Environmental System Science

Summary of projects awarded in summer 2024 under the Environmental System Science Funding Opportunity Announcement DE-FOA-0003196.

Program Overview

The goal of the Environmental System Science (ESS) program in the U.S. Department of Energy, Biological and Environmental Research program (BER) is to advance an integrated, robust, and scale-aware predictive understanding of terrestrial systems and their interdependent microbial, biogeochemical, ecological, hydrological, and physical processes. To support this goal, the program uses a systems approach to develop an integrative framework to elucidate the complex processes and controls on the structure, function, feedbacks, and dynamics of terrestrial systems, that span from molecular to global scales and extend from the bedrock through the soil, rhizosphere, and vegetation to the atmosphere. The ESS program scope advances foundational process knowledge with an emphasis on understudied ecosystems. Supported research emphasizes ecological and hydro-biogeochemical linkages among system components and characterization of processes across interfaces (e.g., terrestrial-aquatic, coastal, urban) to address key knowledge gaps and uncertainties across a range of spatial and temporal scales. Incorporation of scientific findings into process and system models is an important aspect of the ESS strategy, both to improve predictive understanding as well as to enable the identification of new research questions and directions.

Funding Opportunity Announcement Overview

The Funding Opportunity Announcement (FOA) DE-FOA-0003196, was issued by the Environmental System Science program and released in the fall of 2023. The goal of this FOA was to improve the understanding and representation of terrestrial ecosystem and watershed science in ways that advance the sophistication and capabilities of local, regional, and larger scale models (e.g., Energy Exascale Earth System Model (E3SM)). Using new measurements, field experiments, synthesis, and/or more sophisticated modeling, this FOA encompassed three Science Research Areas (SRA): (1) plant–microbe interactions in the rhizosphere; (2) consequences of large-scale shifts in vegetation composition; and (3) synthesis studies using existing data that address testing of ESS-relevant hypotheses and development of transferable insights across ecosystems, watersheds, and regions.

Applications to this FOA were expected to take a hypothesis-driven, systems approach to understand ecosystems and watershed functioning over the multiple temporal and spatial scales that are represented in models (e.g., single process models, ecosystem or watershed models, and global models). This emphasis on the capture of advanced empirical and theoretical understanding in models had 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 datasets to identify knowledge gaps and future research directions. It also sought to encourage an iterative dialogue between the empirical and modeling research communities such that research objectives were co-designed to address key model deficiencies and modeling efforts were 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 (DOE) and the scientific community. ESS research also provides a public benefit through experiments, observations and modeling that acts to inform next-generation model projections of ecosystem processes, watershed function, and disturbances that can be used in decision support.

Overall, the FOA considered research applications that included and coupled measurements, experiments, and/or modeling to provide improved quantitative and predictive understanding of terrestrial ecosystems and watershed function 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 appropriate scale models and model frameworks. While the ESS program supports 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 Science Research Areas:

SRA 1 – Plant–Microbe Interactions in the Rhizosphere: Investigate plant–microbe interactions in the rhizosphere with respect to biogeochemical aspects of nutrient cycling and vegetation–environmental feedbacks, focused on interactions in the rhizosphere as they relate to rapidly changing environmental conditions.

For this SRA, the rhizosphere is the complex ecosystem within the soil environment where plant roots and microbial communities coexist and are influenced by hydrologic conditions, soil structure, biogeochemistry, and gaseous constituents. Applications were required to advance the mechanistic understanding of plant–microbe interactions, specifically through a systems science approach that integrates hydrology, geochemistry/mineralogy, soil structure, and gaseous constituents with microbial processes and the roots and/or root hairs of vegetation in terrestrial ecosystems. A specific focal ecosystem must be identified, and a laboratory and/or field-based experiment undertaken, to address current gaps in existing knowledge, developing fundamental mechanistic understanding that is broadly transferable/translatable across the targeted vegetation type, region, and/or ecosystem.

SRA 2 – Consequences of Large-Scale Shifts in Vegetation Composition: Investigate the consequences of large-scale vegetation shifts from disturbance, climate change, invasive species, and anthropogenic activity on below- and/or aboveground biogeochemical cycles with a focus on the mechanistic understanding of how these vegetation shifts impact below- and/or aboveground biological/microbial, and/or biogeochemical processes.

For this SRA, vegetation shifts are defined as recent (over the past 20 years) changes to vegetation species composition due to loss of previously dominant species, introduction of a previously absent invasive species, change in the relative abundance of the dominant species in a given vegetation community, or change to the dominant vegetation form (i.e., shrub encroachment into grassland or bog) and/or vegetation structure (i.e., a closed canopy becoming open savannah).

Models were encouraged to capture fundamental understanding of the consequences of large-scale shifts in vegetation composition.

SRA 3 – Synthesis Studies: Accelerating scientific discovery and building predictive understanding by harnessing existing data to identify and evaluate emergent patterns, generalizable principles, and fundamental insights from extensive existing datasets. Specifically, applications were required to address one of two subtopics, including (A) Legacy Effects – applications that will improve the understanding of legacy drivers and feedbacks to coupled soil-plant-atmosphere processes – and (B) Carbon Cycle Disturbance – applications that advance the mechanistic understanding of the processes and feedbacks that link natural episodic disturbance (e.g., wildfire, flood, hurricane, drought, heat waves) to immediate-to-long-term impacts on carbon cycle processes. Both subtopics in this SRA focused on novel, hypothesis-driven studies addressing topics within the ESS program scope that can be investigated by integrating and interrogating findings and/or data from prior observational and/or experimental research activities.

