Environmental System Science

Summary of projects awarded in summer 2021 under the Environmental System Science Funding Opportunity Announcement DE-FOA-0002392.

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-0002392, was issued by the Environmental System Science program and released in the Fall of 2020. 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 more sophisticated modeling, this FOA encompassed three Science Research Areas (SRA): 1) Terrestrial-Aquatic Interfaces, 2) Perturbations and Disturbances, and 3) Novel Methods for Hot Spots/Hot Moments.

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 – Terrestrial-Aquatic Interfaces</u>: Improved understanding of environmental and ecological processes in the hydrologically oscillating zones within terrestrial-aquatic interfaces (TAI) to better understand hydro-biogeochemical processes and their drivers in these complex environments.

Applications were required to 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. The terrestrial-aquatic interface research focus was limited to those processes that incorporate and connect directly to terrestrial ecosystems at their immediate interface with freshwater and/or brackish water systems.

<u>SRA 2 – Perturbations and Disturbances</u>: New or improved understanding of ecosystem or watershed changes, responses, and trajectories following perturbations and their feedbacks to Earth system hydro-biogeochemical processes at local to global scales.

Applications were limited to investigation of droughts, floods, temperature and precipitation shifts and/or extremes, chronic sea level rise, and wildfires, with particular interest in studies that address compounding effects of contemporaneous chronic shifts and episodic events. Successful applications were required to target feedbacks and interactions among distinct ecosystem, watershed, and/or Earth system components and processes in a coupled, integrated systems framework. Studies that focus on microbial or vegetative processes and community shifts, eco-hydrologic responses (e.g., evapotranspiration), surface-subsurface interactions, and connections between above- and belowground processes at local to global scales are encouraged.

<u>SRA 3 – Novel Methods for Hot Spots/Hot Moments:</u> Demonstrate methodologies suitable for precisely measuring the occurrence and quantifying the magnitude of “hot spots” and “hot moments” of biogeochemical activity in ways that are transferrable across ecosystems, watersheds, or regional scales to enable robust incorporation of causal factors into a range of process-based models.

Successful applications were required to demonstrate how the proposed methodology will quantify and distinguish between sustained and episodic activity (“hot moments”) or resolve the spatial representation necessary for isolating “hot spots”. Special consideration will be given to those applications that develop approaches to characterize/quantify both “hot spots” and “hot moments” for systems where both phenomena co-occur.

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.

Seventeen awards (eight of which were exploratory awards) were made through this Funding Opportunity Announcement totaling $10,777,714 over three years.

Funded Projects

Linking root and soil microbial stress metabolism to watershed biogeochemistry under rapid, year-round environmental change

- **Principal Investigator:** Jennifer Bhatnagar (Boston University)
- **Collaborators:** Kristen DeAngelis (University of Massachusetts-Amherst), Charles Driscoll (Syracuse University), *Unfunded Collaborator* – Elsa Abs (University of California-Irvine
- **Total Award:** $989,201
- **Award Type:** Standard

Climate change is occurring rapidly in northern forests, where air temperatures and precipitation are rising, but winter snowpack is shrinking, leading to more frequent soil freeze/thaw cycles in winter. These contrasting changes in soil temperature–moisture regimes are a major stressor for plant roots and soil microorganisms and can lead to changes in cycling of carbon and nutrients through whole forested ecosystems. Warming during the growing season may destabilize and release soil carbon (C) and nitrogen (N) into soil solution, but the severe thermal impact of soil freeze/thaw cycles in winter could magnify (in the case of N) or reverse (in the case of C) these losses. The combination of warming and increased freeze/thaw cycles appear to initially induce oxidation-reduction stress that selects for anaerobic N cycling-microbes and metal oxidizers, while shifting the majority of aerobic microbial C-cycling activity into deeper soil layers during winter. Soil microbes are also evolving under these extreme conditions to increase decomposition of plant and soil C, but decrease decomposition of organic P, potentially decoupling C, N, and P outputs to associated aquatic ecosystems. These climate change effects on microbial metabolism could impact the export of dissolved organic matter and nutrients in ways that may explain longer-term changes in stream water chemistry and productivity of forested watersheds, yet they are poorly represented in ecosystem models. The objective of this research is to improve mechanistic understanding and model representation of the combined effects of warming during the growing season and soil freeze/thaw cycles in winter on belowground biogeochemical cycles in northeastern forests. The overarching hypothesis is that under climate change across seasons, microbes and plants exhibit a trade-off between stress metabolism and soil C, N, and P uptake and assimilation (short term) and biomass stabilization (longer term) that scales up to impact soil carbon and nutrient export at the watershed-level.

To test this hypothesis, this project proposes a model-data integration study using the Climate Change Across Seasons Experiment (CCASE) at the Hubbard Brook Experimental Forest (HBEF) and a complementary plot-to-watershed-level biogeochemistry model, PnET-BGC. At CCASE, replicate field plots receive one of three climate treatments: growing season warming (+5°C above ambient), warming + freeze/thaw cycles (+5°C above ambient in growing season plus up to four freeze/thaw cycles in winter), and reference conditions (no treatment). The project proposes to couple new seasonal belowground biogeochemistry measurements at CCASE (net and gross C, N, and P fluxes and rates of plant- and microbial-derived DOC/N/P production in soil solution) in organic and mineral soil horizons, with omics data on soil microbial communities (population genomics, metagenomics, metabolomics) to reconstruct potential plant and microbial C, N, and P metabolism and export to the HBEF watershed over the past decade. To quantify the evolutionary trajectory of microbial evolution *in situ* during this time period, the team will combine soil metagenomics datasets with new high-throughput characterizations of trait and gene evolution in individual soil bacteria and fungi collected from CCASE. To develop an integrated, scale-aware understanding of the consequences of evolving microbial stress and resource use traits for forest nutrient and C retention, the team will incorporate both immediate and evolved responses of microbial C, N, and P cycling into new versions of PnET-BGC by applying an evolutionary algorithm to control specific C, N and P flux fluxes. Outputs of the revised PnET-BGC will be validated with over 40 years of existing forest C, N, and P pool and flux data from HBEF watersheds. By leveraging the versatile PnET-BGC model with a genes-to-ecosystems analysis of C, N, and P cycling at CCASE, this research will test the conceptual understanding of plant and microbial physiology responses to severe compounding soil temperature perturbations across seasons, as well as the utility of a forest stand–level manipulative climate change experiment to understand the biogeochemical dynamics of a forest watershed undergoing rapid environmental change.

