U.S. DEPARTMENT OF ENERGY

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

Environmental System Science

Summary of projects awarded in summer 2023 under the Environmental System Science Funding Opportunity Announcement DE-FOA-0002849.

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-0002849, was issued by the Environmental System Science program and released in the Fall of 2022. The goal of this FOA was to improve the understanding and representation of terrestrial ecosystem and watershed science in ways that advance the sophistication and capabilities of local, regional, and larger scale models (e.g., Energy Exascale Earth System Model, E3SM). Using new measurements, field experiments, synthesis, and/or more sophisticated modeling, this FOA encompassed three Science Research Areas (SRA): (1) improved understanding of hot spots and hot moments of biogeochemical cycling in terrestrial-aquatic interfaces; (2) investigations of cold-region ecosystem and watershed process responses to changing cold-season climate drivers; and (3) synthesis studies using existing data that address testing of ESS-relevant hypotheses and development of transferable insights across ecosystems, watersheds, and regions.

Applications to this FOA were expected to take a hypothesis-driven systems approach to understand ecosystems and watershed functioning over the multiple temporal and spatial scales that are represented in models (e.g., single process models, ecosystem or watershed models, and global models). This emphasis on the capture of advanced empirical and theoretical understanding in models had two goals. First, it sought to improve the representation of these integrated processes in coupled models, thereby increasing the sophistication of the projections. Second, it encouraged the community to understand and use a diversity of existing models and to compare model results against observations or other datasets to identify knowledge gaps and future research directions. It also sought to encourage an iterative 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 to support decision-making.

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 and gaps in state-of-the-art models. Applicants were required to provide details on how the results of the proposed research, if successful, would be incorporated into appropriate scale models and model frameworks. While the ESS program supports a broad spectrum of fundamental research in environmental system science and considered research applications within this scope, this FOA particularly encouraged applications in the following Science Research Areas:

SRA 1 – Improved Understanding of Hot Spots and Hot Moments of Biogeochemical Cycling in Terrestrial Aquatic Interfaces (TAIs): Investigate biogeochemical “hot spots” and/or “hot moments” within TAIs, thereby leading to better quantification of their process drivers, magnitude, and occurrence and enabling robust incorporation of these processes and their causal factors into a range of process-based models.

For this SRA, hot spots/moments are defined as episodic or isolated occurrences of biogeochemical cycling that are substantially greater or lesser than would typically be expected. The TAI research focus was limited to those terrestrial system processes occurring at and influenced by the immediate interface between terrestrial ecosystems and freshwater and/or brackish water systems. Applications were required to deliberately link field research to models to help advance predictive, scale-aware understanding of the role of hot spots and hot moments of TAI processes in key element and nutrient biogeochemical cycling in ecosystem, watershed, and/or Earth system models.

SRA 2 – Cold-Region Ecosystem and Watershed Process Responses to Changing Cold-Season Climate Drivers: Investigate mechanistic and process-level interactions between shifts in cold-season climate drivers and ecosystem and watershed responses, especially ones that lead to large changes in ecosystem and watershed scale functioning and feedbacks (e.g., whole ecosystem productivity, ecosystem/watershed-scale carbon or nutrient fluxes or exports, and watershed-scale water and energy balance changes) in cold-region systems.

For this SRA, cold regions are defined by the climatically average presence of snow and/or ice that regularly lasts for several days per occurrence for at least part of the year, including mountain watersheds, boreal forests and peatlands, and high-latitude tundra. Applications were required to improve understanding of ecological and/or hydrological processes and their responses to changing cold-season duration, precipitation regimes, and/or soil temperatures within the cold season. Models were encouraged to adequately capture transient dynamics, sensitivity to change, and potential state shifts in these critical ecosystems.

SRA 3 – Synthesis Research for Transferable Insights: Accelerating scientific discovery and building predictive understanding by harnessing existing data to identify and evaluate emergent patterns, generalizable principles, and fundamental insights from extensive existing datasets. Specifically, this SRA focused on novel, hypothesis-driven studies addressing topics within the ESS program scope that can be investigated by integrating and interrogating findings and/or data from prior observational and/or experimental research activities.

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

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

Seventeen awards were made through this Funding Opportunity Announcement totaling $13,096,651 over three years.

Funded Projects

Nitrite-Dependent Methane Oxidation: An Overlooked Nitrogen Sink in Riparian Zones

- **Principal Investigators:** Anthony Bertagnolli (Montana State University)
- **Collaborators:** Frank Stewart, Stephanie Ewing, Robert Payn (Montana State University)
- **Total Award:** $998,671 over 3 years

The wetlands adjacent to streams (riparian zones) provide critical services to ecosystems. These services include supporting diverse microbial communities that break down pollutants and regulate the cycling of carbon and greenhouse gases, such as methane. Fertilizer runoff from agriculture can disrupt the services provided by riparian zone microorganisms, for example by shifting the availability of oxygen for microbial metabolism. Current models that predict how excess nitrogen from fertilizer influences stream-associated methane cycling are limited by focusing primarily on metabolisms that operate in the presence of oxygen. These models are incomplete if they do not account for methane consumption due to oxygen-independent metabolisms. This project investigates a potentially overlooked contribution by bacteria that thrive in the absence of oxygen and derive energy by linking the consumption of methane to nitrogen supplied by fertilizer or other sources. In preliminary studies, we detected the bacteria associated with this process—termed nitrite-dependent anaerobic methane oxidation (N-DAMO)—at relatively high abundance in agriculturally influenced riparian zones of the Judith River Watershed (JRW), Central Montana. We hypothesize that N-DAMO is an important methane-consuming process sensitive to environmental change in these and other riparian zones. We will test the role of N-DAMO and other oxygen-independent methane-consuming processes using a combination of environmental sampling over temporal and spatial gradients in the JRW, experimental manipulations, and biogeochemical modeling. This work will (1) map the amount and distribution of soil porewater methane, nitrogen, and other important chemicals acted upon by microorganisms; (2) use isotope labeling to quantify the rates at which microorganisms consume methane and nitrogen under different oxygen regimes; (3) verify how changes in riparian zone chemistry are linked to the metabolic diversity (genomics) and gene expression of the resident microbial community; and (4) develop a solute transport model that uses knowledge of chemistry and gene distributions to predict the contribution of oxygen-independent microorganisms to methane consumption. Results of this project will help predict the fate of methane and nitrogen in stream-associated wetlands, notably under increasing disturbances associated with human activity.

