Environmental System Science

Summary of projects awarded in summer 2018 under the Environmental System Science Funding Opportunity Announcement DE-FOA-0001855.

Program Overview

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

Funding Opportunity Announcement Overview

The Funding Opportunity Announcement DE-FOA-0001855, was issued by the Terrestrial Ecosystem Science program and was released in the winter of 2017. The goal of this FOA was to improve the representation of terrestrial ecosystem processes, with a view towards advancing sophistication and accuracy of Earth system models, thereby improving the quality of Earth and environmental model projections and providing the scientific foundation needed to support DOE's science and energy missions. Applications to this FOA were expected to take a systems approach to understand ecosystems over the multiple temporal and spatial scales that are represented in models (e.g., single process models, ecosystem models, and global models such as the Energy Exascale Earth System Model and Community Earth System Model). This emphasis on the capture of advanced empirical and theoretical understanding in models has two goals. First, it sought to improve the representation of these integrated processes in coupled models, thereby increasing the sophistication of the projections. Second, it encouraged the community to understand and use a diversity of existing models and to compare model results against observations or other data sets to identify knowledge gaps and future research directions. It also sought to encourage an iterative dialog between the empirical and modeling research communities such that research objectives are co-designed to address key model deficiencies and that modeling efforts are designed to inform empirical research. By connecting the modeling and experimental components, this approach maximizes the return on scientific investments by reducing duplication of efforts and encourages collaboration, thus generating a significant benefit to both the Department of Energy and the scientific community. Research in environmental system science also provides a public benefit through experiments, observations and modeling that acts to inform next-generation model projections of ecosystem processes and disturbances that can be used in decision support.

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

<u>Science Area 1 – Interactions between Above- and Belowground Processes and Traits</u>: New or improved understanding of the mechanisms, interactions and feedbacks between aboveground and belowground processes, and their mediation by plant and microbial traits, that impact the critical biogeochemical transformations across scales under a changing environment and Earth system;

- Interactions and feedbacks across this continuum with a specific emphasis on critical biogeochemical transformations across spatial and temporal scales.
- Plant mediated transformations such as priming, hydraulic redistribution, plant-microbe interactions such as mycorrhizal interactions, regulation of biogeochemical fluxes, nutrient redistribution, and belowground drivers/regulators of photosynthesis.
- Trait-based approaches and that develop mechanistic knowledge through experiments linking trait-based information, and associated trait tradeoffs, to function of the soil-plant-atmosphere continuum.

<u>Science Area 2 – Terrestrial-Aquatic Interfaces</u>: New or improved understanding of critical vegetative and coupled biogeochemical processes at the terrestrial-aquatic interface which have the potential for direct feedbacks to the Earth system (e.g., soil carbon transformation, methane biogeochemistry);

- Processes that incorporate and connect directly to terrestrial ecosystems and their immediate interface with freshwater and brackish water systems, such as riparian zones, hyporheic zones and wetlands.
- Biogeochemical cycling and processes that have the potential to provide major feedbacks to the Earth and environmental systems at a variety of scales from plot to global.

<u>Science Area 3 – Disturbance</u>: New or improved understanding of the natural disturbance impacts and feedbacks on vegetation dynamics and critical biogeochemical pathways in terrestrial ecosystems.

- Processes and feedbacks that govern plant-soil interactions, vegetation dynamics, hydrobiogeochemical fluxes and transformations, and land-atmosphere exchange, in response to rapid perturbations from the 2017 hurricane, drought and wildfire disturbances.

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

Seven awards (two of which were exploratory awards) were made through this Funding Opportunity Announcement totaling $5,049,997 over three years.