Interactive effects of press and pulse disturbances on biogeochemical cycling of a wet tropical forest in Puerto Rico

- **Principal Investigators:** Molly Cavaleri (Michigan Technological University) Sasha Reed (USGS)
- **Collaborators:** Tana Wood (Ciudadanos Del Karso), Xiaojuan Yang (ORNL), *unfunded collaborator* – Anthony Walker (ORNL)
- **Total Award:** $1,000,000
- **Award Type:** Standard

Tropical forests represent one of Earth's most active biogeochemical engines: Although only ~12% of the planet's terrestrial surface supports tropical forests, they account for over 2/3 of live terrestrial plant biomass, nearly one-third of all soil carbon. Tropical forests exchange more carbon dioxide with the atmosphere than any other terrestrial biome. The primary objective of the work is to use a one-of-a kind field warming experiment in Puerto Rico and a cutting-edge modeling approach to advance a robust, predictive understanding of how the individual and interacting disturbances of increasing temperatures and altered precipitation affect above- and belowground carbon cycling in tropical forested ecosystems. The Tropical Responses to Altered Climate Experiment (TRACE) in Puerto Rico is the only field warming experiment in the world that integrates both plant and soil warming in a tropical forest, and thus is uniquely positioned to investigate and model the controls and interactions critical to forecasting tropical forest responses to a changing climate. In particular, TRACE has amassed an exceptional dataset of above- and belowground processes and conditions that include identification of the individual and interacting effects of multi-year *in situ* warming, natural extreme climatic disturbances (e.g., drought, large precipitation events), and associated changes to forest communities and biogeochemical cycles. With the help of TRACE's long-time modeling partners, the project is ready to incorporate data from multiple facets of TRACE inquiry into a synthetic modeling framework, as well as iteratively collect new data to assess the potential for acclimation over the longer term as well as advance the understanding and capacity to numerically represent these productive ecosystems. The team will integrate and scale complex above- and belowground processes using ELM, the land component of the DOE Earth System

Model (E3SM), coupled with a model that represents vegetation demography (FATES). This effort will enable the synthesis of whole-forest effects of warming and precipitation disturbance—from one meter deep in the soil to the tops of the canopy—and will directly address DOE missions to develop fruitful dialogs between modelers and experimentalists and investigate ecosystem responses, feedbacks, and recovery from extremes events and chronic perturbations. The ability to accurately represent tropical forests in climate models lags far behind that of many temperate ecosystems and, as a result, they account for numerous large uncertainties and biases in ESMs. The team has developed an integrative, hypothesis-driven approach to directly address this large gap in existing state-of-the-art models and to significantly advance understanding of how tropical forest carbon cycling will respond to global change.

Predicting hot spots and hot moments of biogenic gas accumulation and release in a subtropical ecosystem using airborne ground-penetrating radar (GPR)

- **Principal Investigator:** Xavier Comas (Florida Atlantic University), Neil Terry (USGS)
- **Collaborators:** Caiyun Zhang (Florida Atlantic University), *unfunded collaborator* – Angela Gallego-Sala (Exeter University)
- **Total Award:** $149,999
- **Award Type:** Exploratory

Peat soils are large natural producers of biogenic greenhouse gases (like methane and carbon dioxide) that accumulate in the soil matrix to subsequently be released to the atmosphere. Remarkable advances have been made in the last few decades in predicting these carbon fluxes at a variety of spatial and temporal scales in peat soils; however, many uncertainties exist regarding the spatial distribution of hot spots for biogenic gas accumulation and hot moments for the rapid release of biogenic gases. Imaging and identifying these areas are difficult since most methods either: (1) require disturbance to the soil and typically can only characterize isolated local conditions that may not be representative of the heterogeneous conditions in peat soils, or (2) have sampling volumes that are too large to properly capture hot spots of increased geochemical activity. In this two-year exploratory study, the team intends to use a prototype GPR unit mounted on a small unoccupied aircraft system (sUAS) to efficiently identify the presence of hot spots and hot moments for biogenic gas accumulation and release in subtropical peat soils of the Everglades and to explore how certain physical (i.e., soil structure) and biochemical properties (i.e., metabolic pathway) may influence its dynamics.

Understanding spatial and temporal drivers of variation in tree hydraulic processes and their consequences for climate feedbacks

- **Principal Investigator:** Jeffrey Dukes (Purdue University)
- **Collaborators:** Elin Jacobs (Purdue University), Kimberly Novick and Richard Jacobs (Indiana University), Chonggang Xu (LANL), *unfunded collaborators* – Yilin Fang and Chang Liao (PNNL)
- **Total Award:** $1,000,000
- **Award Type:** Standard

Trees can cool the global climate by storing carbon during photosynthesis and can cool the local climate by pulling moisture out of the ground with their roots and releasing it from pores in their leaves as water vapor; a process known as transpiration. Photosynthesis and transpiration generally increase when trees have access to sufficient water in the soil and decrease during dry periods when soil water is less abundant. While there is a general understanding that these processes depend on soil moisture (and air humidity) and that these relationships differ by tree species, less is known about how a tree’s past exposure to water stress affects its later response to water availability. Without this information, scientists cannot improve computer models that help us better understand how climate change affects tree growth and carbon uptake. The team will study the water responses of trees growing in different positions across the landscape that afford different levels of access to water (e.g., hilltop vs. streamside), as well as trees that have been deliberately exposed to different levels of reduced precipitation in recent years. The research will focus on species growing in hardwood forests of northern and southern Indiana that have different levels of response to water stress. Questions this research aims to answer are: How different are the water responses of individuals of the same species that have experienced different moisture conditions? How do the differences within a species compare to differences between species? For example, trees that are used to periods of drought may develop strategies to be able to continue photosynthesis during droughts, while trees without these strategies cannot. The researchers will develop ways to represent these within-species differences in model representations of trees in order to more realistically simulate the functioning of trees within the land component of the E3SM climate model. The improved model could provide a better picture of how much carbon trees will be able to ingest and store under different climate scenarios and how forests will affect local and global climates in the future.