Deciphering the Role of Anaerobic Microsites for Hot Spot/Hot Moment Dynamics of Metal Redox Chemistry and Methane Emissions within Riverine Floodplains

- **Principal Investigators:** Amrita Bhattacharyya (University of San Francisco)
- **Collaborators:** Amalia Kokkinaki (University of San Francisco), Ruth M. Tinnacher (California State University East Bay), Kristin E. Boye, Vincent Noël (SLAC)
- **Total Award:** $1,000,000 over three years

Anaerobic microsites, a defining feature of soil redox heterogeneity, are zones of oxygen depletion in otherwise oxic environments. Subsequently, anaerobic microsites can serve as hot spots for biogeochemical (BGC) processes, generating and exporting reduced products to oxic environments. Anoxic microsites have been predicted to contribute 21% to the global production of methane (CH_4), an important greenhouse gas affecting climate change. They are often generated at terrestrial–aquatic interfaces (TAIs), such as riverine floodplains which are dynamic transition zones between land and water, where seasonal changes in river and groundwater flow conditions lead to redox fluctuations. As a result, TAIs play a significant role for elemental cycling and greenhouse gas (GHG) emissions, while only occupying small areas of the Earth's surface (0.07%–0.22%).

Despite the presumed importance of anaerobic microsites in TAIs, significant knowledge gaps still exist regarding their abundance over time and space under varying environmental conditions, as well as their specific contributions to BGC processes, especially with regard to CH_4 production.

Using the novel LOAMS (Laboratory for Observing Anaerobic Microsites in Soils) approach, we will specifically detect and examine the role of anaerobic microsites in methanogenesis and metal redox processes across spatial and temporal scales at current DOE ESS natural floodplain research sites. The main objectives of this work are to: (1) quantify the abundance and the impact of anaerobic microsites on methanogenesis and elemental speciation; (2) compare microscale anaerobic microsite characteristics to macroscale field observations of methanogenesis and metal redox chemistry; and (3) quantify reaction kinetics of relevant BGC processes within anaerobic microsites based on data from controlled laboratory experiments paired with modeling. Furthermore, our experimental data and parametric modeling results will support the future development of refined conceptual and quantitative models and improve predictions of metal cycling and production of GHG emissions in TAI environments.

Responses of Plant and Microbial Respiration Sources to Changing Cold Season Climate Drivers in the East River Watershed

- **Principal Investigators:** Mariah Carbone (Northern Arizona University)
- **Collaborators:** Andrew Richardson, Ben Lucas (Northern Arizona

University), Adrianna Foster, Will Wieder (National Center for Atmospheric Research)
- **Total Award:** $999,383 over three years

Winter is changing in the western U.S. mountains. There is less snowfall, snow is melting earlier in the spring, and the warm summers are becoming longer. These changes in winter and water availability impact forests. Belowground in the forest soil, microorganisms break down organic matter, releasing carbon dioxide (CO_2), an important greenhouse gas that is warming Earth. Plant roots produce CO_2 also, via their metabolism. Our research seeks to understand how changes in winter snowpack influence the amount of CO_2 produced in soils in the East River watershed, near Crested Butte, Colorado. We will quantify the production of CO_2 by microorganisms and plant roots across different elevations and seasons. We will work in the two main forest types of the region, evergreen spruce/fir and deciduous aspen, applying unique experimental measurements. We will make use of existing long-term measurements to understand how past changes in snow amount and duration of cover have affected soil CO_2. Information gathered from our experimental work and data analyses will be used to improve predictions of soil CO_2 produced in the future using models. Our proposed work is motivated by the hypothesis that changing winter snow amounts will impact how microorganisms and roots function separately, and thus understanding these influences is necessary to predict how the ecosystems will respond to future climate.

Dynamics of Interconnected Surface-Subsurface Flow and Reactive Transport Processes Across the Hillslope-Riparian Zone-River Corridor Continuum of Cold, High-Latitude Watersheds

- **Principal Investigators:** M. Bayani Cardenas (University of Texas at Austin)
- **Collaborators:** Bethany Neilson, Pin Shuai (Utah State University), Rose Cory, George Kling (University of Michigan), Ethan Coon (Oak Ridge National Laboratory)
- **Total Award:** $999,999 over three years

The Arctic is warming almost four times faster than the rest of the world, in the process thawing large stores of permafrost soil carbon. The thawing amplifies climate change if the carbon is released to the atmosphere as greenhouse gases like carbon dioxide and methane. The conversion of soil carbon to greenhouse gases occurs in watersheds, and this process is largely controlled by how water flows through the soils from the hillslopes to valley bottoms and into streams. The hydrologic processes within watersheds are shifting in response to dramatic changes in extreme weather events like heat waves, flooding and storms, and more frequent tundra wildfires, along with a shorter cold season and longer summer thaw season. However, scientists do not know how the concurrent thawing of permafrost soils and changes in watershed hydrology will affect greenhouse gas emissions. There is a clear need to improve models of cold-region watershed hydrology in order to predict how warming and permafrost thaw now will affect greenhouse gas release in the future. This research will use state-of-the-art mathematical models of watershed hydrology and advance them to provide the first integration of highly dynamic water flow over the landscape, through soils, and to rivers with key physical, biological, and chemical processes that control greenhouse gas generation and transport. Realistic coupling of the hydrology, biology, and chemistry in these models will be validated by key field observations. Our expectations are that (1) hydrological flow patterns from hillslopes through valley bottoms control the landscape export of carbon from soils to rivers and the relative production of greenhouse gases (carbon dioxide versus methane); (2) variability in extreme events, freeze-thaw cycles, and day-to-day weather will alter the magnitudes of biological and chemical reactions through the hillslope to valley bottom and then to the river; and (3) watershed-scale carbon exports are controlled by valley-bottom processes, but hillslope and stream processes can dominate as climate change alters weather patterns and hydrology. We will test these ideas under scenarios of shifting cold- and warm-season climate, by adding novel physics and chemistry to two coupled DOE models, the Advanced Terrestrial Simulator (ATS) model for thermal hydrology and PFLOTRAN for reactive chemical transport.

