U.S. Department of Energy • Office of Science
Office of Biological & Environmental Research
Earth & Environmental Systems Sciences Division

Environmental System Science

Summary of projects awarded in summer 2022 under the Environmental System Science Funding Opportunity Announcement DE-FOA-0002584.

Program Overview

The goal of the Environmental System Science (ESS) program in the U.S. Department of Energy, Office of Biological and Environmental Research (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-0002584, was issued by the Environmental System Science program and released in the Fall of 2021. 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, and/or more sophisticated modeling, this FOA encompassed three Science Research Areas (SRA): 1) Plant-Mediated Ecohydrology Across Scales, 2) Wildfire and Flood Disturbances, and 3) Role of Fungi in Shaping System Function.

Applications to this FOA were expected to take a 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 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 were co-designed to address key model deficiencies and that 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 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, 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:

<u>SRA 1 – Plant-Mediated Ecohydrology Across Scales</u>: Investigate plant-mediated hydraulic redistribution and its influence on ecosystem function, biogeochemical cycling, hydrologic dynamics, and/or land-atmosphere exchange that produce ecosystem or watershed responses that would not be predicted by physical drivers alone.

Applications were required encompass observational and experimental research as well as linkage to modeling in a ModEx approach to advance predictive, scale-aware understanding of biogeochemical cycling in ecosystem, watershed, and Earth system models. Applications targeting ecohydrological responses of vegetation and their indirect influence on soil hydro-biogeochemical processes were of particular interest.

<u>SRA 2 – Wildfire or Flood Disturbances</u>: Improved integrated understanding, model representation, and predictive capacity of ecosystem or watershed system changes, responses, and trajectories following wildfire or flood disturbance and their feedbacks to Earth system processes at local to global scales.

Applications were limited to investigation of wildfire and/or floods, defined as episodic events occurring at landscape scales as the result of natural processes, as an integral control and component of ecosystem and/or watershed systems. Applications were to focus on understanding the impact of disturbance regime change on long-term, multi-cycle system stability to improve our Earth system predictive capabilities. Studies that also characterized mechanisms and/or tipping points of disturbance regime change that induce chronic shifts in system function were particularly encouraged.

<u>SRA 3 – Role of Fungi in Shaping System Function:</u> Investigate fungal-mediated plant-soil interactions in the coordination of ecophysiological or biogeochemical response of the rhizosphere system to stress, ephemeral soil resources, or transient environmental factors

Successful applications to this limited-scope topic were required to use new observations and experiments to demonstrate the role of mycorrhizal fungal networks in shaping ecosystem responses to hydro-biogeochemical cues, with a focus on multi-species interactions and/or coordination that produce synergistic ecosystem functional responses (e.g., mutualisms) different from that of the summed collective components.

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 ESS research.

Twelve awards were made through this Funding Opportunity Announcement totaling $10,584,402 over three years.

Funded Projects

How do wildfire severity and post-fire precipitation influence fate and transport of pyrogenic organic carbon and nitrogen in terrestrial-aquatic interfaces?

- **Principal Investigators:** Alex Chow (Clemson University), Jeffrey Atkins (USDA Forest Service)
- **Collaborators:** Huan Chen, Barbara Campbell (Clemson University), Carl Trettin (USDA Forest Service), Scott Brooks, Scott Painter, and Peijia Ku (ORNL)
- **Total Award:** $999,802

Wildfire significantly changes the composition and quantity of forest biomass, converting lignin and polysaccharide rich and relatively degradable carbon pools to polycyclic aromatic compounds, charcoal, and recalcitrant black carbon. Abundance and distribution of these carbon pools are affected by the severity of the wildfire, and the intensity and frequency of post-fire rainstorms. However, there is no comprehensive knowledge available about the impacts of both fire conditions and post-fire rainstorms on the fate of pyrogenic organic carbon (PyOC) and nitrogen (PyON) in burned terrestrial and aquatic ecosystems. To address the knowledge gap, we will collaborate with scientists at USDA Forest Service and Oak Ridge National Laboratory to conduct watershed-scale wildfire experiments in the Department of Energy - Savannah River Site, South Carolina. Production, composition, fluxes, and temporal dynamics of PyOC and PyON in both soil and surface runoff under different fire severity conditions as well as intensity and frequency of post-fire rainstorms will be determined under controlled field conditions. Leachability, degradability, and mobility of PyOC and PyON will be quantified in controlled conditions. Microbial communities will be assessed for resistance and resilience as well as function in relation to watershed perturbation and post-fire nutrient pools. Data obtained from the experiments will be used to develop, calibrate, and evaluate a reactive transport model of PyDOM and nutrients in burned landscapes. The results from field and laboratory experiments will be used to develop a reaction network accounting for dissolved and particulate black carbon and black nitrogen as well as production of C and N gases. The reaction network will be implemented in the PFLOTRAN software. Flow and transport of particulate and dissolved phases will be modeled with ATS, which uses the Alquimia interface to access PFLOTRAN's reaction capability. Key parameters appearing in the flow and reactive transport model will be estimated by uncertainty-aware inverse modeling using the measured C and N fluxes. ATS-PFLOTRAN models of the plot and small watershed experiments will then be used to assess transferability of estimated parameters across scales.