Methane dynamics described through vegetation-soil interactions in bald cypress and other bottomland hardwood forests

- **Principal Investigator:** Bassil El Masri (Murray State University)
- **Collaborators:** Jessica Moon and Gary Stinchcomb (Murray State University), Benjamin Runkle (University of Arkansas-Fayetteville)
- **Total Award:** $299,900
- **Award Type:** Exploratory

Natural wetland methane (CH_4) fluxes play an important role in global climate change as CH_4 is one of the major greenhouse gases. Current understanding of the response of natural wetlands, particularly mineral soil wetland CH_4 fluxes, to climate change is still uncertain leading to large uncertainties in the global CH_4 budget. While the Lower Mississippi Alluvial Valley has experienced the largest loss of forested wetlands in the United States—supporting 21 to 25 million acres of bottomland hardwoods before European settlement—an estimated 5 million acres remain. This landscape remains understudied from a CH_4 flux perspective, particularly in determining woody vegetation contributions to landscape CH_4 emissions.

The project's overarching objectives are (1) to improve understanding of the controls on CH_4 fluxes in forested mineral soil wetlands, and (2) to better understand the effects of landscape position and forest composition on the CH_4 fluxes between terrestrial ecosystems and the atmosphere. The main goal is to elucidate the dynamics of CH_4 fluxes within forested wetland ecosystems to improve regional predictions in response to climate change and shifting hydrological oscillation patterns. Using a coupled modeling-experimental (ModEx) approach, the main scientific goal is to investigate the spatial and temporal carbon dynamics of a temperate bald cypress (*Taxodium distichum*), mineral soil wetland, and an adjacent bottomland hardwood stand using a suite of measurements including new soil and tree (i.e., stem and "knee") methane (CH_4) flux observations.

This study is therefore based on the premise that understanding methane fluxes in a temperate, forested wetland will advance mechanistic and model-ready science across a wide range of terrestrial-aquatic interface processes. The processes and model modification will help to simulate the adaptation of wetland ecosystems to a changing climate through better representations of the soil-vegetation interactions. By improving understanding and modeling of CH_4 processes at Bald Cypress Swamp, this work aims to make significant contribution to two key sciences question in DOE objectives: (1) new or improved understanding of environmental controls and ecological processes in hydrologically oscillating zone on CH_4 fluxes; and (2) collection of new CH_4 measurements.

From tides to seasons: How cyclic tidal drivers and plant physiology interact to affect carbon cycling at the terrestrial-estuarine boundary

- **Principal Investigator:** Inke Forbrich (Marine Biological Laboratory)
- **Collaborators:** Zoë Cardon (Marine Biological Laboratory), Teri O'Meara (ORNL), *unfunded collaborators* – Ann Giblin (Marine Biological Laboratory), Ben Sulman (ORNL)
- **Total Award:** $998,713
- **Award Type:** Standard

Coastal ecosystems are among the most biologically and biogeochemically active and diverse systems on Earth. Because they act as important linkages between terrestrial ecosystems and the open ocean, their incorporation in Earth system models (ESMs) is critical to predict coastal and global responses to environmental changes. However, they vary greatly in the magnitude of tides and the volume and timing of freshwater input from land, making it challenging to model the major biogeochemical reactions that control productivity and greenhouse gas emissions across coastal terrestrial aquatic interfaces (TAIs). Key characteristics that distinguish coastal wetlands, such as tidal oscillation, sulfur biogeochemistry, and plant structural adaptations to anaerobic soil, have only very recently been incorporated in land-surface models such as ELM-PFLOTRAN. There remains large uncertainty in their parameterization. Particularly challenging are: 1) the small-scale, dynamic, heterogeneous redox conditions in wetland soils; 2) the aerenchyma tissue in wetland plants that greatly facilitates gas flow into and out of sediment; and 3) the temporal and spatial variability in salinity, which is a key determinant for plant species distribution and productivity, as well as organic matter decomposition. The project's overarching goal is to improve mechanistic process understanding and modeling of tidal wetland hydro-biogeochemistry in coastal TAIs. Working in brackish marsh, the team will combine intensive and new spatially explicit sediment redox measurements with continuous sediment redox, salinity, and water table data, testing relationships between these sediment data and eddy covariance measurements of carbon and energy exchange. Measurements will be guided by, and will inform, new developments in ELM-PFLOTRAN designed to capture critical features of diverse coastal TAI functions. Three questions, spanning small to ecosystem scales, and short to long-term drivers, guide the approach:

1. How do tidal water level oscillations, evapotranspiration-driven water level changes, and oxygen (O_2) transport from roots into the rhizosphere control tidal marsh redox and sediment oxygen distribution?

2. How do hydrology, biogeochemistry and plant biology interact on different timescales to influence energy and greenhouse gas fluxes?

3. How will carbon sequestration and greenhouse gas fluxes respond to changes in climate and sea level?

This project will test six hypotheses within the framework of these three questions. The team plans integrated measurements and modeling at two locations with contrasting hydro-biogeochemistry in an oligohaline marsh in the Parker River Estuary, Massachusetts. The estuary is the largest remaining tidal wetland complex in the northeastern United States. Research at this location will be synergistic with ongoing efforts by the modeling team at the Global Change Research Wetland GCReW. The project will use field measurements to help constrain three phases of ELM-PFLOTRAN development designed to improve simulations of brackish marsh biogeochemistry under fluctuating oxygen availability and salinity influenced by tides, diel and seasonal changes in plant physiology, and river discharge.

Ultimately, the team will be poised to combine new process understanding and model formulation with existing long-term data already in hand from two more saline salt marsh sites in the Parker Estuary. As sea level rises, saline conditions will become more common in many coastal TAIs, but they will also potentially be exposed to more flashy freshwater riverine input from intense, sporadic storms. By having information from marshes at both ends of the full salinity gradient, the team will be able to better constrain biogeochemical reactions in ELM-PFLOTRAN, validate ecosystem-scale modeled fluxes with eddy covariance measurements, and simulate present and future hydrological variations and resulting carbon dioxide and methane fluxes in tidal wetlands in the face of expected global change.