Tidal Triggers and Hot-Spot Switches in Coastal Marsh

- **Principal Investigators:** Zoe Cardon (Marine Biological Laboratory)
- **Collaborators:** Anne Giblin (Marine Biological Laboratory), Inke Forbrich (University of Toledo), Jennifer Bowen (Northeastern University), Teri O'Meara, Ben Sulman (Oak Ridge National Laboratory)
- **Total Award:** $999,724 over three years

Coastal marshes lie at the dynamic interface between land and sea, where materials from multiple sources are mixed and transformed, and marsh productivity is extraordinarily high. Among the organisms supported by marsh plant productivity are highly diverse microbial communities, some of which support the plants themselves, and others that recycle nutrients, produce or consume greenhouse gases, or even contribute to carbon storage in marsh sediment. A powerful feature of coastal tidal marshes is the presence of a highly simplified plant community; single plant species can blanket marsh platforms, meaning that what is learned from studying that species' interactions with microbes and the local environment is more easily expanded to represent the whole marsh system. We plan to capitalize on this naturally simplified system at a brackish, coastal marsh vegetated with the cattail *Typha angustifolia*, where last July a remarkably rapid whole-system-scale switch in biogeochemical function was detected by micrometeorological measurements. Early in the season, emission of the greenhouse gas methane from the brackish marsh to the atmosphere was quite high—approximately 200 nmol m^{-2} s^{-1}. But because of drought, a flooding tide in mid-July was particularly saline, and within hours of marsh flooding by that saline tide, methane emissions to the atmosphere dropped to near zero. A whole marsh scale switch had been triggered. Lab, field, and modeling work are planned that target small-scale hot spot/hot moment mechanisms we hypothesize underlie this system-scale switch that stopped methane emissions for months. We will test four hypotheses:

- H1: Salinity stress induces increased catalase activity in roots of *Typha angustifolia*, leading to root oxygen release from hydrogen peroxide produced during stress. Aerobic methanotrophy may therefore increase in rhizosphere hot spots of enhanced oxygen availability.
- H2: Anaerobic methane oxidation in the upper 10 cm (hot layer) of sediment is stimulated by saline inundation. ANME archaea in consortia with sulfate reducing bacteria are potential actors.
- H3: Methylotrophic methanogenesis produces methane despite high porewater sulfate concentration in the brackish marsh.
- H4: *Typha angustifolia* roots produce glycine betaine as a compatible osmolyte. Glycine betaine, once fermented to trimethylamine, could preferentially support methylotrophic methanogens producing methane in *Typha* marsh.

Experiments testing these four hypotheses will inform modeling of coastal marsh systems within an E3SM-PFLOTRAN modeling framework. Understanding the hot spot/hot moment causes and consequences of the dramatic system tipping point that we observed is essential if coastal system functions such as greenhouse gas emissions are to be predicted, particularly as sea level rises and storm precipitation becomes more intense and sporadic.

Synthesizing Bryophyte Functional Response to Environmental Variation to Improve Terrestrial Carbon Cycle Forecasting

- **Principal Investigators:** Kirsten Coe, Middlebury College, Sasha Reed (US Geological Survey)
- **Collaborators:** Verity Salmon, Benjamin Sulman, Peter Thornton (Oak Ridge National Laboratory)
- **Total Award:** $399,998 over two years

Our understanding of current and future drivers of carbon cycling at ecosystem and global scales relies on the ability of Earth system models to accurately represent plant-environment interactions and feedbacks. While there is strong fundamental knowledge about how plant processes influence carbon cycling for many plant functional types, land surface models that inform Earth system models currently are unable to accurately characterize plant responses to environmental variability, especially dynamic and intra-annual responses to moisture availability. One group of plants that has a nearly ubiquitous terrestrial presence (found on all Earth's continents) but has remained unrepresented in Earth system models is bryophytes (mosses and their relatives). Bryophytes regulate carbon cycling, storage, and biogeochemical responses to global change across many ecosystem types and respond to precipitation in ways that are incredibly dynamic and functionally distinct from vascular plants. For these reasons, inclusion of a bryophyte plant functional type could dramatically improve carbon cycle forecasting. Due to increased recognition of the functional roles of bryophytes, much empirical data on bryophyte-carbon cycling processes now exist but have yet to be synthesized to allow for parameterization and evaluation of a bryophyte plant functional type.

To improve the predictive understanding of how carbon cycling is influenced by hydrology and is responding to climate change, as well as to simultaneously advance our capacity to forecast carbon cycling contributions of bryophytes, we will conduct a global synthesis of bryophyte-carbon cycling processes, their drivers, and their responses to change. We will (1) leverage existing datasets to generate a database of bryophyte processes that relate to carbon cycling and (2) elucidate, analyze, and test key relationships between bryophyte functional processes and environmental variables suitable for inclusion into Earth system models and development of a novel bryophyte plant functional type. To accomplish these aims, we will select focal plant process functions in the land surface model of the Energy Exascale Earth system model (E3SM), collect data from published literature and long-term experiments to build a bryophyte database, and conduct a meta-analysis to determine statistical relationships between bryophyte parameters and function outputs. Based on these analyses, we will develop empirical relationships for bryophyte-carbon cycling by modifying parameters in existing E3SM functions and by developing novel functions for processes important for carbon cycling but unique to bryophytes and not yet represented in models. We will test and evaluate empirical relationships that can be used to predict or constrain bryophyte plant functional type traits, ultimately resulting in a complete set of functional relationships representing bryophyte-carbon cycling processes.