Hydraulic redistribution in forests: Spatial and temporal drivers of variation, and consequences for climate feedbacks

- **Principal Investigator:** Elin Jacobs (Purdue University)
- **Collaborators:** Jeffrey Dukes (Carnegie Institution for Science), Lisa Welp (Purdue University), Zoe Cardon (Marine Biological Laboratory), Yilin Fang (PNNL)
- **Total Award:** $991,308

The amount of water stored in soils, and how this varies over time and with depth, controls the amount of carbon dioxide plants can photosynthesize and, subsequently, accumulate as stored carbon. During droughts, when there is little water in soils, plants close the leaf pores to prevent water loss to the dry air, but also limiting their ability to withdraw carbon dioxide from the atmosphere. With the ongoing changes in climate, droughts are becoming more common in many parts of the world. The computer simulation models scientists use to predict future climate and environmental change are still limited in their ability to accurately reproduce observed soil moisture and therefore carbon uptake by forest ecosystems. One reason for this may be that these models do not realistically represent a process known as hydraulic redistribution, where plant roots transport water from wet to dry soils. During droughts, plants can access water stored deeper in the ground, transport the water through the root system, and release the water in shallower, dry soils where most nutrients the plants need are stored. After the water mixes with the nutrients, plants can use the nutrient-rich water to continue photosynthesizing longer than would be possible without hydraulic redistribution. In this project, the researchers will measure water content in different parts of the soil and plants to track the transportation of water in trees exposed to different levels of drought to detect and quantify hydraulic redistribution. The project will focus on species that have different levels of response to drought growing in hardwood forests of northern Indiana. The questions the researchers aim to answer are: Which species use hydraulic redistribution as a way to ease drought stress, and when? Do trees have to be a certain age or size before they are able to hydraulically redistribute water? To what extent does hydraulic redistribution alleviate water stress in trees and contribute to maintaining photosynthesis rates during droughts? The researchers will then use the measured data and the answers to those questions to generate better model representations of hydraulic redistribution in the DOE-sponsored E3SM climate simulation model. With this information, scientists can make predictions of how much less carbon plants take up during droughts under different climate scenarios.

Integrating tree hydraulic trait, forest stand structure, and topographic controls on ecohydrologic function in a Rocky Mountain subalpine watershed

- **Principal Investigator:** Lara Kueppers (University of California, Berkeley)
- **Collaborators:** Benjamin Blonder (University of California, Berkeley), Max Berkelhammer (University of Illinois), Thomas Powell (University of the South, Sewanee), Ian Breckheimer and Christopher Still (Rocky Mountain Biological Laboratory), Erica Siirila-Woodburn (LBNL)
- **Total Award:** $1,000,000

Complex mountainous terrain comprises more than 25% of the terrestrial surface, and water discharge from mountain zones accounts for at least half of the world's freshwater resources. In the Colorado River Basin alone, mountain watersheds provide the primary water source for more than 40 million people. Accurately representing interactions among vegetation, terrain, and the hydrological cycle in mountain zones remains one of the critical unsolved challenges in integrated Earth system modeling. The complex topography and subsurface heterogeneity constrain water flow paths to produce hydrological heterogeneity that is currently not well represented in land-surface or hydrological models. In forested watersheds, trees mediate ecohydrological processes via physiological controls on water use and drought tolerance, but also via tree size, density and species composition, which alter precipitation interception and water retention. Therefore, plants respond and contribute to hydrological heterogeneity in ways that are only very recently integrated into some land surface models. This project aims to improve understanding and spatially explicit 3D prediction of tree-mediated water and energy fluxes and subsurface flow that together regulate ecohydrologic function in a forested subalpine watershed. Four hypotheses will be tested:

1. Rooting depth and stem capacitance, more so than other hydraulic traits, explain the differences in diurnal and seasonal transpiration patterns and in growth sensitivity to climate across the dominant species in subalpine watersheds.