A general mechanistic framework for cross-scale understanding of hot spots and hot moments in carbon and water fluxes

- **Principal Investigator:** Steven Kannenberg (University of Utah)
- **Collaborators:** Mallory Barnes (Indiana University), *unfunded collaborator* – William Anderegg (University of Utah
- **Total Award:** $150,000
- **Award Type:** Exploratory

Semi-arid ecosystems, like those in the American Southwest, exert a massive impact on the interannual variability of carbon and water cycling. Unfortunately, these carbon and water fluxes are notoriously difficult to predict due to their high spatial and temporal variability, which is poorly captured by the current generation of vegetation models. Indeed, this region is exemplified by the 'hot spots and hot moments' concept, which states that small areas in space ('hot spots') and transient moments in time ('hot moments') exert an outsized influence on biogeochemical cycling. However, the factors that regulate these pulses in biogeochemical activity are unknown, as is their variability across space and time. These uncertainties severely limit efforts to better represent hot spots and hot moments in models. Here, the project seeks to develop a generalized method for detecting and quantifying the importance of hot spots and hot moments from individual plant to regional scales. Underpinning this method is a recently developed statistical approach for identifying hot spots and hot moments. By applying this method to semicontinuous measurements of plant water status, a depth profile of soil water potential, and ecosystem fluxes via eddy covariance, the team will track the fate of water through the soil-plant-atmosphere continuum and identify mechanistic drivers of these transient pulses in biogeochemical activity. Then, the team will expand this approach across a broad network of Ameriflux towers and apply a machine learning approach that will allow upscaling of measurements of hot spots and hot moments across the American Southwest and quantifying of their impact on carbon and water cycles. These products will allow the team to identify hot spots and hot moments across spatiotemporal scales and will serve as crucial data sources for validating a new generation of models that can better capture highly dynamic carbon and water fluxes. The method will be easily transferable across biomes and will serve as a framework for future research on hot spots and hot moments across the plant ecophysiology, biometeorology, and vegetation modeling communities.

Rewriting the Redox Paradigm: Dynamic hydrology shapes nutrient and element transformations in a Great Lakes coastal estuary

- **Principal Investigator:** Lauren Kinsman-Costello (Kent State University)
- **Collaborators:** John Senko (University of Akron), Chelsea Monty-Bromer (Cleveland State University), Tim Morin (SUNY-ESF), Gil Bohrer and Ethan Kubatko (Ohio State University), *unfunded collaborator* – Elizabeth Herndon (ORNL)
- **Total Award:** $297,959
- **Award Type:** Exploratory

Fine-scale biological, geochemical, and chemical reactions underlie environmental system function. Many of these processes, including oxygenic photosynthesis and aerobic respiration, are coupled reduction-oxidation, or "redox," reactions. Redox reactions transfer energy by moving electrons from an electron donor, such as an organic molecule, to an electron acceptor, often oxygen. In flooded organic soils, oxygen is depleted by microbial respiration more rapidly than it is regenerated. When oxygen is depleted, organisms can use other molecules to accept electrons in a specific order, in part because the energy yields of redox reactions differ based on thermodynamic principles. When competing for labile organic substrates, organisms that can capture more energy should outcompete organisms using metabolisms that yield less energy, in what is sometimes called the "thermodynamic exclusion principle." However, recent research challenges predictions based on this "redox ladder" paradigm. At small scales, it is now apparent that rather than exclude one another, redox processes of variable energy yield co-occur in space and time, such that the theoretically discrete "rungs" of this metaphorical ladder seem out of place or even intermingled.

Microbes that mediate environmental processes experience conditions at much smaller scales than scales at which they are typically detected. Thus, the project hypothesizes that fine-scale heterogeneity causes apparent departures from "redox ladder" predictions at larger scales. The team predicts that it will detect this heterogeneity in electrochemical signatures measured as redox potential (Eh) and zero resistance ammetry (ZRA) at fine spatial scales and high temporal resolution and that this heterogeneity has whole-ecosystem consequences. Objectives are to combine custom-built sensors, direct measurements of biogeochemistry, and process-based modelling in a Great Lakes river mouth wetland system (Old Woman Creek, Ohio) to (1) relate dynamic hydrology to redox regimes in contrasting soils; (2) determine how redox heterogeneity in space and time drives C, N, P, S, Fe, and Mn cycling, and (3) assess the sensitivity of ecosystem scale process-based models to fine-scale variability in redox conditions.

Wetland systems, including river mouths and estuaries at terrestrial-aquatic interfaces, are often called "the kidneys of the landscape" because of their potential to filter, store, and transform contaminants. Many of the processes that drive "purifying" functions are redox reactions, and thus understanding how fine scale redox processes relate to whole-ecosystem function is highly relevant to wetland and watershed management. Current policies and best practices are based largely on structural indices of wetland function, and thus visible variability in habitat is a common goal. Less common, but often implied or assumed, is that structural heterogeneity will promote nutrient removal by creating redox heterogeneity. This project will formalize relationships between hydrology, electrochemical conditions, and biogeochemical processes at nested scales to inform ecosystem- and watershed-scale management for nutrient and elemental cycling.

The potential for advanced snowmelt timing to decouple plant and mycorrhizal fungal phenology and biogeochemical cycling

- **Principal Investigator:** Stephanie Kivlin (University of Tennessee)
- **Collaborators:** Aimee Classen (University of Michigan), Patrick Sorensen (LBNL), David Inouye and Heidi Steltzer (Rocky Mountain Biological Lab), *unfunded collaborators* – Eoin Brodie (LBNL), Ben Sulman (ORNL)
- **Total Award:** $996,998
- **Award Type:** Standard

As climate changes, snowpack is expected to diminish, and snowmelt timing is expected to advance. Shifts in snow quantity and melt dates are especially relevant in mountain ecosystems, which provide 50% of the Earth's fresh water. As snowmelt advances, the phenology (e.g., timing of growth and life history events) of organisms that rely on the water and nutrient pulses provided at snowmelt may also change. However, all organisms may not respond the same ways to advanced snowmelt. If previously interacting organisms shift their phenologies in different ways, previously synchronous interactions may become asynchronous with climate change (i.e., phenological mismatch).

Nowhere is the threat of temporal interaction decoupling more relevant than among plants and associated mycorrhizal and decomposer fungi. Decomposer fungi mineralize soil organic compounds into plant-available nutrients. Arbuscular mycorrhizal (AM) fungi then provide plants with these nutrients, up to 80% of their required nutrients. While belowground plant growth has been observed under snow, the timing and magnitude of this plant root growth is largely understudied. Decomposer and AM fungal growth under snowpack has not been addressed. Snowmelt date can vary by two months at the study site. If plants and fungi respond to different cues (e.g., plants respond to temperature, but fungi respond to soil moisture), then their growth may become decoupled. If this occurs, nutrients that would have been mineralized by decomposer fungi, acquired by AM fungi, and shunted to fuel plant productivity could instead be leached from soil into the underlying hydrological system. If this occurs consistently, plant productivity will decrease and watershed nutrient loads will increase in a warmer climate.