Funded Projects

Sticky Roots -- Implications of Widespread, Cryptic, Viral Infection of Plants in Natural and Managed Ecosystems for Soil Carbon Processing in the Rhizosphere

- **Principle Investigator:** Zoe Cardon (Marine Biological Laboratory)
- **Collaborators:** Marco Keiluweit (University of Massachusetts, Amherst); Carolyn Malmstrom (Michigan State University); William Riley (Lawrence Berkeley National Laboratory)
- **Award:** $299,999 over 1 year

One powerful way that plants influence soil properties is through rhizodeposition, in which exudates diffuse from roots, additional secretions are actively released, and root cells are sloughed into the soil. The core objective of this project is to test whether rhizodeposition can destabilize the association of soil organic matter (SOM) with minerals, making that SOM more vulnerable to microbial attack. Mineral-SOM associations preserve very large soil carbon pools in terrestrial ecosystems, and DOE's newly developed E3SM Land Model (ELM) includes a representation of that soil carbon preservation. However, the potential vulnerability of SOM–mineral associations to effects of rhizodeposition is not yet represented in ELM. In a novel approach, we are exploring whether plant virus infection can serve as a tool to intensify rhizodeposition, and therefore potentially enhance liberation of SOM from minerals. Viral infection is widespread in terrestrial ecosystems; 25-70% of plants have virus infection, yet the influence of such infection on root traits and terrestrial soil carbon dynamics remains largely unexplored. We will use two plant hosts: the annual *Avena sativa* (oats) and the genetically tractable, model grass *Brachypodium distachyon*. We will infect these grasses with the broad host range virus Barley yellow dwarf virus (BYDV). BYDV infects at least 150 grass species in agricultural and natural ecosystems, and in previous experiments, roots of oats infected with BYDV had extraordinarily sticky roots, strongly suggesting that infection enhanced rhizodeposition. Five uninfected and five infected individuals of each host species will be grown individually in replicate "rhizoboxes," which are rectangular pots equipped with sensors. These sensors will be used to probe the changes in the types of organic compounds inside roots (before they diffuse out into soil), the biogeochemistry and microbial activity around roots, and the dynamics of mineral-SOM associations. A larger-scale, year-long greenhouse experiment will test whether BYDV-infected *Avena sativa* drives more decomposition of isotopically labeled SOM than uninfected *Avena sativa*. Mechanistic understanding derived from these lab and greenhouse data will inform future development and application of ELM. If our experiments indicate that high rates of rhizodeposition drive mineral-SOM disruption, then future research combining experimentation and modeling should explore the strength and larger-scale significance of that cascade of processes. And if viral infection does lead to "sticky roots", our understanding of the potential importance of prevalent virus infection in terrestrial landscapes will be transformed.

Peatland Hydrology Across Scale: A Probabilistic Framework for Confronting Variability, Heterogeneity, and Uncertainty

- **Principle Investigator:** Xue Feng (University of Minnesota)
- **Collaborators:** Gene-Hua Crystal Ng (University of Minnesota); Stephen Sebestyen (USDA Forest Service)
- **Award:** $255,585 over 2 years

Northern peatlands are key ecosystems that regulate greenhouse gasses, such as carbon dioxide (CO_2) and methane (CH_4), in the atmosphere. These peatlands are widespread in northern latitudes and, in-total, store up to one-third of global soil carbon. Though some greenhouse gases have always been emitted from peatlands, their wetness has generally allowed them to take in more carbon from the atmosphere than they emit. That may change in a warmer world. Unfortunately, existing Land Surface Models that are currently used to understand greenhouse gas concentration in the atmosphere do not realistically represent peatlands or their hydrology. Our research aims to develop a series of novel interconnected tools to better quantify and predict effects of climatic variability on peatland hydrology and carbon emissions. We will use long-term data from a site where peatlands hydrological research has been a focus for over five decades. We will use data on different peatland types and under a range of climatic conditions to address our questions about three key drivers of water table variability: 1) A warming climate and changing rainfall variability; 2) The subtle, yet distinct topography in peatlands, and 3) How peatlands interact with their surrounding watersheds.

We will combine these data with state-of-the-art modeling approaches (i.e., stochastic representation of uncertainties and variability) to quantify the timing and overall magnitude of carbon release in these types of peatland watersheds. By identifying and simulating appropriate representations of peatlands in their surrounding landscapes, our new stochastic framework will guide improvements to Land-Surface Models that are needed to accurately predict carbon feedbacks between the land surface and the atmosphere.