2. Across forest stands, soil moisture, canopy water content, transpiration, and radial growth covary and depend on non-linear interactions between stand density, species dominance, and topographic setting. The highest canopy water content and transpiration rates are expected in broadleaf tree-dominated forest stands.

3. Interannual differences in forest stand-scale soil moisture, canopy water content, transpiration, and growth are smallest in more convergent, high-elevation topographic positions with low incident solar radiation. Interannual differences are expected to be largest in convergent zones with high incident radiation, where maximum transpiration and the potential range of fluxes is very high.

4. Forest structure and composition have little influence on seasonal soil moisture and transpiration dynamics at more convergent landscape positions where subsurface lateral flow contributions are higher, but have stronger influence on these dynamics in more divergent and neutral positions, particularly during periods of drought.

The research approach integrates field measurements of tree hydraulic traits, transpiration, canopy water content, tree ring-width variation, and soil moisture; airborne observations of transpiration and canopy water content; and coupled 3D hydrologic-vegetation demographic modeling using ParFlow-ELM-FATES across a heterogeneous watershed in the Upper Colorado River basin. The project will partner with DOE's field-based Watershed Function SFA and the Rocky Mountain Biological Laboratory, hydrologic model developers at PNNL, and DOE's computational facilities to achieve project goals. Project data will be archived in DOE's ESS-DIVE archive.

Expansion and stimulation of the rhizosphere during hydraulic redistribution

- **Principal Investigator:** Richard Marinos (University of Buffalo)
- **Collaborators:** Scott Mackay (University at Buffalo), Angela Possinger (City University of New York), *unfunded collaborators* – Jim Moran and Adam Mangel (PNNL)
- **Total Award:** $500,000

Plant root systems can act as conduits for water from wet regions of soil to dry regions of soil, a phenomenon known as hydraulic redistribution (HR). HR plays a variety of ecological roles, including preventing root desiccation, increasing plant resilience to drought, and providing water to soil organisms. This is one of the many ways that roots shape the soil environment. Another important way is through the release of sugars and other photosynthesis products into the soil, which fuels the metabolisms of soil microbes. This process is called exudation and is known to be an important control on soil microbial activity and soil health.

In this project, we propose to examine the interplay between HR and root exudation. We hypothesize that HR will increase exudation during drought conditions, acting to stimulate microbial activity and sustain soil biogeochemical processes during drought. To examine this hypothesis, we will perform an integrated suite of experiments and modeling to determine how HR modifies the quantity and quality of root exudates and how this in turn impacts microbial activity in the soil. We will quantify changes in exudate quantity and composition using state-of-the-art high-resolution mass spectrometry techniques. We will determine if HR alters spatial patterns of root exudation using mass spectrometry imaging. Further, we will track the transport and fate of exudates in the soil with isotopic imaging techniques. These experiments will inform two cutting-edge models. The first model simulates the transport and microbial uptake of exudates from the root into the soil at the scale of individual roots. The second model simulates the incorporation of these root-scale processes into a model of whole plant-soil ecophysiology, allowing us to determine how HR impacts plant performance and soil health. Results from this study will enhance our ability to predict ecosystem responses to drought and better plan for extreme climatic events.

MycoPhen: Linking mycorrhizal network phenology to above- and belowground plant phenology and environmental factors

- **Principal Investigator:** Michael McCormack (Morton Arboretum)
- **Collaborators:** *unfunded collaborators – Peter Kennedy (University of Minnesota), Dan Ricciuto and Colleen Iverson (ORNL)*
- **Total Award:** $299,966

Mycorrhizal networks and fine roots together represent a critical link between aboveground plant nutrient and water demands and belowground resources. However, the patterns and processes underlying the growth of mycorrhizal networks in soil, their relationships to whole-plant phenology, and their responses to environmental factors are largely unknown. Models are therefore strongly limited in their ability to represent current and predict future productivity in terrestrial ecosystems. To overcome these limitations, studies are needed that can identify the timing and drivers of mycorrhizal network phenology together with the closely related phenology of their plant hosts.

In this project we will address three objectives: 1) identify changes in the growth, abundance, and composition of mycorrhizal fungal networks across the growing season and their responses to stress, ephemeral soil resources, or transient environmental factors; 2) determine the coordination of mycorrhizal network phenology with whole-plant phenology and ecophysiology; and 3) improve the ability of models to represent the timing and magnitude of fine-root and mycorrhizal network growth. To address these objectives, new data regarding mycorrhizal network phenology and composition will be linked with observations of leaf, stem, and fine-root phenology in mature, monospecific forestry plots at The Morton Arboretum (Lisle, IL, USA). These will then be used to guide and parameterize ongoing development of the E3SM Land Model (ELM) in collaboration with colleagues at Oak Ridge National Laboratory.