This project links with the existing LBNL Watershed SFA to assess the potential for climate-induced temporal disruption of plant and fungal exchange of nutrients and consequences on watershed biogeochemical nutrient cycling with shifts in the magnitude of snowpack and snowmelt timing. The project will evaluate temporal decoupling of plant–AM fungal symbioses and decomposer fungi using observational elevational gradients that capture both local and regional snowmelt heterogeneity, (AIM I) in paired early and late snowmelt plots (AIM II) and connect these to functional consequences by modeling soil biogeochemical fluxes at the watershed scale (AIM III). The team will first determine plant and fungal growth belowground by installing ingrowth cores at eight time points in each of three years at four elevations (2500 – 3900 m) that vary in length of growing season, soil nutrients, climate, and snowmelt date. The team will then explicitly determine how snowmelt timing affects belowground plant and fungal growth by installing ingrowth cores into early snowmelt manipulations at one elevation (2900 m) at eight time points in each of three years. In all these sites and times, the team will also measure soil nutrient concentrations within the rooting zone and below the rooting zone (to assess leaching). During the growing season, the team will also assess plant productivity (e.g., NDVI) and nutrient acquisition traits (e.g., SLA, tissue stoichiometry) to understand if particular plant and fungal traits are selected for across ecosystems that vary in snowmelt timing and soil nutrient concentrations. All data will be integrated into structural equation models to understand plant versus fungal control on soil nutrient retention at the watershed scale. Finally, the team will parameterize E3SM model runs with collected phenological and biogeochemical data across the RMBL watershed.

Identifying Hot Spots and Hot Moments of Metabolic Activity in Salt Marsh Sediments through BONCAT-FISH Microscale Mapping

- **Principal Investigator:** Jeffrey Marlow (Boston University)
- **Total Award:** $149,664
- **Award Type:** Exploratory

Complex microbial communities are essential constituents of soil and sediment ecosystems: they modulate nutrient and metabolite flux in ways that filter runoff, determine greenhouse gas emissions, and support higher trophic levels. However, the ability to derive net biogeochemical fluxes from knowledge of a community's constituents is limited by a lack of suitable methods connecting metabolic activity on a single-cell level to emergent, bulk processes. In salt marsh sediments, where redox zones are highly compressed due to substantial organic loading, this challenge is particularly pronounced: connections between dominant electron-donating (carbon) and electron-accepting (sulfur) metabolic cycles lack spatial and temporal specificity.

This project aims to fill these knowledge gaps in three specific ways. First, the team will enhance its newly developed microscale metabolic mapping technique to identify the “hot spots” of metabolic activity in intact salt marsh sediment. The approach combines *in situ* incubations, substrate analog probing, resin embedding, μ-CT scanning, and correlative fluorescence and electron microscopy to map the pore network, mineral grains, all biomass, and the anabolically active subset of organisms. To link identity and catabolic function with spatial and anabolic information, the team will incorporate multiplexed fluorescence *in situ* hybridization into the workflow, targeting known lineages (through 16S rRNA hybridization) and specific carbon- and sulfur-processing metabolic pathways (through mRNA hybridization). Second, by deploying the approach across daily and seasonal cycles, the team will clarify the “hot moments” of particular microenvironments and metabolisms. For example, the team anticipates measurable shifts from photosynthesis-derived carbon sources to chemolithotrophically derived carbon sources as drivers of sulfate reduction during the day and night, respectively. Finally, the team will optimize a metabolic model using the microscale map information as well as measurements of bulk carbon and sulfur metabolite changes over the course of the incubations. By tuning environmentally relevant parameters to link cell-centered “bottom-up” activity with net “top-down” bulk measurements, the project will advance efforts to build a scale-aware, predictive understanding of how complex environmental microbiomes shape emergent biogeochemical fluxes.

The team anticipates that the work will generate several ecosystem-specific and interdisciplinary outcomes. At Little Sippewissett Salt Marsh, research will clarify the spatiotemporal links between the microbial community and carbon and sulfur cycling; understanding these mechanistic details of ecosystem function will allow better predictions of changes in biodiversity and emergent biogeochemical fluxes, particularly in the context of continued environmental change. More broadly, by building microscale maps of metabolic activity in the context of an intact and mineralogically diverse sediment column, fundamental principles that structure environmental microbiomes will emerge. For example, the workflow will expose relationships between a cell’s metabolic activity and its microenvironment—pore connectivity, mineral identity, and the function and distance of microbial neighbors. By incorporating these primary data into flux balance analysis–reaction transport models, the work will provide a blueprint for scientists to directly link bottom-up, single cell ecophysiological measurements with top-down assessments of net fluxes for microbiomes, environments, and biogeochemical cycles of interest.

High-frequency Data Integration for Landscape Model Calibration of Carbon Fluxes Across Diverse Tidal Marshes

- **Principal Investigator:** Patty Oikawa (California State University-East Bay), Lisamarie Windham-Myers (USGS)
- **Collaborators:** Chris Gough (Virginia Commonwealth University), Karina Schäfer (Rutgers University-Newark), Sara Knox (University of British Columbia), Rodrigo Vargas (University of Delaware)
- **Total Award:** $999,908
- **Award Type:** Standard

Terrestrial aquatic interfaces (TAIs), and tidal wetlands in particular, store large amounts of carbon yet are not well represented in Earth System Models (ESMs). Predictions of carbon cycling and greenhouse gas (GHG) emissions in tidal wetlands are highly uncertain. Eddy covariance (EC) towers provide ecosystem-scale GHG flux data at a temporal resolution (every 30min) that is helpful for parameterizing and improving mechanistic realism in ESMs.

The team proposes to use a network of eddy covariance towers and standardized ancillary data streams, along with mesocosm experiments and statistical analyses, across diverse tidal wetlands of North America to develop and improve biogeochemical modeling at the TAI. The overarching objective is to improve understanding and process-based modeling of gross primary productivity (GPP) and CH_4 emission responses—both nonlinear and asynchronous—to stressors including plant inundation, disturbance, salinity, and nitrogen loading.

The network of seven eddy covariance towers will measure net ecosystem exchange of CO_2 and CH_4 along with critical ancillary variables including water table height, plant inundation, porewater and tidal channel salinity and nitrate, and soil respiration measurements. First, the research team will develop new algorithms for partitioning net ecosystem exchange measurements of CO_2 (NEE) into GPP and ecosystem respiration (Reco) and validate the new algorithms using stable isotope partitioning. Using the flux and ancillary data streams across the tower network, researchers will use statistical analyses (i.e., piecewise regressions, wavelets, and information theory) to identify thresholds and lag responses between GPP and CH_4 emissions and changes in plant inundation, salinity and nitrate across multiple temporal scales (e.g., diel-interannual). Thresholds and nonlinear or asynchronous responses detected in statistical analyses will be targeted using mesocosm experiments where inundation, salinity, and nitrate pulses will be studied under controlled conditions.