Successful applications to this limited-scope topic were required to propose new science that is focused on meta-analysis and synthesis research efforts that address development and testing of ESS-relevant hypotheses and priorities using existing data. Leveraging of existing ESS-supported data resources and networks and use of artificial intelligence and machine learning (AI/ML) techniques were particularly encouraged. The collection of new data or field research, support for field-related supplies or equipment, or travel to or maintenance of field sites or research facilities was not permitted.

Overall, proposed research across SRAs 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 ESS research.

Twelve awards were made through this Funding Opportunity Announcement totaling $8,987,609 over three years.

Funded Projects

Disentangling Fire Legacies and Climate to Advance Cross-Scale Earth System Models

- **Principal Investigators:** Raelene Crandall (University of Florida)
- **Collaborators:** Jennifer Fill and Benjamin Baiser (University of Florida)
- **Total Award:** $399,783 over two years

Plant biodiversity in grasslands is strongly affected by fire regimes. Fires that burn at different times of year can change plant communities over time, affecting ecosystem functions such as carbon storage. Over the last 30 years, the global area of grasslands has shrunk significantly due to human activities and shifting climate conditions. As the planet's climate continues to change, weather patterns are likely to interact with the legacies of long-term fire regimes to affect plant diversity in grasslands worldwide. Long-term studies at many different sites are necessary to understand universal effects, but studies of shifts in plant diversity are typically done at only a few sites for short periods of time (i.e., less than ten years), limiting an ability to generalize to other sites.

In this project, the team will synthesize 16 long-term grassland studies from different regions of the southeastern and central United States. They will identify how long-term fire regimes (legacies) and climate affect the diversity of plant species and their traits over time and space.

They will also develop predictive, trait-based models that may be used to inform Earth system models and models in other grassland regions. Specific objectives are (1) determine how fire legacies and current climate patterns change plant communities and individual species over time within sites; (2) identify trait-based functional groups and the strongest predictors (i.e., fire legacies and current climate) of their change over time across sites; and (3) measure how the relationship between biodiversity and ecosystem function changes over time and space under different fire regimes and climates.

This project will produce: (1) models of change over time in plant communities with different fire legacies; (2) models of climate and fire regime effects on variation in grassland plant traits over time; and (3) predictive models of how biodiversity and ecosystem function are affected by climate and fire regimes over time and space. The project's synthesis effort will benefit scientific researchers and modelers because the resulting models can be adjusted for use in other grasslands and in Earth System models.

Tree Growth Legacies of Combined Soil and Atmospheric Drought Across Climatic, Plant Trait, and Morphological Gradients in the United States

- **Principal Investigators:** Matthew Dannenberg (University of Iowa)
- **Collaborators:** A. Park Williams (University of California, Los Angeles), Nate McDowell (Pacific Northwest National Laboratory)
- **Total Award:** $398,756 over two years

Background
Carbon uptake by plants on land removes around 25% of anthropogenic carbon dioxide (CO_2) emissions from the atmosphere, much of which is stored in long-lived forest woody biomass. The extent to which drought affects tree growth could therefore affect both the total ecosystem carbon uptake and the amount of time it spends sequestered in the ecosystem. Droughts reduce photosynthesis and growth and increase the risk of mortality, but the nature of drought itself is changing due to warming. Anthropogenic warming has increased the vapor pressure deficit (VPD) of the atmosphere, which increases evaporative demand and thus (all else being equal) increases the rate of water loss from plants and the soil. Increasing VPD negatively affects plant function on its own, but it also increases the risk of compound "soil drought" and "atmospheric drought," wherein low soil moisture coincides with high temperatures and high VPD. During combined soil and atmospheric drought, plants are thus exposed to moisture stress on both ends of the soil-plant-atmosphere continuum.

Project Objectives and Methods
In the proposed project, researchers ask: are the negative effects of "soil drought" (low soil moisture) and "atmospheric drought" (high VPD) on growth greater than the sum of their parts? Do the legacies of combined soil and atmospheric drought persist longer? And what plant traits and characteristics make tree growth more sensitive to combined soil and atmospheric drought? Researchers will answer these questions in the conterminous U.S. using large tree-ring databases spanning tens of thousands of individual trees across hundreds of sites and dozens of species. This project will specifically examine how growth reduction during and time-to-recovery following soil-only drought, atmosphere-only drought, and combined soil and atmospheric drought vary along aridity gradients, among species with different physiological and hydraulic traits, and among trees of different sizes.

Potential Impact of the Project
The proposed project fits within the "Synthesis Studies" SRA, especially the Carbon Cycle and Disturbance subtopic, as it will "generate new knowledge and mechanistic understanding" on how an important sink for anthropogenic CO_2 emissions (forest growth) responds to the kind of global change-type drought that will become increasingly common in a warmer world. Current ecosystem models struggle both to simulate

turnover time of carbon and to simulate the legacy effects of drought on plant production and growth. Understanding the extent to which combined soil and atmospheric drought affect forest growth and its post-drought legacies would improve theoretical understanding of forest carbon cycling and guide improvement of ecosystem models, including how both soil and atmospheric drought responses and legacies are shaped by specific plant traits. The proposed research could also inform understanding of how drought in a warmer world could affect the composition of U.S. forests, which have already been reshaped by anthropogenic land use and fire management in much of the United States. Focusing on the physiological, hydraulic, and morphological traits that make trees susceptible to combined soil and atmospheric drought will shed light on how forest structure and composition may change in a hotter world.

