial communities will respond rapidly to environmental changes associated with permafrost thaw. This will result in the decomposition of old soil carbon that has been stored in these ecosystems due to cold temperatures. However, the trajectory of thawed permafrost soils into wetter and drier alternate states due to ground subsidence will determine whether soil saturation can continue to protect soil organic matter, as well the proportion of carbon dioxide and methane that is released to the atmosphere. Based on our latest results, we also hypothesize that changes in surface hydrology and thaw increases lateral carbon loss that can bypass the local microbial community, and that this pathway is significant in magnitude relative to direct atmospheric losses. Plant carbon uptake is expected to in part offset soil carbon losses, but this dynamic will change on a longer timescales (decades) as compared to the timescale of change for the microbial community. The plant response will be more limited than that of microbes especially where soils are dry. The slower successional dynamics of the plant community will cause greater time lags in potential long-term ecosystem carbon gain (after the initial ecosystem response phase), and also will be affected by the hydrologic change that exports nutrients and leads to the drier and wetter alternate states.

Quantifying the response of plants and soil organisms that control overall ecosystem carbonbalance requires a coupled experiment and model research approach in order to understand the global-scale implications of changes in these sentinel ecosystems. This proposal will conduct a final suite of measurements focused on new hypotheses that will complete the intensive phase of this experiment. Additionally, past work has identified critical shortfalls of model projections of the permafrost carbon feedback to climate. As one solution, mechanistic understanding from this experiment will be incorporated into an Ecological Platform for Assimilating Data framework that interactively couples measurements and modeling. The data assimilation technique will help address key structural and parameterization shortcomings of some widely-used models. Model analysis will not only provide future simulations, but will also evaluate the core experimental datasets (plants, soil, ecosystem) to determine the optimal measurement scheme for this experiment such that, after completion of this final intensive phase, long-term manipulation at lower measurement intensity could be maintained if the science continued to call for this long-term experimental perspective in the future.

**Leveraging Synthetic Root-Soil Systems to Quantify Relationships Between Plant Traits and the Formation of Soil Organic Matter**

- **Principle Investigator:** Bonnie Waring (Utah State University)
- **Total Award:** $295,967 over 2 years

Soil organic carbon (SOC) represents the largest terrestrial C pool, yet there is substantial uncertainty surrounding the ecological mechanisms that shape SOC formation and loss. Long-held paradigms about the dominant controls on soil C cycling are changing, calling for a re-evaluation of four major drivers of SOC dynamics: plant tissue traits, microbial community traits, rhizosphere dynamics, and soil mineralogy. To predict changes in SOC cycling in the long term, it is necessary to accurately represent feedbacks among these drivers in ecosystem models. However, reflecting the uncertainty induced by rapidly evolving paradigms of SOC cycling, these models exhibit wide variation in structure and parameterization, placing different emphases on primary mechanisms of SOC stabilization. Thus, the overall goal of the proposed research is to identify the mechanisms by which plant and microbial traits mediate soil C cycling, and leverage this understanding to evaluate and improve microbe-explicit biogeochemical models. To do so, this project will target two linked research aims:

- Research Objective 1: assess the independent and interactive effects of plant litter chemistry, microbial community structure, root exudation, and soil mineralogy on the formation and loss of SOC
- Research Objective 2: utilize empirical data generated in Objective 1 to evaluate and compare three influential microbially explicit biogeochemical models

Research objectives will be addressed using a new experimental platform: the creation of ‘synthetic root/soil systems.’ This approach allows for independent manipulation of chemical characteristics of plant C inputs (including root exudates), the taxonomic and functional composition of soil microbial communities, and the mineral composition of the soil matrix.

<u>Project Description.</u> To address Research Objective 1, synthetic root/soil systems will be constructed using a range of soil mineral types and microbial inoculum treatments, thereby establishing differences in microbial community-level physiological traits. Subsequently, artificial soils will be exposed to varying C inputs representing a range of chemical recalcitrance, including synthetic root exudates. Isotope tracer techniques will be used to monitor microbial biomass growth, respiratory $CO_2$ losses, and the physicochemical stabilization of C inputs. Shifts in SOC cycling will be evaluated in relation to microbial community structure and functional potential, which will be characterized through shotgun metagenomics sequencing. To address Research Objective 2, data generated during the synthetic soil study will be leveraged to evaluate three ‘microbially explicit’ biogeochemical models that represent soil C cycling as a

function of microbial physiology. These models vary in their representation of the relationships among plant traits, microbial traits, and soil C cycling, entraining different hypotheses about the dominant controls on SOC formation and loss. Each model will be run under a suite of scenarios representing the different experimental conditions established in the synthetic soils experiment. Models will be evaluated for their ability to simulate observed C pools and fluxes and their responses to experimental treatments. This exercise will provide insight on the model structures which are necessary to capture C cycle responses to shifts in plant and microbial community traits.

Potential Impact. This work will support the development of a novel artificial soil method to identify directional relationships among plant traits, microbial communities, and key biogeochemical processes that those microbes mediate. The synthetic soils experiments will allow rigorous evaluation of competing hypotheses regarding the effects of plant litter quality and root exudation on the size of the SOC sink. Moreover, these data will directly inform the structure of biogeochemical models with explicit microbial mechanisms of SOC formation and loss. This is a pressing research need, given that current models represent outdated mechanisms of soil carbon cycling and cannot accurately capture the response of the land C sink to global change.

Further information on TES objectives along with a listing of past and current funding opportunities discussed in this document, is available at http://tes.science.energy.gov/.

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