The observational and experimental data and statistical analyses will be used to inform model structural improvements of a tidal wetland biogeochemical model MEM-PEPRMT. MEM-PEPRMT will be parameterized using a model-data fusion approach. The CH_4 submodule of MEM-PEPRMT will be compared with a machine learning model built using CH_4 emission data. MEM-PEPRMT model performance will be evaluated against the validation dataset (a subset of sites not included in model parameterization) and the machine learning model. Finally, the improved MEM-PEPRMT model will be compared with PFLOTRAN-E3SM at an independent site in Chesapeake Bay, an ESM that has recently been adapted for improved performance in tidal wetlands. This comparison will help inform how model structure and structural error in ESMs can be improved and quantified, respectively. This research will improve predictive modeling of GPP and CH_4 by ESMs in tidal marshes, a critical but poorly constrained TAI that plays a disproportionately large role in soil carbon storage.

Plant carbohydrate depletion, mycorrhizal networks, and vulnerability to drought: an experimental test in the field

- **Principal Investigator:** Ana Sala (University of Montana)
- **Collaborators:** Gerard Sapes and Ylva Lekberg (University of Montana), Roger Koide (Brigham Young University)
- **Total Award:** $296,784
- **Award Type:** Exploratory

Frequency and severity of droughts is increasing with climate change and causing an increase in forest drought-induced mortality (DIM). Because forests provide many services to society and represent a major terrestrial carbon sink, increased DIM will have profound ecological, social, and economic consequences from local to global scales. Predicting when, where, and which trees will die of drought remains a challenge, in part, because the processes leading to DIM and their interactions are neither fully understood nor fully represented in mechanistic models. Both impaired plant hydraulics and depletion of stored non-structural carbohydrates (NSC) have been implicated in DIM and empirical and modelling evidence indicate that most DIM occurs as a result of their interaction. However, the mechanistic nature of this interaction is not well understood, and, therefore, cannot be currently modelled. In the greenhouse, the research team has experimentally shown that NSC storage depletion has a direct negative effect on osmoregulation and plant water retention. These results are exciting because they provide a mechanistic link to quantify and model the interaction between NSC storage and plant hydraulics, which has been identified as a major challenge. However, there is lack of evidence that such effects occur in the field. The greenhouse experiments also showed that plant carbohydrate depletion can spread through ectomycorrhizal networks and impair water relations. If a carbon allocation tradeoff exists between maintaining water relations and sustaining symbionts, this provides an opportunity to mechanistically incorporate symbiotic biotic agents into DIM models via their effects on NSC storage. In this exploratory research, the project proposes to test: 1) the mechanistic link between plant hydraulics and NSC storage in the field, 2) the potential for belowground fungal networks to affect this link and to influence forest vulnerability to drought. Such effects are expected to occur, for instance, when some—but not all—individuals in a network die and cease to supply carbon to the network, therefore increasing carbon demand from the network on surviving neighbors. The team proposes a field experiment in *Pinus ponderosa* saplings, where researchers will manipulate carbon supply to the ectomycorrhizal (EM) network, water availability, and sapling connections to the EM network to test effects of NSC depletion on plant hydraulics and potential carbon allocation tradeoffs between maintaining water relations and sustaining symbionts with consequences on forest vulnerability to drought. The research addresses two significant challenges for modelling forest responses to drought: how to quantify and model the interdependency between plant hydraulics and carbohydrate availability, and how to incorporate interactions with below ground symbiotic organisms. The data from this research will greatly improve the development of models of tree mortality, a global phenomenon with large consequences.

Trees as conduits for connecting belowground microbial processes to aboveground CH_4 emissions at the Terrestrial-Aquatic Interface

- **Principal Investigator:** Scott Saleska (University of Arizona)
- **Collaborators:** Laura Meredith, Joost van Haren (University of Arizona), Plinio Barboas de Camargo (University of Sao Paulo), Raimundo Cosme Oliveira (Embrapa-Santarem), Jose Mauro, Mouro Rodrigo de Silva, Raphael Tapajos, Amanda Mortati (Federal University of West-Para), *unfunded collaborator* – Dan Ricciuto (ORNL)
- **Total Award:** $999,260
- **Award Type:** Standard

The seasonally inundated floodplain forests of the Amazon River and its whitewater tributaries, known as várzea forests, are an iconic example of ecosystems at the terrestrial-aquatic interface. Though the Amazon basin várzea forests have been estimated to emit more methane from the stems of its trees than is emitted from all Arctic wetlands combined, integrated study of the controls, budget and seasonal dynamics of methane cycling in these great forests is lacking. This project would establish the first continuous whole-ecosystem measurements of methane emissions, via eddy covariance methods, from a seasonal floodplain forest in the Amazon. The goal is to improve process-based understanding and modeling of the biogeochemistry of this important greenhouse gas in this globally critical habitat.

Two puzzles challenge understanding of Amazonian CH_4 cycling: First, the mismatch between top-down estimates (from satellites or aircraft), which show a large source of CH_4 to the atmosphere, and bottom-up estimates (from individual sites and soil flux measurements), which show a much smaller source or even a sink. The second puzzle is the gap in understanding of the controls on methane emission and seasonal dynamics from this forested terrestrial-aquatic interface.

This project will test the hypothesis that both of these puzzles are manifestations of a common mechanism not well represented in models: the transport of significant amounts of microbially produced CH_4 from lower soil depths via tree roots and stems to the atmosphere.

Recent work shows that this mechanism likely supports large CH_4 emissions from Amazonian floodplain forests and that accounting for this could reconcile top-down and bottom-up estimates. This project will provide the first whole-forest flux measurements to test whether that mechanism can work. The team's general hypothesis is based on the idea that a similar mechanism (of tree stems as methane conduits) also operates in drier upland forests, whose soils are commonly observed to be CH_4 sinks.