Compound Impacts on Forest Carbon Uptake and Storage from Wind, Heat, and Drought

- **Principal Investigators:** Anna Harper (University of Georgia Research Foundation)
- **Collaborators:** Gabriel Kooperman, Thomas Mote (University of Georgia), Maria Uriarte (Columbia University), Charles Koven (Lawrence Berkeley National Laboratory), Mingjie Shi (Pacific Northwest National Laboratory), Arthur Argles (UK Meteorological Office, Hadley Centre)
- **Total Award:** $399,795 over two years

Ecosystems can be damaged by extreme events such as hurricanes, heatwaves, and droughts. The frequency and/or intensity of these disturbances is expected to increase with anthropogenic climate change. Predicting the impacts of these changing disturbances is a key challenge for global change research. Heat and drought can change forests from net absorbers of carbon to net emitters. In addition, damage to forests during these events could alter their vulnerability to damage during tropical cycles. Meanwhile, wind damage opens up the canopy and increases light availability in the understory, potentially changing the species composition of the forest. But the long-term effects of wind damage on forests composition and carbon fluxes are not well understood and difficult to project. The proposed project will analyze the effects of compound threats from tropical cyclones, heat, and drought on the carbon cycle of coastal and inland forests.

Advances in understanding of impact of compound disturbances on ecosystem carbon cycle would greatly benefit terrestrial ecosystem and dynamic global vegetation models, which are used to predict the future ecosystem structure and function and feedbacks between the carbon cycle and climate. For example, large-scale mortality due to warming and drying would result in additional carbon dioxide being released to the atmosphere, which would further exacerbate climate change.

This project will use existing datasets and provide a comparison of findings from scales spanning satellite and airborne remote sensing data and ground-based observations. The proposed work will leverage and synthesize existing data, including ground-based observations from DOE-supported resources and measurements collected at the Luquillo Long Term Ecological Research site in Puerto Rico, LiDAR measurements of forest structure, as well as satellite-based data for broader regional analysis. The proposed synthesis project will address research gaps through four objectives:

Objective 1: Create a database of compound events for the study area.

Objective 2: Apply a case study approach and machine learning methods to (A) determine the impacts of heat extremes and drought (either separately or in tandem) on vulnerability of forests to damage from strong winds, and (B) determine the impacts of hurricane-related disturbance on vulnerability of forests to future drought and/or heat extremes.

Objective 3: Use data from Puerto Rico to understand the reasons for the impacts seen at a larger-scale impacts and how they lead to either an increase or decrease in vulnerability. Objective 4: Provide datasets that can be used by process-based models that represent forest structure and wind damage to improve their representations of carbon cycle responses to compound events and wind.

The outcomes of the project will be improved mechanistic understanding of the relationship between disturbance from heat, drought, and storms; and datasets useful for validating and improving ecosystem models and future projections of the forest carbon cycle.

How do Plant-Associated Microbes Mediate Vegetation Shifts in Response to Interactive Global Change Factors in P-limited Dry Forest Systems?

- **Principal Investigators:** Jason Hoeksema (University of Mississippi)
- **Collaborators:** Nicole Hynson (University of Hawai'i-Mānoa), Jennifer Bhatnagar (Boston University), Edward Brzostek (West Virginia University), Jeff Powell, Jonathan Plett, Catriona Macdonald, David Ellsworth (Western Sydney University), Emiley Eloe-Fadrosh (DOE Joint Genome Institute)
- **Total Award:** $999,036 over three years

The compounding effects of multiple global change factors such as elevated atmospheric carbon dioxide (CO_2) concentrations (eCO_2), drought, temperature, and land use change are causing fundamental changes in biogeochemical cycles on a global scale. To date, free-air CO_2 enrichment (FACE) experiments have provided profound insights into how predicted future climate change scenarios may continue to impact ecosystems services upon which all life relies. However, FACE experiments have largely focused on fertile temperate ecosystems, which only represent a quarter of the planet's terrestrial biomes. Therefore, it remains unclear (and unlikely) that findings from temperate zone FACE sites can be applied to the remaining three quarters of the globe. For instance, in dryland, infertile subtropical forests, CO_2 enrichment has not led to an increase in ecosystem storage of carbon (C); instead, eCO_2 has caused increases in soil respiration and fundamental shifts in the understory plant community composition from mixed shrubs and grasses to specific (C3) grasses dominating. C3 grass invasion and its negative ramifications for important ecosystem functions such as water and nutrient cycling are becoming commonplace in much of the tropics and subtropics and are a pressing area of concern. Sites such as EucFACE in southeastern Australia provide a foreboding forecast of how future predicted increases in atmospheric CO_2, warming, and drought will further enhance these invasions and their negative impacts. However, the mechanisms by which understory plant communities shift under changing climate conditions are unknown, thus limiting the ability to predict which ecosystems may be most at risk.