Catastrophic Forest Disturbance and Regrowth in Puerto Rico Following Hurricane Maria: Benchmarks for Earth System Models from Forest Inventory and Remote Sensing Measurements

- **Principle Investigator:** Michael Keller (USDA Forest Service)
- **Collaborators:** Douglas Morton (NASA Goddard Space Flight Center); Maria Uriarte (Columbia University); Sebastian Martinuzzi (University of Wisconsin); Charles Koven (Lawrence Berkeley National Laboratory)
- **Award:** $499,956 over 3 years

The mechanisms of tree mortality and forest canopy damage are poorly represented in current Earth System Models. We propose to leverage extensive forest inventory and airborne remote sensing data acquired before and after Hurricanes Irma and Maria in Puerto Rico to quantify variability in tree mortality and canopy damage. We will study canopy damage, mortality, and post-disturbance forest recovery across landscape gradients in climate, geology, topography, forest age, past land use and species composition. Time series of field and airborne remote sensing data will enable us to contrast hurricane damage with estimates of background forest mortality and canopy dynamics in the absence of storms across the entire island. New landscape-level knowledge of damage, mortality, and post-disturbance recovery will provide benchmark data sets for modeling changes in forest structure, composition, and biogeochemical cycling from forest disturbance. Together, these studies will advance our mechanistic understanding of tropical forest resilience to catastrophic disturbance as a function of disturbance intensity, climate, geology, topography, forest age, past land use and species composition.

These advances are necessary to improve representation of vegetation demography and successional recovery from disturbance in Earth System Models at ecologically meaningful spatial and temporal scales.

Coastal Wetland Carbon Cycling Processes in a Warmer Climate

- **Principle Investigator:** J. Patrick Megonigal (Smithsonian Institution)
- **Collaborators:** Matthew Kirwan (Virginia Institute of Marine Sciences); Peter Thornton (Oak Ridge National Laboratory); Genevieve Noyce (Smithsonian Institution); Roy Rich (Smithsonian Institution); Teri O'Meara (Smithsonian Institution); Glenn Guntenspergen (United States Geologic Survey); Kerri Sendall (Georgia Southern University)
- **Award:** $1,00,000 over 3 years

Coastal wetlands are global hotspots of carbon storage, and locations where carbon and nitrogen cycles have a disproportionately large impact on land, water, and air in comparison to the area they occupy. The mechanisms by which coastal wetlands respond to elevated CO_2 and warming are similar to other terrestrial ecosystems, but coastal wetlands are also unique because biological and physical responses to disturbance are strongly mediated by rates of sea level rise. High rates of carbon sequestration in these systems are the result of complex feedbacks between vegetation and the physical environment. Plants are "ecosystem engineers" because they build soil elevation, and control aerobic and anaerobic microbial decomposition of organic matter. Such complex feedbacks are largely absent in present day global-scale forecast models. We will investigate the complex interactions between plants, soils, and climate that influence carbon cycling using an existing experiment that began in 2016, the Salt Marsh Accretion Response to Temperature eXperiment (SMARTX). SMARTX is a field experiment located at the Global Change Research Wetland, a 23 hectare brackish tidal marsh on the western shore of Chesapeake Bay in Maryland. The site is operated by the Smithsonian Environmental Research Center with support from the Department of Energy (the site's original sponsor), National Science Foundation, United States Geologic Survey, and National Oceanic and Atmospheric Administration for over three decades. Several other experiments located at the site will be leveraged to extend the data provided by SMARTX.

SMARTX is a whole-system experiment deployed in two plant communities, with warming from the plant canopy to 1.5 m depth. Warming treatments are applied as a gradient from ambient to +5.1°C. Elevated carbon dioxide is crossed at the temperature extremes in one of the plant communities. To date, we observed that warming and elevated carbon dioxide change shoot and root growth in ways that are most easily explained by a warming-induced increase in microbial decomposition leading to higher soil nitrogen availability. Warming also increased emissions of the greenhouse gas methane in SMARTX.