The team will compare CH_4 dynamics in a floodplain forest (várzea) of the Amazon River (anchored by the ecosystem scale CH_4 eddy flux measurements, brought by this project) to fluxes at a reference AmeriFlux tower at a long-studied upland forest (the km67 site in the Tapajos National Forest). The team will quantify individual flux components (from soil/water surfaces and from diverse tree stems) and combine these with novel methane isotope spectroscopic measurements to infer how net fluxes partition between methanogenic production and methanotrophic methane oxidation—coupling this to information on microbial diversity and abundance. This project would thus simultaneously bring a critical but neglected new ecotype (the great iconic várzea forests of the Amazon River) into the growing global database of ecosystem scale measurements of CH_4 and also make key important contributions to development and improvement of ecosystem model performance in representing methane dynamics. The team will use DOE's ELM model to represent tropical Amazon dynamics and as a basis to more confidently project future CH_4 dynamics under climate change, such as expected increases in Amazonian drought frequency. Methane dynamics in these models have been mostly developed and tested in the Arctic or northern temperate systems (e.g., as part of DOE's SPRUCE experiment), so the opportunity to challenge model simulations in tropical systems is an especially high-value one.

Using probability distribution function as a scaling approach to incorporate soil heterogeneity into biogeochemical models for greenhouse gas predictions

- **Principal Investigator:** Debjani Sihi (Emory University)
- **Collaborators:** Eric Davidson (University of Maryland Center for Environmental Science), Jianqiu Zheng (PNNL), *unfunded collaborators* – Patrick Megonigal (Smithsonian Environmental Research Center), Michael Weintraub (University of Toledo)
- **Total Award:** $300,000
- **Award Type:** Exploratory

Terrestrial-aquatic interfaces (TAIs) with dynamic hydrological exchange represent the most biogeochemically active and diverse systems. Frequent hydrological oscillations due to tidal inundations and storm surges regulate oxidation-reduction (redox)-driven biogeochemical transformations and fluxes of carbon and nutrients across TAIs. Soil microsites, the most biogeochemically active soil components, further complicate such hydrological dynamic–driven redox biogeochemistry by creating spatial heterogeneity and variations in reaction kinetics. The functional forms of the interactions among water, carbon, and redox-sensitive compounds may differ at microsite-, plot- and ecosystem-scales. How microsite-scale processes manifest into plot-scale and ecosystem-scale functions will control long-term dynamics of GHGs in these dynamic interfaces. These complex interconnected processes across TAIs are underrepresented in current ecosystem and Earth system models (Bailey et al., 2017) because we lack a dynamic modeling framework that (1) captures the heterogeneity of soil microsites driving non-normal distribution of microbial activities and (2) integrates interconnected processes across scales.

The project proposes a new modeling framework to capture the heterogeneity of soil microsites to enable dynamic predictions of redox processes and associated greenhouse gas (GHG) emissions across TAIs. The overall goal is to predict GHG dynamics in the TAIs by incorporating probability distributions of redox processes at soil microsites using a coupled modeling-experimental (ModEx) approach. The team will build a new modeling framework merging the capabilities of microsite probability distribution functions (PDFs) of the DAMM-GHG (Dual Arrhenius and Michaelis Menten-GreenHouseGas, Sihi et al., 2020a, b) model with a redox reaction network model (Zheng et al., 2019). The new model framework contains three key components: (1) microsite PDFs, (2) PDF-constrained redox reaction networks, and (3) redox reaction networks within soil pore-network informing diffusion limitation of substrates related to productions and consumptions of GHGs. This project will test the modeling framework by synthesizing long-term field data, coupling laboratory (and field) manipulation experiments, and leveraging potential activities in the COMPASS program. Specifically, research will focus on a tidal wetland site (Global Change Research Wetland, GCREW, in Maryland) and a freshwater wetland site (Old Woman Creek National Estuarine Research Reserve in Ohio).

The exploratory work closely aligns with the COMPASS program goal to advance understanding of the interactions of the ecology and biogeochemistry of microbes, water, soils, and plants within coastal TAIs, and to improve representations of coupled TAI processes in site/regional scale models and ultimately Earth system models like E3SM. Soil heterogeneity represents an important yet unresolved component in biogeochemical models. This project, building and validating a microsite PDF function based computational tool, represents a great advance in generating transferrable modeling capability from fine-scale processes to ecosystem-scale functions (Sihi et al., 2018), and directly supports BER priorities of understanding multiscale Earth system dynamics and processes. The ModEx work is tightly aligned with DOE-BER missions supporting robust development of models that examine the feedback between biosphere and Earth's climate system.

Droughts and deluges in semi-arid grassland ecosystems: Implications of co-occurring extremes for C cycling

- **Principal Investigators:** Melinda Smith (Colorado State University), David Hoover (USDA-ARS)
- **Collaborators:** Anping Chen, Daniella Cusack, Alan Knapp (Colorado State University), *unfunded collaborators* - Andrew Felton (Chapman University), Seth Munson (USGS), Anthony Walker (ORNL)
- **Total Award:** $999,998
- **Award Type:** Standard

The frequency of extreme climate perturbations including multi-year droughts and deluges (persistent, torrential rain events) is expected to increase with changing climate. Such climate extremes are known to have substantial impacts on ecosystems, but when these co-occur as compound climate extremes (e.g., deluges occur during droughts), their impacts are expected to exceed their independent effects. Although there is anecdotal evidence to suggest that droughts and deluges combined may lead to pulses or "hot moments" in carbon cycling processes, the ecosystem consequences of compound climate extremes are poorly known. The overall research goal is to assess how co-occurring drought and deluge climate extremes will impact key carbon cycling processes known to be important for carbon-climate feedbacks. The project will address this goal via research in the 280,000 km^2 semi-arid shortgrass steppe ecoregion located at the western edge of the U.S. Great Plains. Semi-arid regions, such as this one, respond strongly to precipitation extremes and play a dominant role in interannual variability of the global land CO_2 sink.