The overarching hypothesis is that a shift to increasing relative dominance of C3 grasses under eCO_2 is accompanied by shifts in the composition and traits of critical root symbiotic fungi, resulting in reduced C storage in soil. Objective 1: Assess the consequences of eCO_2 for microbial communities and their traits and resulting shifts in dry forest understories and C cycling. Objective 2: Model and experimentally test how the interaction between eCO_2 concentrations and increased predominance of C3 grasses impacts plant-soil-microbe interactions, microbial traits, and C cycling in dry subtropical forest systems. These objectives will be accomplished through a combination of three approaches: (A) field sample analysis at EucFACE, in which microbial, and plant biogeochemical cycling (C, nitrogen (N), and phosphorus (P) pools and fluxes) will be measured, as well as plant and fungal gene expression in roots and soils, (B) controlled-environment Experimentation, using growthchamber experimentation with soil from EucFACE, in which the interactive effects of eCO_2 and understory vegetation on morphological and molecular traits of mycorrhizal fungi, and association of those traits with the performance of key C3 and C4 grasses will be tested; and (C) ecosystem modeling, in which observational and experimental data will be leveraged to improve the ability of a plant-microbial interactions model (FUN-CORPSE) to predict the impacts of eCO_2 on understory vegetation shifts, and shifts in fungal traits on coupled C-N-P cycling in forests. Outcomes and benefits of the project will include an improved understanding of the mechanisms and ecosystem consequences of vegetation shifts in the understory of dry forests in response to eCO_2, and substantial improvements in the ability of ecosystem models to capture those dynamics and project their impacts on important ecosystem services such as nutrient cycling and carbon storage.

From Rhizosphere to Forest: Scaling Shifts in Plant–Microbe Interactions in Infected Eastern Hemlocks to Predict Changes in Ecosystem Carbon and Nitrogen Cycling

- **Principal Investigators:** Ashley Keiser (University of Massachusetts, Amherst)
- **Collaborators:** Kristen DeAngelis (University of Massachusetts, Amherst), Debjani Sihi (Emory University), Benjamin Sulman (Oak Ridge National Laboratory)
- **Total Award:** $999,990 over three years

Non-native insects and diseases have proliferated across U.S. forests, resulting in a reduction of carbon (C) stored within infected live trees. However, unmeasured changes belowground could further shift ecosystem C cycling in infected forests. A combination of altered climate plus non-native pests can influence how trees interact with the soil. Chemical interactions at the root–microbial interface, called the rhizosphere, can help trees fight non-native pests by stimulating shifts in the rhizosphere microbial community or soil physicochemical properties. Exudate compounds released by the roots help provide energy for rhizosphere microorganisms to mineralize soil organic matter (SOM); thus a shift in the amount or composition of exudates could alter C and nitrogen (N) cycling and storage for an infected forest. Infected eastern hemlocks demonstrate variable rates of decline across space, and this variation could be explained by rhizosphere plant-microbial feedbacks as mediated by local soil chemical or physical properties. This project’s goal is to understand how rhizosphere plant–microbe feedbacks temper the decline of tree species infected by non-native pests and the subsequent impacts on ecosystem C and N cycling. Researchers will use a model-experiment (ModEx) approach combining field, lab, and modeling experiments to test the central hypothesis that C and N cycling in forests infected by non-native pests is controlled by shifts in exudate quantity and quality driving changes in the composition of the rhizosphere microbial community and SOM mineralization but mediated by soil type and chemical properties.

The hemlock woolly adelgid (*Adelges tsugae*, or HWA), which infects the eastern hemlock (*Tsuga canadensis*), is one of 15 non-native insects and diseases responsible for the most significant damage to U.S. forests. Researchers will use the eastern hemlock as a model species for the growing pressure on U.S. forests from non-native pests to test three specific objectives: (1) quantify changes in eastern hemlock root exudates and associated shifts in the rhizosphere microbial community across variable infection levels and soil physicochemical properties; (2) evaluate microbial and soil organic matter (SOM) turnover under altered root exudation and precipitation regimes; and (3) integrate empirical data into two variations of an ecosystem model, FUN-CORPSE (couples SOM cycling with plant–microbe feedbacks) and Myco-CORPSE (explicitly represents mycorrhizal and saprotrophic rhizosphere communities), to refine predictions of ecosystem C and N cycling across altered hemlock forests.

Working across two field gradients with uninfected, low infection, and high infection stands of mature hemlocks (Gradient A) or seedlings (Gradient B), researchers will collect *in situ* root exudates to analyze for quantity and composition. Researchers will then quantify changes along the rhizosphere root-microbe-soil continuum, including the composition and size of the microbial community, the size and quality of SOM pools, C and N transformations, and soil physicochemical properties, to advance understanding of how plant–soil feedbacks moderate the impact of a non-native pest and alter C and N cycles. The team will complement field measurements with a laboratory incubation study using model exudates enriched with ^{13}C to isolate the formation and turnover of soil C pools and shifts in microbial community composition across soil types. Field and laboratory measurements will support an iterative ModEx approach to parameterize an ecosystem model that couples mechanisms represented by FUN-CORPSE and Myco-CORPSE. While FUN-CORPSE combines plant–microbe interactions with SOM turnover, Myco-CORPSE incorporates competition between rhizosphere saprotrophs and mycorrhizal fungi. Combining these two models within a single platform will allow researchers to test whether microbially-explicit parameters belowground (Myco-CORPSE) are more important for constraining C following shifts in plant–soil feedbacks (FUN-CORPSE) occurring in the rhizosphere. This ModEx approach will advance understanding of and ability to accurately predict forest ecosystem C and N cycling when belowground rhizosphere dynamics are altered by aboveground stressors.