This project leverages existing resources at The Morton Arboretum, where 23 plots have been instrumented for repeated, long-term measurements of above- and belowground phenology. Our platform includes minirhizotrons to capture fine-root phenology and aspects of fungal phenology, digital dendrometers for stem-wood growth, phenocams for leaf/canopy phenology, sap flow sensors for whole-tree water movement, and continuous monitoring of abiotic soil and weather conditions. We propose to further augment a subset of 10 plots where we will increase the frequency of our minirhizotron imaging and incorporate repeated sampling of fungal abundance and communities in bulk soil to identify seasonal and short-term fluctuations in mycorrhizal network biomass based on qPCR and community composition using high-throughput sequencing (HTS). The instrumented plots capture a diverse suite of host plants that allow us to experimentally compare patterns and responses of mycorrhizal networks for multiple model-relevant plant functional groupings including deciduous and evergreen species, gymnosperm and angiosperm species, as well as species that dominantly associate with either of the two main mycorrhizal types, arbuscular and ectomycorrhizal fungi.

Our long-term observations and repeated sampling of mycorrhizal fungal networks across the growing season will allow us to quantify patterns of fungal growth and biomass across the season and determine how fungal species dominance within these networks shifts across the growing season and in response to the environment. These results would represent a substantial advance in our understanding of mycorrhizal network functioning in terrestrial systems. Furthermore, the combination of our novel data characterizing mycorrhizal network growth in conjunction with measurements of whole-plant phenology across diverse host tree species gives us the capacity to address fundamental questions regarding coupled above- and belowground ecosystem processes in a transformative manner. Our collaborative work updating representations of belowground processes in ELM also provides an immediate opportunity where our findings can be used to improve predictions of earth's responses to future climate change and environmental variability in the coming decades.

Investigating hydrologic connectivity as a driver of biogeochemical flood response in wetland systems

- **Principal Investigator:** Behzad Mortazavi (University of Alabama)
- **Collaborators:** Corianne Tatariw and Nathan Jones (University of Alabama), Xingyuan Chen and James Stegen (PNNL)
- **Total Award:** $999,942

Wetlands are critical "control points" for nutrient processing and retention, improving water quality in streams and rivers. In particular, wetlands are important for removing nitrogen (N), mitigating negative impacts such as eutrophication in downstream waters. Much of N processing in wetlands is carried out by microbes that live in the soil, whose activity is regulated in part by the availability and quality of organic matter (i.e., dead plant material) and oxygen. Flood disturbances affect both organic matter delivery and oxygen dynamics in wetlands, potentially altering N removal processes. However, we do not understand how hydrologic connectivity, that is, the mode through which wetlands receive and export water, affects organic matter delivery to floods or the subsequent effects on wetland N removal. The objective of this study is to investigate wetland hydro-biogeochemical responses (specifically, N processing) to flood disturbances and the subsequent impacts on watershed nutrient export. We will use event-centered measurements at the wetland and watershed scales to integrate wetland and watershed models to advance our predictive capacity for assessing how flood disturbances impact watershed biogeochemical cycling and nutrient export. This study will address the DOE stated need to understand how flood disturbance impacts watershed biogeochemical function.

Improving models of stand and watershed carbon and water fluxes with more accurate representations of soil-plant-water dynamics in southern pine ecosystems

- **Principal Investigators:** Thomas O'Halloran (Clemson University), Jean-Christophe Domec (Duke University), Cheng-Wei Huang (Portland State University), Chris Oishi (USDA Forest Service)
- **Collaborators:** Jamie Duberstein (Clemson University), Brian Viner (SRNL), *unfunded collaborator* – Thomas Williams (Clemson University)
- **Total Award:** $899,346

Plant responses to water limitations involve a complex set of interactions with soil, the atmosphere, and other plants. While there is strong fundamental knowledge about the key processes through which plant hydraulics affect productivity, we currently lack several key components necessary for a predictive understanding of ecosystem response to future climate conditions. These components include (1) mechanistic understanding of plant-mediated hydraulic processes in under-studied systems and (2) representations of biophysical factors affecting coupled water-carbon cycles in models. To address these challenges, we will employ a

Model-Data Experiment (MoDEx) design informed by our project team's previous field experiments and numerical model development.