This project brings together researchers from plant ecology, biogeochemistry, and modeling disciplines in an iterative bidirectional modeler-empiricist collaboration to generate, evaluate, and calibrate model-relevant plant-environment relationships for a currently unrepresented category of terrestrial plants: bryophytes. The outcomes of this project will be (1) advanced capacity to forecast carbon cycling contributions of bryophytes, a globally important plant functional type and (2) expanded predictive understanding of how carbon cycling is influenced by hydrology and responding to climate change.

Water and Carbon Dynamics of Coastal Plain Wetlandscapes

- **Principal Investigators:** Matthew Cohen (University of Florida)
- **Collaborators:** Stefan Gerber, James Jawitz, Amanda Subalusky (University of Florida), David Lewis (University of South Florida), Daniel McLaughlin (Virginia Tech), Nicholas Ward (Pacific Northwest National Laboratory)
- **Total Award:** $999,999 over three years

Predicting and adjusting the dynamics of the carbon (C) cycle at landscape scales is foundational to climate change mitigation and avoidance. Water storage (in soils and wetlands) and export (in streams and groundwater) is the core control on landscape C dynamics, influencing both ecosystem production as well as pathways of C storage and losses to the air and water. This project is focused on understanding the role of hydrological variability, which influences when and how much water is stored and released from the landscape, on C dynamics. We are especially interested in understanding how hydrological variability impacts the storage vs. loss of C, and the relative importance of lateral (stream) vs. vertical (atmosphere) pathways of C loss. We adopt a variety of tools, including experiments in the field and laboratory, detailed measurements of landscape hydrology and C fluxes, and models that allow us to both synthesize measurements and guide new ones to understand C dynamics in wetland-rich landscapes of the U.S. Southeastern Coastal Plain. Our project will develop new understanding of how the terrestrial-aquatic interface (TAI; where the land and water meet) shifts in both space and time and the role of that variation in controlling local processes of C storage and loss. This understanding will allow us to better quantify and predict the aggregate water and C functions of landscapes comprised of mosaics of uplands, wetlands, and streams. Our goal is to develop a new fundamental understanding of how, when, and where C is stored and how C exports are partitioned between atmospheric and stream pathways. We will apply that new understanding into improved representation of TAI dynamics in mosaic landscapes within Earth systems models.

Improving ESS Approaches to Evapotranspiration Partitioning Through Data Fusion

- **Principal Investigators:** Stephen Good (Oregon State University)
- **Collaborators:** Kelly Caylor (University of California Santa Barbara), Lixin Wang (Indiana University–Purdue University Indianapolis), Richard Fiorella (Los Alamos National Lab)
- **Total Award:** $399,007 over two years

This project aims to address the uncertainty in modeled estimates of T/ET, which is the ratio of transpiration (T) to evapotranspiration (ET). Previous research has shown that models often exhibit total ET estimates that match observations well, while also exhibiting strongly divergent T/ET ratios. This uncertainty in T/ET ratios limits the utility of Earth system models in applications that heavily rely on this partitioning, including investigations of soil moisture dynamics, vegetation dynamics and productivity, food security, and watershed hydrologic response. This projects aim is to provide new insight for mechanistic modeling of ET partitioning within Earth system models and improve future predictions by addressing three objectives.

The first objective is to create a benchmark dataset of T/ET values and associated uncertainties at select AmeriFlux locations, using established T/ET methods. Specifically, we will investigate four broad and overlapping categories of methods to estimate T/ET: theoretical models, high- frequency approaches, remote sensing, and geochemical models. We will synthesize these different approaches through colocation analysis, a diagnostic approach to assess the uncertainty in a targeted quantity by analyzing multiple inputs of the same quantity when the ‘truth’ is not well known. The second objective is to improve parameterization of transpiration and evaporation processes within an advanced Earth systems model through a combination of surrogate modeling and Bayesian optimization. This approach uses machine learning methods and detailed uncertainty characterizations from Objective 1 to find parameters that result in model output best matching observational data. An ensemble of Energy Exascale Earth System (E3SM) Land Model (ELM) simulations will be run at select AmeriFlux sites used to create a data fusion product to evaluate patterns and uncertainties in T/ET estimates. The third objective is to forecast trends in T/ET in the future under different scenarios using the posterior parameter distributions from Objective 2. ELM will be run with future forcing conditions to determine if T/ET will decrease in the future. This will address key uncertainties in future ecohydrologic conditions relevant to carbon, water, and energy cycling.

In summary, this project will evaluate different T/ET partitioning methods and use them to produce benchmark T/ET data products at long-term research sites and in an upscaled estimate, global T/ET estimates derived from calibrated ELM model simulations under current and future conditions. In doing so, the project will provide fundamental advancements in the characterization of process-based model uncertainty, improvement of modeling with T/ET fusion estimates, and estimation of future declines in T/ET under changing climates. The proposed research will leverage data from AmeriFlux networks and other networks and aligns with the DOE Model-Experiment (ModEx) paradigm and broad DOE Environmental System Science objectives to improve understanding across the water, carbon, and energy cycles.

Are Trees Dormant During the Dormant Season? Determining the Importance of Plant Nutrient Uptake in Changing Cold Seasons in Cold-Region Catchments

- **Principal Investigators:** Christine Goodale (Cornell University)
- **Collaborators:** Peter Hess (Cornell University), Peter Groffman (City University of New York), Qing Zhu (Lawrence Berkeley National Laboratory)
- **Total Award:** $999,999 over three years

Plant uptake of nitrogen, a vital nutrient, is typically assumed to cease over winter in cold-region forests, in concert with seasonal patterns of plant growth. Most models built to simulate Earth’s future climate and atmospheric CO_2 concentrations (Earth System Models) link plant nutrient uptake to growth and predict large nitrogen losses from soils during the dormant season and subsequent scarcity during the growing season that limits the ability of plants to sequester carbon. However, plants are more active belowground during the dormant season than previously recognized, and some can take up nitrogen over winter. Yet, it is not known whether dormant-season plant nitrogen uptake is widespread or how the process varies with plant traits or in response to warming winters. Winter temperatures have increased steeply across the northeastern U.S., with less snowfall, more thaws, and decreased depth and duration of snow cover. Snow insulates the soil, and prior snowpack reduction experiments caused soil frost that damaged fine roots and their capacity to take up nitrogen.