Unraveling Continental-Scale Patterns and Processes of Terrestrial and Aquatic Carbon Fluxes Under Hydroclimate Extremes

- **Principal Investigators:** Li Li (Pennsylvania State University)
- **Collaborators:** Rodrigo Vargas (University of Delaware), Benjamin Bond-Lamberty (Pacific Northwest National Laboratory)
- **Total Award:** $400,000 over two years

This project seeks to determine the patterns and processes that drive vertical (terrestrial) and lateral (aquatic) carbon flux response to hydroclimate extremes across gradients of climate, vegetation, and watershed characteristics. Vertical effluxes are defined as the soil carbon dioxide (CO_2) effluxes to the atmosphere and lateral fluxes as the carbon (C) export to rivers and streams, including dissolved organic and inorganic C (DOC and DIC) and particulate organic C (POC). Hydroclimate extremes, including storms, floods, and droughts, are projected to become more frequent and intense, and can cause substantial changes in the C reactions and fluxes. Such changes can potentially transform terrestrial ecosystems into net carbon sources, exert long-lasting effects on surface water quality and aquatic ecosystems, and threaten water supplies. Extreme events are rare and difficult to track and replicate in space and time. C responses to extremes are complex and nonlinear, such that small shifts in event characteristics can substantially alter responses. Existing studies have mostly adopted approaches in separate disciplines, demanding more systematic and integrated understanding of how, how much, and to what extent C reactions and fluxes respond to extremes.

The project seeks to answer these questions by leveraging interdisciplinary data synthesis and harnessing the power of deep learning and process-based reactive transport modeling. At the continental U.S. scale, the team plans to synthesize existing C concentrations and soil CO_2 efflux data, that are often measured separately in ecosystems, soils, and aquatic biogeochemistry. Deep learning approaches will be used to “reconstruct” consistent data to identify patterns of C flux response to hydroclimate extremes.

At the watershed scale, the team plans to focus on two ESS-supported sites with intensive, coordinated data and use reactive transport models to understand the processes that drive C fluxes. One site is the Upper East River site in Colorado, which is experiencing rapid warming and frequent droughts; the other is the TEMPEST site in Maryland, where controlled experiments and a rich dataset can help understand threats of storms and floods that loom large in the coastal United States. The proposed work forges a new collaboration across hydro- and terrestrial biogeochemistry, thus breaking discipline silos. Rich datasets will set the stage for new ideas that advance multiple fields. The proposal aligns with the DOE mission to "incorporate AI into models, analytics, and data generation," and will support women and minority students in STEM, helping diversify the machine learning field and the geosciences.

Effects of Yellow Cypress Decline on Coastal Temperate Rainforest Climate Interactions

- **Principal Investigators:** Gavin McNicol (University of Illinois, Chicago)
- **Collaborators:** Max Berkelhammer (University of Illinois, Chicago), Hélène Genet, Benjamin Gaglioti, Allison Bidlack (University of Alaska, Fairbanks), David D'Amore, Robin Mulvey (U.S. Forest Service Pacific NW Research Station), Avni Malhotra, Qing Zhu (Pacific Northwest National Laboratory)
- **Total Award:** $999,554 over three years

The North Pacific coastal temperate rainforest in Southeast Alaska (SEAK) stores vast quantities of organic carbon in its plants and soils, due to high forest integrity, a cool and very wet climate, and limited disturbance by fire and logging. However, the relative abundance of the ecologically and culturally significant tree species, *Callitropsis nootkatensis* (yellow cypress, or yellow-cedar), is declining due to tree mortality across at least 2,800 km^2 of the SEAK rainforest, with more than 70% mortality of mature trees in affected areas. The cause of tree mortality has been linked to loss of late-winter snow cover, which exposes yellow cypress's shallow roots to frost injury. Yellow cypress decline is predicted to become more prevalent across SEAK as more of the region crosses a winter snow-to-rain precipitation threshold in the coming decades. Despite the large range of these observed and predicted SEAK yellow cypress declines, it is unknown whether decline will affect the amount of organic carbon and moisture stored in plants and soils, and if it does, whether these changes will accelerate or dampen future climate changes in the coastal temperate rainforest.

In this study, with permission of landowners and managers, researchers will revisit after 14 years a gradient of yellow cypress decline on the western coast of Chichagof Island, SEAK. This land is federally protected within the W. Chichagof-Yakobi Wilderness area of the Tongass National Forest and is within the unceded territories of the Sheet'ká Kwáan (Sitka Tribe of Alaska) on Lingít Aaní (Tlingit lands). Study plots will be spread evenly between two decline classes: live, and recent mortality, dominated by trees that died within the last ~20 years. Each plot has detailed tree inventory data collected in 2011 and 2012; forest structure and composition will be re-surveyed using the same methods. At a subset of plots within each of the two decline classes, researchers will quantify the amount of carbon stored in plants and the soil, including roots, and quantify rates of decomposition over three years using bags of common leaf material placed on the surface of, or buried within, the soil. At new plots near Fick Cove, a sheltered inlet on the east coast of Chichagof Island, the team will set up a research-grade weather station and a soil and tree stem sensor array to measure radiation, temperature, and moisture conditions in the air, soil, and trees, respectively. Researchers will analyze data from the yellow cypress decline plot network using statistical methods to describe and explain patterns in carbon and moisture variation, and to attribute how much of this variation is caused by yellow cypress decline. The team hypothesizes that increased temperatures and decreased evaporation rates in the forest canopy as well as increased decomposition within the forest floor will cause a reduction in carbon stored in plants and soils over the first few decades of yellow cypress decline, leading to net losses of forest carbon.