To improve our mechanistic understanding of coupled carbon-water processes and to collect necessary data to parameterize and test models, we will conduct an intensive set of field measurements at existing AmeriFlux sites operated by the project team. While a wealth of past work has examined the role of plant-mediated effects on ecosystem water cycling, particularly in arid ecosystems, less is known about these mechanisms in the southeastern U.S., a humid subtropical region characterized by high productivity but experiencing increasing temperature and drought frequency and intensity. Climate change, combined with large-scale structural and compositional changes in vegetation, limit our ability to use existing observational data to predict future responses. This project will focus on longleaf pine ecosystems, once a dominant forest type in the region that is undergoing large-scale efforts to restore it through much of its native range. These savannah-like systems consist of an evergreen pine overstory and grassy understory and are generally found on well-drained, sandy soils with highly variable water tables. While usually characterized as drought tolerant, carbon sequestration rates are dependent on interactions between climate, soil type, hydrology, and plant composition, such that predictions based on simple, empirical responses to environmental drivers are not adequate. Our work will examine plant-level hydraulic coordination of groundwater and soil water uptake, hydraulic redistribution (HR), plant water storage (PWS), transpiration, and leaf-level conductance, as well as competition among plants and the combined effects of hydrologic processes on ecosystem carbon dynamics.

To address mechanisms missing in current land surface models, we significantly expand the functionality of an existing numerical model, developed by members of the project team, by adding components to resolve dynamic groundwater-root-hydraulic interactions and ecosystem respiration. The result will be a novel model that can resolve fully coupled interactions between groundwater, soil moisture, plants, and the atmosphere. We use the extensive field measurements to parameterize and validate the expanded functionality of the new model and use it to test hypotheses that isolate the processes that compete for plant-stored water and quantify the resulting effects on ecosystem water and carbon fluxes. Finally, a series of simulations driven with Energy Exascale Earth System Model (E3SM) future climate scenarios will predict the ability of HR and PWS to buffer longleaf pine productivity under projected extremes of the hydrologic cycle, including higher vapor pressure deficit and periods of drought. The advances in mechanistic understanding of ecohydrological processes and model development generated from this project will be applicable to a broader set of ecosystems and will help to direct future experimental field and modeling efforts.

Empirical measurements and model representation of hydraulic redistribution as a control on function of semi-arid woody ecosystems

- **Principal Investigator:** William Pockman (University of New Mexico)
- **Collaborators:** Marcy Litvak (University of New Mexico), Yiqi Luo (Cornell University)
- **Total Award:** $999,990

Earth System Models (ESMs) allow us to simulate how ecosystems worldwide absorb and release carbon dioxide and how these processes respond to earth's changing climate. The strength of these model projections depend on how well ESMs match the response of biomes (forests, grasslands, shrublands, etc) that each are different in their sensitivity to climate and their relative contributions to the global carbon cycle. Drylands cover more than 40% of the global terrestrial surface and are a major driver of both the long-term trend and the year-to-year variation in total carbon uptake by terrestrial ecosystems. Yet, both the seasonality and magnitude of biogeochemical processes in drylands are challenging to represent in ESMs. Moreover, recent studies suggest that the inability of ESMs to simulate dryland ecosystem function is, in part, due to a failure to represent in the models the fluctuation of plant-available water dynamics and/or to simulate the response of ecosystem carbon exchange to plant-available water.

Plant-mediated hydraulic redistribution (HR) is defined as the flow of water between soil compartments that differ in water content via plant roots connecting parts of the soil profile that differ in water content. Incorporating the role of HR offers a major opportunity for improving the representation of dryland soil moisture dynamics that is thought to limit the ability of ESMs to accurately describe carbon exchange in these ecosystems. The proposed research tests the idea that soil moisture dynamics and ecosystem function in dryland biomes cannot be well understood or modeled without a better representation of HR. To improve the representation of HR in ESMs, we will combine measurements of water flow through roots and the water content of different parts of the soil, with ecosystem-scale measurements of ecosystem carbon exchange, and the use of an approach called data assimilation to improve ability of the Terrestrial Ecosystem (TECO) model to address three objectives:

1. Identify the key factors that determine whether or not HR occurs and the amount of water moved by HR when it occurs in species/biomes across a range of semi-arid western woodlands and forests.

2. Quantify seasonal patterns of HR across dryland species and biomes to determine when HR has the biggest impact on soil moisture dynamics and the mechanisms driving these patterns.

3. Use plant-level patterns in HR to estimate ecosystem-level NEE, GPP and Re in response to precipitation anomalies (periods of drought and unusually high water availability).