We propose a set of activities designed to characterize cold-season nitrogen uptake by temperate forests. Our overarching hypothesis is that temperate trees take up ecologically important amounts of nitrogen over winter and that this uptake varies with tree type and with warming winter conditions. We will test this hypothesis with a set of studies that add an isotopically distinct form of nitrogen (the stable isotope ^{15}N) to track plant N uptake, as well as experimental snowpack manipulation experiments and use of a state-of-the-art Earth System Model (the ELM-ECA version of the E3SM model). Instead of linking nutrient uptake to plant growth, this model simulates plant nitrogen uptake based on root properties and interactions with the soil environment. First, we will both simulate (ELM-ECA) and measure (^{15}N tracers) winter plant N uptake by trees spanning a range of plant traits, and we present preliminary data indicating surprisingly large amounts of cold-season N uptake by six species of juvenile trees. Next, at the ecosystem scale, we will both simulate (ELM-ECA) and measure (^{15}N tracers) competition for nitrogen among mature trees, microbes, and gaseous and hydrologic N losses in response to experimentally reduced winter snowpacks at two temperate watersheds with contrasting stream nitrate seasonality: Arnot Forest, New York, and Hubbard Brook Experimental Forest, New Hampshire. Last, we will use the model to assess how future conditions (warming, rising atmospheric CO_2) will alter winter snowpacks, cold-season plant N uptake, and terrestrial carbon and nitrogen dynamics. Together, the proposed activities will advance fundamental understanding and model representation of plant nitrogen uptake, as well as its seasonality, controls, and effects on terrestrial carbon and nitrogen balances.

Seasonal Cycles Unravel Mysteries of Missing Mountain Water

- **Principal Investigators:** Jessica Lundquist (University of Washington)
- **Collaborators:** Ethan Gutmann (National Center for Atmospheric Research), Rosemary Carroll (Desert Research Institute)
- **Total Award:** $981,322 over three years

Snow provides over 60% of water supplies in the western United States, and in general, spring snow measurements provide a good prediction of summer streamflow. However, in some years, these streamflow predictions are not accurate, and water managers struggle to efficiently allocate water resources. In many studies, warming temperatures correspond to less observed streamflow per precipitation input unit. However, key elements, including basin heterogeneity, gauge undercatch, groundwater flow, and water storage, are often not represented in models or predictions, and physical hydrologic models diverge widely in their hydrologic sensitivity to warming. In this project, we will combine distributed observations and modeling to test the following hypotheses:

1) Fall rainstorms recharge soil moisture and groundwater, increasing subsurface connectivity and the efficiency of winter snowpack to generate streamflow.
2) More uniformly distributed snow cover leads to greater subsurface water connectivity and more efficient water delivery to the stream. More variable snow cover, either through a greater elevational gradient or increased patchiness, leads to less effective recharge and greater evaporative losses. Only modeling that represents subsurface water transfer from snow-covered to snow-free grid cells will represent these effects.
3) Warming temperatures and increased rain relative to snow over recent decades have changed snow distributions in ways that decrease runoff efficiency, increasing the frequency of snow-free areas at lower elevations fed by snow at higher elevations, which increases basin total evapotranspiration.

Our questions require both long time series and detailed, distributed observations. We propose to first investigate our hypotheses over the well-instrumented East River (Colorado) and Tuolumne River (California) basins. These long-term observations are augmented with detailed distributed surface flux observations obtained during the 2021-23 multi-agency atmospheric campaigns of SAIL, SPLASH, and SOS in the East River basin. We will use models to establish essential process representations and to directly test hypotheses. We will then test for the essential minimum observations and process representations to expand to larger scales.

Our study will directly inform modelers and water managers of the key processes that must be represented to accurately predict runoff originating from seasonal snow in mountain watersheds, leading to improved understanding, prediction, and planning at seasonal and longer timescales.

Cross-Scale Methane Dynamics at Terrestrial-Aquatic Interfaces in Temperate Forests

- **Principal Investigators:** Jaclyn Matthes (Harvard University)
- **Collaborators:** N. Michelle Holbrook (Harvard University), Charles Harvey (Massachusetts Institute of Technology)
- **Total Award:** $1,000,000 over three years

Interfaces between well-drained upland soils and wetlands are critical sites for biogeochemical processing in temperate forests. The location of these interfaces fluctuates with water table depth, which is controlled by incoming precipitation, and small ephemeral and perennial wetlands are particularly dynamic. In many locations, including the Harvard Forest within the northeastern U.S., water table fluctuations are changing with more frequent extreme precipitation events, higher total precipitation, and more variation in total precipitation among years due to climate change. In the saturated zone below the water table, conditions are anaerobic, and methane is produced. Dissolved gas may diffuse or bubble up to the water table or escape to the atmosphere through plant roots and stems. In the unsaturated zone above the water table, conditions are oxic, carbon dioxide is produced, and methane is oxidized. The timing and location of these processes fluctuate with precipitation variation. Additionally, methane transported by ebullition and tree stems have high variation across the landscape and through time, and the mechanisms driving plant-mediated methane transport are not well understood.