The observational and experimental field data generated by this study will help the broader scientific community, landowners and managers, and the general public to better anticipate the future climate and ecosystem conditions of the North Pacific coastal temperate rainforest. Data on carbon stocks, decomposition rates, and local temperature and moisture changes associated with yellow cypress decline will be used to iteratively test and refine new tree mortality processes in the Dynamic Organic Soil version of the Terrestrial Ecosystem Model. Community connections will be maintained throughout the project via outreach activities facilitated by the Sitka Sound Science Center, the Alaska Coastal Rainforest Center and the U.S. Forest Service Pacific Northwest Research Station, and the University of Alaska. Through DOE collaborators at the Pacific Northwest and Lawrence Berkeley National Laboratories, the team will roadmap how to integrate its temperate rainforest model improvements into the land surface module of DOE's Energy Exascale Earth System Model (E3SM).

Synthesis of Existing Tropical Root Data: How do Natural, Episodic Disturbances Alter Tropical Forest Carbon Cycles Via Changes in Belowground Dynamics?

- **Principal Investigators:** Jennifer Powers (University of Minnesota)
- **Collaborators:** Daniela Cusac, Kelly Andersen, Amanda Cordeiro (Colorado State University), Jennifer Holm (Lawrence Berkeley National Laboratory), Daniela Yaffar (Oak Ridge National Laboratory), Laynara Lugli (Technical University of Munich)
- **Total Award:** $399,998 over two years

Disturbance is a key feature of the natural history of all ecosystems, and those in tropical latitudes are no exception. Tropical ecosystems have experienced disturbances such as wildfires, droughts, flooding, and cyclones (also known as hurricanes) for millennia, and many species are adapted to these disturbance regimes. However, tropical ecosystems are currently experiencing diverse and more extreme changes in abiotic conditions and disturbance events, with an intensification observed in recent years. While many studies have focused on understanding how aboveground properties of ecosystems such as plant biomass, plant species composition, and/or functional characteristics or traits of species respond to different disturbance regimes, understanding of the consequences of natural, episodic disturbances on belowground processes and properties has lagged behind understanding of aboveground processes.

Plant roots fulfill multiple ecological roles: they anchor plants in the soil, facilitate water and nutrient uptake, host symbiotic relationships with mycorrhizal fungi, in some plant species host nitrogen-fixing bacteria, and act as a direct conduit of organic carbon to the soil via rhizodeposition and root death, which has important implications for soil carbon storage and dynamics. Roots respond to ecosystem disturbance events such as those described above, which may alter their ecological function. Thus, roots directly mediate ecosystem feedbacks to climate change via shifts in water, nutrient, and carbon cycles after episodic disturbance, both directly and through linkages to aboveground and other soil responses. This team estimates there are now sufficient data to understand how tropical root stocks, traits, and dynamics respond to disturbances across the large gradients in soil fertility and mean annual precipitation that characterize tropical ecosystems. Unfortunately, these data have not yet been collated and synthesized. Thus, the main objective is to synthesize existing data from published studies to determine how a range of episodic disturbances in tropical forests affect belowground dynamics and develop a new mechanistic understanding of feedbacks between disturbances and the carbon cycle. This project's database will be compatible with and freely available to the public through the DOE-supported FRED (Fine-Root Ecology Database) and will help resolve uncertainties in how root dynamics are modeled in response to disturbances.

The team will complete this project using best practices for literature review and synthesis developed through the inclusive and successful TropiRoots Collaborative Network. First, the team will renew its literature search to add to the 700+ papers already identified. A postdoc will lead a team of undergraduate student researchers to select and extract data from the papers with disturbances. This data extraction will include all root data and ancillary data such as spatial coordinates, climate, and soil characteristics, as well as any information on plant species composition and functional traits, biodiversity, and aboveground variables such as basal area and carbon stocks. Second, researchers will use this dataset to address three core hypotheses: (1) rainfall regimes and soil properties such as phosphorus availability modify root responses to disturbance; (2) the duration and type of disturbance agent determine the extent of root responses, with disturbances such as flooding and cyclones having larger effects on root systems than fire, drought, heat waves, or nitrogen deposition, and (3) the diversity of plant species and their traits mediate the community-level effects of changes in roots on ecosystem carbon stocks and fluxes such that higher diversity ecosystems are more buffered against changes in root characteristics following disturbance in comparison to lower diversity ecosystems. Researchers will use a structural equation modelling approach to evaluate the mechanistic relationships between root responses and disturbances, and which environmental factors moderate those relationships. Next, the team will use the database to train and validate the DOE-supported FATES (Functionally Assembled Terrestrial Ecosystem Simulator) model to improve how roots are represented for tropical ecosystems. Last, the dataset will be uploaded and freely available via FRED, DataDryad, and ESS-DIVE, allowing for future analysis and use by the global community. Thus, this project advances conceptual and dynamic vegetation models and data availability to develop a novel understanding of root responses to disturbances in tropical ecosystems.