To address these objectives, we will measure HR in dominant dryland species at existing sites instrumented to sensitive and continuous measurements of carbon exchange with the atmosphere in three key biomes (ponderosa pine forest, pinon-juniper woodland, and juniper savanna) that vary in elevation, climate, deep soil moisture availability and the presence of experimental manipulations. At each site, we will supplement existing instrumentation to add measurements of root sap flow, and soil water potential to measure the timing and magnitude of HR in each dominant species (Objective 1) and we will measure root sap flux patterns on a broader group of dominant and subdominant woody species to characterize the broader extent of HR regionally. Across sites, we will establish the differences in timing of HR and the conditions under which it is observed (Objective 2). Using newly-collected data and data from the flux towers (2009-present), we will employ data assimilation to improve model structures and parameterization in TECO to provide important advances in the ability of ESMs to capture HR and predict dryland ecosystem function. Finally, we will compare the tree-level measurements of HR with measurements of ecosystem function to correlate the HR patterns associated with variation in carbon exchange using empirical data for comparison with the TECO-HR model. TECO-HR will be used to test hypotheses about the role of HR in soil moisture dynamics under future climate change scenarios to identify tipping points when HR will either fail or be insufficient to sustain roots in drying surface soil.

Plant-mediated hydraulic redistribution: a valve controlling watershed solute transport?

- **Principal Investigator:** Pamela Sullivan (Oregon State University)

- **Collaborators:** Kamini Singha (Colorado School of Mines), Holly Barnard (University of Colorado at Boulder), Emily Graham (PNNL) *unfunded collaborator* – Li Li (Pennsylvania State University)
- **Total Award:** $997,893

Roots can move water from wetter areas to drier areas in soil. This process is called hydraulic redistribution and has been observed around the world. This movement of water can change how soil holds carbon and how soil particles are arranged. The size and arrangement of soil particles controls how water moves through the ground and to streams. As water moves through the ground it transports nutrients and it can also transport pollutants. Small changes to the arrangement of soil particles can have large impacts on the amount of water in streams and the nutrients and pollutants carried to the stream. This three-year award will focus on testing three hypotheses at the well-studied H.J. Andrews (HJA) Experimental Forest. First, the structure of soil will break down where hydraulic distribution creates wetter conditions. This breakdown is a result of an increase in the decomposition of organic matter and a decrease in soil water salt concentrations. Second, a greater portion of soil organic carbon will be lost in water as dissolved organic carbon as compared to gas as carbon dioxide where hydraulic redistribution creates wetter soils. Finally, wetter conditions created by hydraulic redistribution will increase the loss of nutrients and weathering products transported to the stream.

To test our hypotheses, we will use greenhouse experiments and field observations to measure changes in soil structure, properties, and chemistry. We will rely on mathematical models to better understand how variable water, nutrient, and metal fluxes are to changes in hydraulic redistribution. Our efforts will involve the development of new geophysical methods to measure water fluxes related to hydraulic redistribution in greenhouse and field settings. Together, these data and models will be used to quantify how variations in hydraulic redistribution influence fluxes of carbon, nutrients, and metals from the critical zone to the stream. This effort will involve the collaboration of ecohydrologists, ecosystem ecologists, geophysicists, geochemists, and environmental engineers from Oregon State University, Colorado School of Mines, University of Colorado Boulder, Pacific Northwest National Lab, and Pennsylvania State University. Results from our study will improve mathematical models of water movement and chemistry, and increase our understanding of the water cycle and water chemistry.

STEEP-CF: Storm Treatment Effects on Ecosystem Processes of Coastal Forests

- **Principal Investigator:** Rodrigo Vargas (University of Delaware)
- **Collaborators:** Angelia Seyfferth (University of Delaware), Anya Hopple (Smithsonian Environmental Research Center), Benjamin Bond-Lamberty (PNNL), *unfunded collaborator* – Fabiola Murguia-Flores (Universidad Nacional Autonoma de Mexico)
- **Total Award:** $996,156

Coastal forests and other coastal ecosystems are influenced by complex hydro-biogeochemical processes that are heavily impacted by climate change. Increased frequency and intensity of storm events and sea-level rise (SLR), already occurring and predicted to accelerate due to climate change, affect biogeochemical processes that ultimately shape ecosystem resiliency and can push these ecosystems into an alternative stable state. The result is that areas of coastal forests worldwide are transitioning from upland to wetland leaving behind "ghost forests" with an evident decline in aboveground carbon (C). That said, how these disturbances will affect less evident ecosystem processes, such as belowground C dynamics, is unclear. This lack of understanding is due to relatively less research on belowground processes, particularly at the ecosystem-scale, and the complex interplay between multiple biogeochemical pathways affected by altered hydrodynamics.