In this project, we will conduct cross-scale field measurements of methane dynamics at the Harvard Forest in Petersham, MA. We will collect new field measurements in uplands, ephemeral wetlands, and two small perennial wetlands: a ~14,000-year-old forested peatland and a ~20-year-old beaver-constructed wetland. We will leverage data and infrastructure from core AmeriFlux sites to add new ecosystem-scale measurements of methane and carbon dioxide exchange, and we will measure the lateral flow of carbon in gaged streams. At the process-scale, we will characterize rates of methane production, consumption, ebullition, and diffusion, and we will develop a novel reactive transport model to represent these processes. The model will use data from carbon dioxide and methane concentrations and stable carbon isotopes from soil porewater depth profiles. To quantify the magnitude and drivers of tree stem methane flux, we will deploy automated flux chambers on the stems of trees within wetlands and uplands that are co-located with soil porewater depth profiles.

We will synthesize our new field measurements within a spatiotemporal modeling framework that brings together process-based measurements with net methane flux constraints from eddy flux towers and lateral flow data in streams. Our model will be tested across sub-seasonal to interannual temporal scales to capture variation in precipitation during the study period. The observational design will facilitate understanding of the dynamics of methane within this complex ecosystem that dynamically changes across space and in time with precipitation. This will yield new insights for the spatial scaling of methane dynamics across dynamic terrestrial-aquatic interfaces within earth system models like the E3SM Land Model (ELM).

Understanding and Modeling Current and Future Hot Moments in Coastal Wetlands

- **Principal Investigators:** Genevieve Noyce (Smithsonian Environmental Research Center)
- **Collaborators:** Alia Al-Haj, Roy Rich (Smithsonian Environmental Research Center), Teri O'Meara, Benjamin Sulman (Oak Ridge National Laboratory)
- **Total Award:** $1,000,000 over three years

The coastal terrestrial-aquatic interface (TAI) is a highly dynamic component of the Earth system that plays a critical role in biogeochemical cycling. Due to its dynamic nature, rates of biogeochemical cycling can be highly variable in response to episodic changes in inundation (flooding), salinity, temperature, or nutrient availability. This can lead to hot moments where emissions of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) are unusually high. Even though these hot moments can have a disproportionate effect on annual-scale TAI greenhouse gas emissions, we have a limited understanding of both the underlying biogeochemical mechanisms and the relative frequency, magnitude, and duration of the events. This constrains our ability to represent GHG hot moments in biogeochemical and Earth systems models.

Our overall objective is to gain a predictive understanding of the mechanisms controlling hot moments of greenhouse gas emissions at the coastal TAI, such that these processes and their causal factors can be incorporated into process-oriented biogeochemical models. We have identified the following current knowledge gaps as particularly limiting: (1) magnitude and frequency of hot moments; (2) biogeochemical mechanisms underlying hot moments; (3) effects of simultaneous episodic drivers on mechanisms; and (4) multi-faceted datasets.

To address these knowledge gaps, we have designed a ModEx approach in which we will couple observations and experiments to generate data for ongoing modeling efforts. Observationally, we will use a field-based autochamber system to understand the frequency and magnitude of naturally occurring hot moments and their effect on ecosystem-scale greenhouse gas emissions. Experimentally, we will build a mesocosm system to determine the mechanisms driving hot moments in response to pulses of warming, flooding events, or nitrogen addition. Our proposed efforts will result in the collection of continuous chamber-level CH_4 and N_2O flux measurements, across natural and single-, double-, and triple-crossed episodic events as well as corresponding measurements of porewater chemistry, soil carbon quality, plant biomass, and redox reaction rates, filling key gaps in the datasets currently available for model parameterization and configuration. We will then integrate the data from these empirical components into ongoing modeling efforts in two ways. We will update our PFLOTRAN reaction network to include nitrogen cycling and run simulations of hot moments resulting from pulses of inundation, salinity changes, warming, and nitrogen availability. We will also supply data products to two current DOE-funded modeling projects with modeling objectives that will be greatly facilitated with our high-temporal-resolution measurements of GHG emissions, simultaneous measurements of nitrogen and carbon cycling rates, porewater depth profiles, and contextual sediment characterization. Overall, our proposed project will generate new data leading to a better mechanistic understanding of hot moments of greenhouse gas emissions in the coastal TAI and improve representation of these events in biogeochemical and Earth systems models.

Estimation of Global Methane Soil Sink Using Synthesized Datasets and Knowledge-Guided Machine Learning

- **Principal Investigators:** Youmi Oh (University of Colorado Boulder)
- **Collaborators:** Licheng Liu, Zhenong Jin (University of Minnesota), Qing Zhu (Lawrence Berkeley National Laboratory), Gavin McNicol (University

of Illinois Chicago), Sparkle Malone (Yale University)
- **Total Award:** $400,000 over two years

The objective of this proposed research is to estimate the spatial and temporal variability in global methane soil sinks using a knowledge-guided machine learning (KGML) framework. This novel framework combines process-based and machine-learning models, and synthesizes multisource direct and indirect measurements of soil methane oxidation to improve model training, interpretability, and accuracy across spatial and temporal scales. Natural methane oxidation by microbes in upland soils is the second largest sink in the global methane budget, but its importance has been widely underestimated. The magnitude and long-term trends of global methane soil sinks are highly uncertain due to overlooked microbial processes and contradicting studies. Accurately quantifying global methane soil sinks is extremely important to reduce biases in current and future global methane budgets. In this proposed KGML framework, process-based models will be used as scientific foundations to develop the KGML hierarchical structure and to generate millions of synthetic data for pretraining. We will build separate machine-learning submodules for soil thermal, hydrological, and biogeochemical processes, and an overarching model structure to link the submodules. The key biogeochemical constraints (e.g., soil methane substrate, temperature, and moisture influences) will be carefully embedded into the cost function using known principles and empirical functions as knowledge-guided losses. The developed KGML framework will be trained and validated with direct measurements of soil methane oxidation fluxes from FLUXNET-CH4 and chamber measurements. Using global soil moisture and temperature data, we will further optimize the model to capture temporal and spatial heterogeneity. The finely constrained KGML model will finally be extrapolated to the global scale and be used to generate new global methane soil sink products at daily and 4-km resolution from 1984 to 2022.