The research will test the hypothesis that when a compound climate perturbation of an extreme deluge occurring within the backdrop of extreme drought, a combination of conditions converge (e.g., warm temperatures, abundant soil moisture, and increased soil N availability) to strongly stimulate C cycle processes, potentially resulting in “hot moments” or landscape-level “hot spots” (i.e., increases in biogeochemical processes in time or space that far exceed background levels). To test this hypothesis, the team will conduct a field experiment designed to quantify the magnitude of carbon cycling responses to drought and deluge events (independently and combined) and identify the underlying mechanisms resulting in positive drought-deluge interactions that can lead to hot moments of carbon cycling. Both above- and belowground C cycle responses to climate extremes will be quantified during this three-year experiment. To scale-up from the plot-level experiment to the shortgrass steppe ecoregion, the project will use historical climate data to quantify the regional frequency of potential drought-deluge interactions and remote sensing products (NDVI and solar-induced fluorescence) to estimate carbon cycling sensitivity to droughts, deluges, and their combined effects and to identify hot spots in carbon cycling regionally. Concurrent with these research activities, the team will simulate extreme drought, deluge, and drought-deluge perturbations with DOE’s E3SM Land Model (ELM). The project will explicitly compare the experimental results and remotely sensed observations of drought-deluge compound climate perturbations to ELM simulations, with the expectation that the process-level understanding gained from the field experiment and remote sensing analyses can be used to constrain process representation and parameterization in ELM and to improve Earth System projections of ecosystem carbon-cycling responses to droughts and deluges at the ecoregion scale.

This research will fill an important gap in empirical and modeling efforts to assess the effects of increasing compound perturbations forecast to occur with atmospheric warming—co-occurring extreme drought and deluge events—on key carbon cycling processes, and the role that compound extremes in precipitation may play in generating and sustaining biogeochemical “hot moments” and “hot spots.” The team’s ModEx approach will leverage and complement ongoing development of DOE’s state-of-the-art ELM model to further improve representation of above-belowground interactions and feedbacks for semiarid ecosystems.

Effect of Hydrological Forcing on the Biogeochemical Transformation of Carbon and Greenhouse Gas Emissions in Riparian and Streambed Sediments

- **Principal Investigator:** Martial Taillefert (Georgia Institute of Technology)
- **Collaborators:** Chloe Arson, Thomas DiChristina (Georgia Institute of Technology), Ken Kemner (ANL), Dan Kaplan (SRNL), *unfunded collaborators* – Christa Pennacchio (JGI), Stephen Callister (EMSL)
- **Total Award:** $999,991
- **Award Type:** Standard

Biogeochemical processes in wetland sediments regulate the transformation and exchange of carbon, nutrients, and greenhouse gases (GHGs) with surface waters and thus influence water quality. In fact, streams and wetlands are responsible for a large fraction of global GHG emissions despite constituting a relatively small surface area. Wetlands are terrestrial-aquatic interfaces (TAIs) where water movement creates strong gradients and heterogeneities that are microbially highly variable and influenced by temporal variations in precipitation, temperature, and stream discharge. These hydrological variations create hot spots and moments that are difficult to quantify and account for in reactive transport models (RTMs) used to make predictions of GHG emissions. As a result, conventional RTMs often misrepresent GHG emissions from wetland sediments. In our previous SBR exploratory project, the team developed new microbial equations for RTMs that rely on the activity of microbial communities to identify hidden reactions and more accurately describe microbial competition processes.

The project will apply these new equations in the field to: 1) predict the role of hydrological conditions on the transformation of carbon, nutrients, and biogeochemical processes in wetland sediments; and 2) determine the effect of these processes on GHG emissions. State-of-the-art *in situ* physical and geochemical measurements with high spatiotemporal resolution will be combined with metaomic (i.e., metagenomic, transcriptomic, proteomic, and metabolomic) signals of the active microbial populations. The new microbial equations will be integrated in new RTMs that will be combined with machine-learning algorithms to assess model sensitivity and calculate production and consumption rates of GHGs and other relevant species. Characterizing the distribution of the main geochemical species in wetland sediments with high spatial and temporal resolution will provide unique insights into the processes that control GHG emissions from wetland sediments. The newly developed models will predict how hydrological variations, competition between microbial processes, and changes in sediment properties over time affect carbon and nutrient cycling as well as GHG emissions at TAIs. Ultimately, these efforts will capture the role of sediment heterogeneities in GHG emissions.

Characterizing and predicting the dynamics of carbon transformation processes and GHG emissions in wetland sediments in response to hydrological fluctuations is relevant to the ESS mission and applicable to other environments of interest to ESS, such as permafrost and tropical sediments. This project will also contribute to the WHONDRS and IDEAS watershed programs by disseminating samples, datasets through ESS-DIVE, and new reaction and geomechanics modules for incorporation into community-based models. The interdisciplinary research team consists of geochemists, modelers, and microbiologists with expertise in high spatiotemporal geochemical measurements, reactive transport modeling, and multi-omics that will complement the synchrotron and field capabilities of the ANL SFA and benefit from JGI and EMSL expertise.

Applying "R-osmos" to quantify hot-moments in a high mountain watershed: co-development of novel methodology to advance terrestrial-aquatic interface models

- **Principal Investigator:** Andrew Thurber (Oregon State University)
- **Collaborators:** Frederick Colwell (Oregon State University), Laura Lapham (University of Maryland Center for Environmental Science), *unfunded collaborators* – Ken Williams, Dipankar Dwivedi (LBNL)
- **Total Award:** $149,978
- **Award Type:** Exploratory

Watershed function is driven by habitat heterogeneity and microbial activity integrated over space and time. Different habitats experience redox zonation differently over seasons, and across habitats water flow can lead to episodic release of reactants perturbing microbial communities and shifting biogeochemical cycles on local scales that can be significant enough to alter the overall system function. Features such as meanders can create such hot spots of biological activity, however they must be directly sampled to be understood. This project will quantify the impact of hot spots and moments on microbial rates at the DOE's East River (ER) Science Focus Area (SFA) watershed, focusing on two critical processes: methane oxidation and nitrate reduction. This project proposes a novel method based on existing technologies to measure continuous, time-integrating, *in situ* microbial rates to inform the magnitude and variation in biogeochemical processes across the terrestrial-aquatic interface. The team will refine a reactive transport model for the habitat using these data.

To accomplish this goal, the team will use uniquely configured osmotic samplers (OsmoSamplers) to continuously quantify the rate at which microbial communities transform methane and nitrate on either side of a meander. OsmoSamplers use a diffusion gradient to slowly pump water into tubes of such small diameter that sample mixing is negated. Multiple OsmoSamplers can be used together to continuously add solutes, preservatives, or collect samples for later analysis providing a record of hot moments in long-term datasets. In this work, the project will use rate-osmotic samplers (R-osmos) to acquire spatially explicit rate measurements by adding nitrate and methane (separately) to discern transformation of these critical compounds. Rates will be coupled with quantifications of natural solute composition (both NO_3 and CH_4) and quantitative gene abundance for the relevant processes (i.e., genes responsible for nitrate reductase and methane monooxygenase) allowing us to connect solute, rate, and microbiome characteristics.

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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