We propose to improve integrated understanding and predictive capacity of ecosystem changes, feedbacks, and subsequent responses to different types of flood disturbances in coastal forests. Our overarching objective is to improve the understanding and process-based modeling of complex feedbacks between flooding events and soil C dynamics in a coastal temperate forest. We will use field and mesocosm experiments to improve biogeochemical modeling of flooding events in coastal temperate forests using a Model Experimental (ModEx) approach.

We will take advantage of the ongoing DOE-funded TEMPEST (Terrestrial Ecosystem Manipulation to Probe the Effects of Storm Treatments), a large-scale manipulation experiment that has been established (but treatments have not started) to test flood disturbances of brackish and freshwater pulse events in a temperate coastal forest. We will additionally provide mechanistic understanding of the processes affected by these disturbance events by performing controlled mesocosm experiments on large intact soil columns obtained from the field site, where flooding events can be carefully manipulated and monitored. We will follow a ModEx approach, testing two different, cutting-edge biogeochemical models (one with emphasis on soil organic carbon (SOC) and the other on methanotrophs) to inform the coupled field-mesocosm experiments that will provide insights for future model refinement.

We will address four knowledge gaps and four associated hypotheses. The knowledge gaps include: a) Feedbacks between hydrologic disturbance events & belowground processes; b) Mineral-mediated C release after flooding disturbances; c) Successive hydrologic disturbance impacts on soil CO_2 and CH_4 flux magnitudes and metabolic pathways; and d) Limitations of soil biogeochemical models under flooding scenarios. We will test our hypotheses on these knowledge gaps in our field and mesocosm experiments with a diverse array of techniques such as: automated measurements of CO_2 and CH_4 fluxes and stable isotopes, characterization of organo-mineral associations using NEXAFS-STXM at DOE synchrotron light sources, and using the Millennial model to simulate SOC, and the Soil Methanotrophy Model with respect to soil CH_4 dynamics. We will follow a ModEx approach where information of current model assumptions will be used to define the methods and experiments, and then information from our experiments will be used to refine the models as part of the ModEx framework.

MACROCOSM: Monitor And Constrain tROpical eCOsystem Sensitivity to Moisture

- **Principal Investigator:** Xiangtao Xu (Cornell University)
- **Collaborators:** Xi Yang (University of Virginia), Xavier Comas (Florida Atlantic University), Tana Wood (Ciudadans del Karso, Inc.), Charles Koven (LBNL)
- **Total Award:** $900,000

Water drives ecosystem dynamics and functions in a wide range of terrestrial biomes, including tropical forests that receive meters of precipitation every year. Quantifying ecosystem sensitivity to changes in moisture conditions, especially droughts, is pivotal to predicting the future fates of our terrestrial biosphere under climate change. In the tropics, dense vegetation strongly shapes ecosystem carbon and water cycling. However, large knowledge gaps remain in how plants respond to and regulate ecosystem water dynamics. This has led to considerable uncertainty in ecohydrological predictions across state-of-the-art Earth system models. In this project, we aim to improve our understanding of how drought impacts tropical forests by artificially removing natural water input into forest stands in a Puerto Rican moist forest. We further combine the manipulative experiment with advanced computational modeling to shed light on the critical ecophysiology that governs forest sensitivity to moisture, which will provide critical information on the resilience of tropical forests to climate change.

We propose to monitor soil moisture and vegetation water content at the experimental site using an array of state-of-the-art remote sensing techniques (TLS, GPR, and GNSS). Combined with other traditional observations, these new non-destructive measurements can continuously track high-resolution 3D patterns of both above- and below-ground water dynamics and thus characterize fine-scale heterogeneity in soil and vegetation water dynamics. We will further integrate these water content observations with process-level measurements on vegetation hydrodynamics to understand how these processes respond to moisture changes under experimental drought. Key measurements include root sap flow that quantifies hydraulic redistribution and changes in canopy leaf angle distributions, both of which are key unknown plant processes that can control ecosystem-level water dynamics. We will then assimilate these new data streams and other available or ongoing ecohydrological measurements into a state-of-the-art process-based terrestrial biosphere model ED2.2-hydro. The data assimilation will enable model development and calibration on the key above- and below-ground ecohydrological processes that drive simulated ecosystem sensitivity to moisture. After testing the updated ED2.2-hydro with site-level numerical experiments, we will import calibrated parameters, functions, and modules to DOE's ELM-FATES model and test the generality of the knowledge gained from ED2.2-hydro. Finally, we will explore the implications of tropical ecosystem sensitivity to moisture constrained by the TFE experiment by conducting regional simulations with contemporary and projected hydroclimate in the neotropics.