A Tale of Two Extremes: Temperature Sensitivity of Carbon Loss from Cool and Hot Soils

- **Principal Investigators:** Debjani Sihi (Emory University), Tana Wood (USDA Forest Service, International Institute of Tropical Forestry)
- **Collaborators:** Jianqiu Zheng (Pacific Northwest National Laboratory), Michael Weintraub (University of Toledo), Eric Davidson (University of Maryland Center for Environmental Science), Sasha Reed (U.S. Geological Survey), Jennifer Pett-Ridge (Lawrence Livermore National Laboratory)
- **Total Award:** $400,00 over two years

Soils represent the largest terrestrial C pool, and the flux of CO_2 from soils to the atmosphere is ~ 6-10 times more than anthropogenic emissions. Warming can accelerate soil C loss to the atmosphere, exacerbating warming via positive feedback between soil C and climate. However, the fate of soil C in a future warmer world is still highly uncertain, particularly for arctic and boreal (cool-climate) ecosystems and tropical (warm-climate) ecosystems, which represent dominant portions of the global terrestrial C cycle and which are historically understudied. The uncertainty in soil C-climate feedbacks is exacerbated by extreme climatic conditions typical of ecosystems with large carbon (C) stocks, such as many tundra, boreal, and tropical forested ecosystems, where temperature responses may be dominated by different underlying controls. Reducing uncertainties in soil C-climate feedback requires systematic synthesis of underlying mechanisms related to soil C turnover in these critical and relatively poorly understood regions.

The relationship between microbial respiration and temperature is typically modeled using Q_{10} function. Generally, the apparent Q_{10} of soil respiration is much higher for cool vs. warm-climate ecosystems, reflecting biochemical limits to decomposition at low temperatures. However, results from two field warming experiments in the tropics contradict this expectation, both observing extraordinarily high soil respiration responses to *in situ* warming (e.g., 29-244% increase). Together, these findings suggest that there are many indirect temperature effects on soil C stability and subsequent C flux to the atmosphere at different time scales, thus requiring re-evaluation of various proposed mechanisms that control the sensitivity of soil C across ecosystems with different climate history. It has also become clearer that different assumptions related to the persistence and vulnerabilities of Arctic soil C in biogeochemical models can lead to divergent responses of soil C losses or gains in a future climate. Recent observations showed that episodical cold season CO_2 emissions make a significant contribution to the annual budget. Cold season emissions are linked to the period when soil temperatures are poised near 0°C and soil respiration is extremely sensitive to other factors, such as soil moisture and labile C. Predicting soil respiration across disparate systems and in new future climates will require using mechanistic instead of purely descriptive models. Rather than Q_{10}'s, enzymatic processes can be modeled by Arrhenius kinetics, which work well when there are no other limiting factors. However, many other factors affect the supply and binding of substrates to the extracellular enzymes that control soluble C availability to microbes, thus moderating temperature responses through substrate-limitation of enzyme activities. Substrate limitations to extracellular enzymes include freezing, substrate transport, enzyme-substrate binding, and stabilization of soil organic matter (SOM) and enzymes in aggregates and on mineral surfaces. In addition, changes in the microbial community and its enzymatic capacities, sometimes referred to as acclimation, can alter enzyme activities. Overall, the many direct and indirect temperature effects on rates of biogeochemical processes (e.g., enzyme kinetics), community structure, microbial biomass and activity, water phase and availability, and substrate supply are likely to influence soil C stability and subsequent C fluxes to the atmosphere at different timescales, thus requiring a reevaluation of our assumptions about the mechanisms that control the sensitivity of soil C across ecosystems with different climate histories.

We propose a synthesis of soil respiration data across temperature extremes (e.g., Arctic/Boreal and Tropical regions) to advance our understanding and ability to model soil respiration-temperature relationships. Our overall objective for the proposed work is to reduce uncertainty in soil C-climate feedback by systematically synthesizing underlying mechanisms related to soil C turnover and stabilization. Our data synthesis from sites with high and low temperature extremes will provide generalizable insights for future models. This synthesis closely aligns with the Environmental System Science program goal in Biological and Environmental Research to advance an integrated, robust, and scale-aware predictive understanding of interacting biogeochemical, ecological, hydrological, and physical processes that shape ecosystem function.

Understanding the Geochemical Basis for Soil Organic Matter Storage at the Global Scale

- **Principal Investigators:** Eric Slessarev (Yale University)
- **Collaborators:** Katerina Georgiou (Lawrence Livermore National Laboratory), Lucas Janson (Harvard University)
- **Total Award:** $399,255 over two years

Much of the carbon assimilated by terrestrial ecosystems ends up shed by plants to become soil organic matter (SOM), the largest carbon reservoir in the terrestrial biosphere. The capacity of soil to retain SOM and stabilize additional carbon is moderated by the activity of soil microbial decomposers—but also by the geochemical environment. Soil minerals transform, dissolve, and interact with organic molecules released and synthesized by microbial decomposers. Soil mineral reactivity hence defines the abiotic environment in which soil biological processes unfold and is an overarching control on SOM stabilization. Despite its significance in the carbon cycle, soil mineral reactivity is virtually uncharacterized at the scales relevant to Earth system modeling. We will address this knowledge gap by synthesizing a global database of soil geochemical measurements and modeling the global-scale processes that govern soil mineral reactivity and associated SOM storage. Specifically, we will use this database to test the hypothesis that warmer, wetter, more productive biomes tend to host less reactive soil minerals—but mineral reactivity can be amplified by geologic factors: lithology, topography, and depositional history. Consequently, soil mineral reactivity and accompanying soil organic matter storage vary substantially as a function of geologic factors within major biomes. Our analysis will involve harmonizing global geochemical databases and developing approaches to infer soil mineralogical composition from bulk chemical composition. We will then use the harmonized global database to develop gridded maps of soil mineralogy and mineral reactivity, which we will quantify using weathering indices (e.g., the chemical index of alteration). In the final stage of our analysis, we will quantify spatial correlations between soil mineral reactivity and SOM while controlling for confounding environmental variables in a series of regional case studies. The data synthesis and modeling approaches described here will thus provide a scaffolding for the next generation of belowground biogeochemical models. This research will also test our fundamental understanding of how soils develop and function in different ecological and geological contexts.