The Role of Plant–Mycorrhizal Relationships in Forest Loss Following Wildfire

- **Principal Investigators:** Kathleen Treseder (University of California, Irvine)
- **Collaborators:** James Randerson, Michael Goulden (University of California, Irvine), Morgan Gorris (Los Alamos National Laboratory), William Riley (Lawrence Berkeley National Laboratory)
- **Total Award:** $991,094 over three years

Researchers are studying how a particular type of fungus—mycorrhizal fungi—are affected by climate change, and how their responses to climate change could contribute to losses of coniferous forests in California following wildfire. Mycorrhizal fungi colonize plant roots and grow hyphae into the soil. The hyphae scavenge for nutrients that the fungi transfer to plants in exchange for carbohydrates. Most plants require mycorrhizal fungi to grow well. They essentially fertilize the plant. They also likely help conifer seedlings obtain water as they grow after wildfires. High temperatures and drought can be extreme in surface soils of fire scars, and seedlings may struggle to access water in lower soil depths without mycorrhizal fungi. If climate change harms mycorrhizal fungi that assist conifer seedlings, the seedlings may not reestablish in the fire scar. Instead, shrubs or grasses with hardier mycorrhizal fungi could take over.

This project is testing these possibilities by conducting field, laboratory, and modeling experiments. Researchers will examine soil conditions and water stress in the Bobcat fire scar in southern California. This fire scar spans a range of climates. They will also conduct a set of laboratory experiments to determine the ability of mycorrhizal fungi and plants to tolerate extreme soil conditions. The team will integrate their gained knowledge into models that simulate soils, ecosystems, and landscapes under climate change. This way, researchers can predict whether mycorrhizal fungi contribute to shifts from coniferous forests to shrublands or grasslands in response to climate change and wildfires.

Woody Plant Encroachment and its Consequences on Subsurface Water Redistribution

- **Principal Investigators:** Enrique Vivoni (Arizona State University)
- **Collaborators:** Osvaldo Sala (Arizona State University)
- **Total Award:** $1,000,000 over three years

Global drylands covering nearly 40% of the Earth's land surface have been dramatically transformed by the replacement of desert grasslands with woody shrubs. Woody shrubs with deep roots have a competitive advantage over grasses with shallow roots since they can access deep subsurface water during dry seasons or drought periods. However, the role of deep subsurface water in supporting woody shrubs and the ecohydrological mechanisms by which this occurs are poorly understood globally and for areas with complex topography.

The overall hypothesis is that woody shrubs affect the redistribution of subsurface water depending on the terrain conditions. This is hypothesized to occur due to: (1) a redistribution of overland flow into deep subsurface areas that is enhanced by woody shrubs, (2) a redistribution of water from the wet season to the subsequent dry season, and (3) the access of this subsurface water exclusively by deep-rooted shrubs. This carry-over of deep subsurface water from the wet season to the following dry season and its access by woody shrubs is believed to have important consequences on carbon and water cycles in global drylands.

This proposal has a tight integration of ecosystem monitoring and simulation scenarios using a Modeling-Experimental (ModEx) approach. Researchers formulate five specific hypotheses at four study sites in a 2x2 factorial design that quantifies the effects of terrain slope and of woody shrub density at the Jornada Experimental Range of New Mexico, United States. An ecohydrological model will be iteratively enhanced using data collected at the four sites and then used to extrapolate findings across different terrain, plant cover, and rainfall conditions. This approach will yield new understanding of important, but poorly recognized, subsurface hydrological processes affecting the annual carbon and energy budgets.

Effects of Shifting Temperate Conifer Forest Vegetation Regimes on Above- and Belowground Carbon and Nitrogen Cycling

- **Principal Investigators:** Thea Whitman (University of Wisconsin-Madison)
- **Collaborators:** Ellen Whitman (Northern Forestry Centre, Canadian Forest Service), Benjamin Sulman (Oak Ridge National Laboratory)
- **Total Award:** $999,603 over three years

The overall goal is to explore how wildfire-induced changes in vegetation affect carbon (C) and nitrogen (N) stocks in plants and soils, using field sampling, laboratory experiments, microbial community characterization, and modeling, and to accomplish the three objectives. Objective 1: Quantify above- and belowground C and N stocks in temperate conifer forests from the U.S.–Canada border to central Yukon Territory in Canada that have undergone recovery vs. regeneration failure after wildfire.

Objective 2: Measure the impact of post-fire vegetation transitions on soil microbial community composition and function.
Objective 3: Assess how changes in the quantity and quality of litter inputs and changes in microbial community composition and function affect soil organic matter cycling following vegetation transitions.

In ongoing research led by co-principal investigator E. Whitman, a field sampling campaign is being conducted to characterize aboveground vegetation communities of forests across a latitudinal gradient extending from south-central Alberta to the Yukon Territory. This project will expand this effort by collecting soil samples and additional aboveground measurements. In addition, the project will sample forested areas that burned between 30 and 38 years ago as well as unburned sites. Sites will be located at ecotones where forest areas transition to prairie or tundra. Measurements of living and dead aboveground vegetation, allometric equations, and species-specific C and N concentration measurements will be used to estimate aboveground biomass and C and N pool sizes. Soil samples collected from 0 to 100 cm depth and partitioned by horizon will be used to estimate soil C and N stocks (Objective 1). In addition, the team will characterize soil microbial community composition and function and assess their differences between samples from forests on a trajectory of vegetation regeneration vs. forests experiencing regeneration failure. To assess the impact of broadscale shifts in vegetation community composition on microbial community function, the team will screen soil microbial communities for evidence of a “home-field advantage”. Using soil and litter from areas of forest experiencing regeneration failure or experiencing recovery, the team will use a full factorial design incubation to assess the degree to which shifting microbial community composition may influence soil C cycling during times of vegetation transitions (Objective 2).