Our proposed research will deliver comprehensive data collections over a long-term ecosystem experiment that is essential for developing an integrated, scale-aware, and predictive understanding of ecosystem responses to environmental change. The novel integration of ground-based remote sensing observations can help to prototype transformational ecological monitoring systems, which can apply beyond tropical biomes. The tight coupling between ecosystem monitoring and modeling in our project will scale our site-level research findings to inform regional to global ecosystem sensitivity to moisture. Altogether, the project directly addresses the DOE's research focus on plant-mediated ecohydrology across scales, will complement and synergize with other DOE-funded projects on tropical ecosystem dynamics (TRACE, NGEE-Tropics), and is expected to have sustained impacts on various fields of Earth system and environmental sciences.

Groundwater supported vegetation refugia as a mechanism for forest recovery in a Rocky Mountain Watershed impacted by wildfire

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- **Collaborators:** Andrew Parsekian and Brent Ewers (University of Wyoming), Xiaonan Tai (New Jersey Institute of Technology)
- **Total Award:** $999,999

Under a warming climate, forests in the Rocky Mountains of North America are experiencing significant ecohydrological shifts including reduced snowpack, decreased soil moisture, and multiple vegetation disturbances from drought, insect outbreak, and wildfire. After a fire, healthy tree stands and their crucial role as a seed source are more likely found in areas with shallow water tables and high soil moisture. These groundwater-supported vegetation refugia have also sheltered trees against multiple disturbances, which compels the need to improve our predictive understanding of their location and function in order to maximize the efficiency of land management resources to conserve them. While shallow water table has been identified as a key contributor to refugium formation at the scale of individual tree stands, processes that control water table dynamics at the landscape (i.e., disturbance) scale remain unclear. In a sloping landscape, water table depth (WTD) is controlled by both local and long-distance groundwater flow within a groundwater flow system (GFS). Refugia supported by local groundwater are sensitive to precipitation variability and are less stable while converging local and long-distance groundwater outflows can support persistently shallow water tables that act as long-term vegetation shelters. These hidden, albeit dynamic, GFSs are hypothesized to drive the trajectory of forest recovery after wildfire and other disturbance: refugia can exhibit a range of stability depending on WTD and its temporal persistence. Besides topography, precipitation, and evapotranspiration, WTD is strongly influenced by subsurface geological heterogeneity which can channel, deflect, and trap groundwater at unexpected locations. Thus, groundwater-supported vegetation refugia are hypothesized to form at both headwater and downstream regions in a landscape. The objective of this research is to test groundwater-supported vegetation refugia as a mechanism of forest recovery after wildfire by jointly examining spatiotemporal drivers that influence groundwater and vegetation. Using a recently burnt Rocky Mountain watershed as a testbed, we propose to collect co-located microclimate, vegetation, and hydrological measurements at five refugium sites along a landscape gradient encompassing a range of WTD and disturbance severity. Field measurements will be used to parameterize, test, and extend a distributed ecohydrological model that couples a new vegetation recovery module to a soil and groundwater model that considers lateral and vertical flow in a GFS. During this model-data integration, parameter and model structural deficiencies will be identified to inform field samplings and model development. Model verification will also be carried out by collecting additional measurements of ecosystem water use and status at a refugium site with vegetation growth data used as an independent test of the ecohydrological model. Given climate change and associated precipitation shifts in the Western mountains, we also hypothesize that existing refugia can be weakened or strengthened depending on how climate change feedbacks drive WTD and its persistence. Therefore, after the model is calibrated against historical (including proxy) and new field measurements, it will be used to project WTD and refugium trajectories in the study area under a range of climate change scenarios. Through quantitative examination of the interaction between GFS and vegetation, the proposed research will improve our predictive understanding of the change, response, and trajectory of forest recovery at the landscape scale. This study will (1) generate insights into groundwater-supported vegetation refugia that can be generalized to other sloping landscapes, (2) test, refine, and enhance wildfire recovery modeling capability of a coupled ecohydrological model, and (3) inform post-fire ecosystem assessments that require knowledge and information at the disturbance scale. Data and models generated in this research will be made available to researchers and other stakeholders. Besides disseminating the study findings through publications and presentations, the participle investigators will present actionable results to government agencies overseeing post-fire remedial actions.

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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