Computational Identification of Bioavailable Organic Matter and Their Traits for Predictive Biogeochemical and Ecosystem Modeling

- **Principal Investigators:** Hyun-Seob Song (University of Nebraska-Lincoln)
- **Collaborators:** Christopher Henry (Argonne National Laboratory), James Stegen (Pacific Northwest National Laboratory), Mikayla Borton (Colorado State University)
- **Total Award:** $400,000 over two years

Microbial degradation of organic matter (OM) plays a crucial role in biogeochemical cycling and ecosystem function. A fundamental understanding of the interplay between microbial and enzymatic processes and substrate chemistry is essential for accurate prediction of OM degradation. Despite increasing availability of high-quality omics data, oversimplified descriptions of substrate pools continue to pose a serious bottleneck in building predictive biogeochemical models. In this regard, the substrate-explicit thermodynamic modeling has emerged as a promising approach that uses high-resolution metabolite data to predict OM degradation and respiration rates. Like other thermodynamics-based biogeochemical models, the substrate-explicit modeling assumes: (1) all chemical compounds detected in the samples are respirable and (2) their degradation rates are determined by thermodynamic favorability. However, a recent study showed that this model fails to correctly predict respiration rates of sediment samples collected from widely distributed river systems, suggesting that the mentioned assumptions may not be universally valid and need further investigation. Agreeably, not all OM are bioavailable, and their degradation may be governed by multiple factors, rather than thermodynamics only. We do not know how to determine bioavailable OM (bOM), what additional factors may control OM bioavailability, how OM chemistry can be connected to microbial metabolic reactions, and how they together impact OM degradation in space and time. To address these issues, we propose to develop new modeling methods and capabilities to effectively incorporate detailed OM chemistry into biogeochemical and reactive transport models. To achieve this goal, we set up three objectives: (1) identification of bOM and their governing traits, (2) incorporation of bOM into metagenome metabolic networks, and (3) coupling the resulting expanded metabolic networks with reactive-transport models. The effectiveness of our methods will be evaluated using public biogeochemical and omics data from the Worldwide Hydro-biogeochemistry Observation Network for Dynamic River Systems (WHONDRS) consortium, including ultrahigh-resolution OM data from Fourier-transform ion cyclotron resonance mass spectrometry, aerobic respiration rates, metagenomes, and various other metadata attributes. By comprehensively accounting for diverse chemical, thermodynamic, and genomic drivers of OM degradation, the project will enable systematic analysis of a variety of river systems with differing biological and chemical characteristics. As a key outcome, the project will produce novel computational capabilities, such as the use of metagenome metabolic networks to incorporate detailed OM chemistry into biogeochemical and reactive transport modeling. We also demonstrate how machine learning techniques can facilitate this integration by achieving computational efficiency. All new developments of simulation and computational tools will be shared publicly with related academic and research communities. Overall, this project will significantly enhance (1) our understanding of the fundamental mechanisms that govern OM degradation by shifting our focus from individual parameters to the interactions of multiple factors and (2) our ability to use molecular-level data and models to inform large-scale ecosystem modeling, accelerating new scientific discoveries by increasing computational efficiency.

Floodplains vs. Hillslopes: Informing the Timing and Tempo of Clay Formation and Organic Matter Stabilization Across an Alpine Watershed

- **Principal Investigators:** Mark Torres (Rice University)
- **Collaborators:** Evan Ramos (Rice University), Matthew Winnick (University of Massachusetts, Amherst), Daniel Ibarra (Brown University), Kenneth Williams (Lawrence Berkeley National Laboratory)
- **Total Award:** $719,294 over three years

Soils store substantial amounts of carbon (C) as organic matter. However, the size of this C reservoir may be sensitive to climatic change, motivating research on the mechanisms governing soil organic matter stabilization. One existing paradigm for organic matter stabilization suggests that the phyllosilicate “clay” minerals that form in soils protect organic matter from breakdown. However, models are not capable of fully representing this process, pointing to knowledge gaps regarding the interactions between organic matter and minerals, their constitutive controls, and their timescales of operation. More broadly, there are persistent challenges in describing the co-evolution of soil mineralogy, structure, and organic matter storage, which limits the treatment of soil dynamics in Earth systems models and their concomitant effects on future climate projections.

Here, we propose to advance our understanding of how clay minerals and organic matter interact at the terrestrial-aquatic interface using the East River watershed as a natural laboratory. In addition to traditional methods, measurements of stable lithium isotopic ratios, which is one of the foremost proxies for quantitatively gauging clay mineral formation, will be central to the proposal. Critically, our approach will enable the detection of hot spots and hot moments of clay mineral formation by studying different landscape elements (e.g., floodplain vs. hillslope), components of the hydrosphere (e.g., groundwater vs. surface water), and timescales of biogeochemical cycling (e.g., rainfall events, the seasonal cycle, and landscape evolution over millennia). Ultimately, these measurements will be used to improve models that relate field and laboratory measurements with Critical Zone processes.

The East River watershed represents an ideal locality to interrogate these questions because of the extensive study that has already characterized it, a large sample archive, and existing sampling infrastructure that permits geochemical analyses at high spatial and temporal frequencies. Given the outsized role of headwater ecosystems in terrestrial biogeochemical cycles, the proposed work will build a theoretical and methodological framework for soil formation and organic matter stabilization that is applicable to other watersheds and will lead to a more accurate depiction of terrestrial carbon cycling in Earth system models. Lastly and importantly, the project will include the training of one graduate student and postdoctoral researcher in laboratory and computational methods.

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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