In addition to the planned field work, the team will use a ModEx approach with the Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment (CORPSE) model, a soil organic matter cycling model that can represent key mechanisms driving soil organic matter stabilization and turnover. Results from Objectives 1 and 2, such as vegetation community composition, above- and belowground biomass, and litter degradation rates, will be used to parameterize the model. The team will also integrate substrate-specific controls on litter decomposition into the model and allow these variables to differ between the recovering vs. regeneration failure microbial communities, thus allowing for a comparison of the effects of changing litter inputs and changing microbial communities over time (Objective 3).

The project will improve understanding of the impacts of vegetation shifts in boreal forest ecosystems on belowground C cycling via two mechanisms – shifts in litter inputs to soil and changing microbial community composition and ability to degrade available C substrates. Furthermore, this research addresses the research needs of the EESSD strategic plan in biogeochemical cycling by investigating the impact of interactions between changing wildfire regimes and climate change on above- and belowground C and N cycling. And finally, the proposed research integrates observations and models by both building off of ongoing modeling work and by linking observations and models to improve understanding of Earth system components.

Incorporating Ericoid Mycorrhizal Shrubs into Biogeochemical Models

- **Principal Investigators:** Nina Wurzburger (University of Georgia)
- **Collaborators:** Caitlin Hicks-Pries (Dartmouth University), Richard Lankau (University of Wisconsin), Benjamin Sulman (Oak Ridge National Laboratory)
- **Total Award:** $1,000,000 over three years

Current biogeochemical frameworks focus on the role of ectomycorrhizal (EcM) and arbuscular mycorrhizal (AM) trees in carbon (C) and nitrogen (N) cycling. Ericaceous shrubs, although smaller in stature, are commonly found in temperate forests, boreal forests, and tundra, but they associate with ericoid mycorrhizal (ErM) fungi. The limited evidence available suggests ErM shrubs have strong effects on C and N cycling by slowing decomposition and reducing soil N availability. A lack of consideration for ErM shrubs in biogeochemical frameworks could lead to the misattribution of such patterns to forest trees. ErM shrubs are expanding in response to disturbances such as fire exclusion, timber harvesting, and species invasions. Given the prevalence of ErM shrub understories in forests of the eastern United States, and the increasing pace of biotic and abiotic disturbances predicted for this region, it is imperative to understand ErM shrub effects on biogeochemistry to accurately predict changes in soil C and N cycling in response to rapid environmental change.

Understanding of which functional attributes of ErM shrubs and ErM fungi drive observed patterns in soils is lacking. Researchers hypothesize there are three main mechanisms by which ErM shrubs affect soil biogeochemical cycles. First, ErM shrub litter is high in tannins that can form complexes with proteins and thereby reduce soil N availability. Second, ErM fungal necromass (dead material) may be higher in melanin than other fungal necromass. Melanin can slow necromass decay and, like tannin from ErM shrub litter, can form organic N complexes. Third, ErM fungi can mine N from organic matter and may therefore be able to access N in these organic N complexes putting decomposers and other types of mycorrhizal fungi at a competitive disadvantage. No coordinated experiments have tested how ErM litter tannins, ErM fungal necromass, and ErM fungal N mining affect organic matter formation and plant N acquisition. The overarching objective is to mechanistically understand how ErM shrubs influence soil C and N cycles. Researchers will use observations across two temperate forests with ErM shrub understories–in North Carolina and Connecticut–and targeted isotopic tracing experiments to tease apart these mechanisms. The data will be used to parameterize and validate a soil biogeochemical model to project the consequences of expanding ErM shrub understories on soil C and N. This work will address the following specific objectives:

Objective 1: Quantify mycorrhizal fungal productivity, turnover and melanin concentration in AM-EcM co-dominated forests with and without an understory of ErM shrubs.

Objective 2: Isolate which functional attributes of ErM shrubs and ErM fungi affect soil organic matter formation and plant N uptake within AM-EcM co-dominated forests.

Objective 3: Extend and parameterize a plant–mycorrhizal soil C-N model with the addition of the ErM association and use the model to project soil C and N cycling under ErM shrub expansion.

Researchers hypothesize that the combination of ErM shrub litter, ErM fungal necromass and ErM fungal mining facilitate ErM shrubs' disproportionate access to organic N relative to non-ErM plants, while stabilizing decay-resistant material in particulate organic matter. The proposed research supports DOE ESS objectives. This project will expand understanding of plant and microbe interactions in the rhizosphere by testing and modeling the mechanisms by which ErM associations affect soil organic matter formation and N acquisition. Because ErM shrubs are expanding due to disturbances, this research also addresses the effects of rapid environmental change. ErM understory shrubs appear to play a key functional role in biogeochemistry but are currently poorly represented in models and frameworks. Researchers will quantify the biogeochemical importance of the ErM functional type using observations, experiments, and models to better predict future soil C and N cycling.

Further information on ESS objectives, along with a listing of current funding opportunities discussed in this document, is available at https://ess.science.energy.gov

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