We will install a new system of soil sensors that continuously measure soil water content and salinity, which we hypothesize are controlling the plant growth response to warming. A new technique will be used to quantify soil organic matter decomposition rates and nitrogen availability to test hypotheses that explain changes in root versus shoot growth across the treatments. A new system of soil oxygen sensors will be installed to test hypotheses about the influence of root growth on methane production and emissions. Finally, stable isotope techniques will be used to gain insights on the mechanisms by which methane is produced, consumed, and emitted, and their response to our treatments. Data from SMARTX will be used to refine our ecosystem-scale marsh carbon model, and to modify an Earth system model to enable the first-ever representation of tidal wetland dynamics at a global scale. The result will be an improved ability to forecast the stability of coastal wetlands and the carbon they contain in the 21st century.

Effects of Rapid Permafrost Thaw on CO_2 and CH_4 Fluxes in a Warmer and Wetter Future

- **Principle Investigator:** Rebecca Neumann (University of Washington)
- **Collaborators:** Qing Zhu (Lawrence Berkeley National Laboratory); William Riley (Lawrence Berkeley National Laboratory)
- **Award:** $996,199 over 3 years

Our primary object is to improve environmental predictability by advancing understanding of how carbon dioxide (CO_2) and methane (CH_4) flux in permafrost thaw-induced wetlands (thermokarst) will change in the future. Northern latitudes are expected to get warmer and wetter, leading to increased thermokarst thaw both in places already thawing, and in places where the permafrost is currently stable. Understanding the land-atmosphere exchange of these important greenhouse gases will help us understand and predict environmental change.

Data previously collected by the research team showed that CO_2 uptake and CH_4 emission by a thermokarst bog in Alaska increased in rainy years. The increase in CH_4 emission was not associated with wetter soils, as is often assumed. Rather, rain carried heat from the atmosphere into the bog, warming peat to deep depths. Warmer peat temperatures supported plant growth within recently thawed areas of the bog, which increased net CO_2 uptake and fueled CH_4 production and emission within these areas. Plant growth within older thaw areas minimally responded to the increased temperatures. We hypothesize the difference in plant response between young and old thaw areas was associated with nitrogen availability, a key plant nutrient which is more available in young thaw areas.

These data imply that the formation of thermokarst wetlands will have dynamic effects on the climate system. Net carbon flux and CH_4 emissions will change not only as thawed landscapes age, but also as environmental conditions shift. Capturing and correctly accounting for dynamic biosphere–atmosphere interactions and feedbacks, such as those involved with permafrost thaw, requires Earth system modeling. However, current Earth system land models, like the Energy Exascale Earth System Model Land Model (ELM), do not include transport of heat into soil from rain, do not represent sub-grid heterogeneity of land units (e.g., differently aged wetlands), do not fully represent soil nitrogen processing and plant nitrogen uptake, and do not explicitly connect plant productivity with CH_4 production. These deficiencies undermine the accuracy and precision of the model and reduce its predictive capability.

We will take a coupled model-experiment-observation approach to advance understanding of thermokarst wetland dynamics and to address these deficiencies in ELM. We have six specific aims:

1. Harness historical data to identify how the amount and timing of rainfall affects peat temperature, nitrogen dynamics, plant productivity, and carbon flux in thermokarst wetlands.
2. Conduct a field manipulation experiment to test our underlying hypothesis that the organic nitrogen content of peat within young and old wetland areas controls the different responses of these areas to rainfall by affecting the production of plant-available nitrogen.
3. Determine how wetland dynamics will change in the future by measuring peat temperatures, vegetation coverage, and carbon flux in differently aged areas of an isolated thawing permafrost bog located in a currently warm and wet climate (i.e., on the Kenai Peninsula).
4. Advance ELM ’s soil thermal-hydrology-biogeochemistry coupling by adding

advective heat transport into soil by rain, improving representation of soil nitrogen dynamics, and directly connecting plant productivity with CH_4 production.
5. Use field data to parameterize the improved ELM, identify model uncertainty, and use the model to conduct site-level experiments that test hypotheses.
6. Extrapolate the model to northern permafrost region and simulate future CO_2 and CH_4 fluxes with different climate forcings and wetland-age projections. Enhance understanding of key interactions and feedback mechanisms that affect thermokarst wetland carbon fluxes.

These efforts will improve knowledge and thus representation of coupled thermal-hydrological-biogeochemical processes within ELM, increasing knowledge of climate–carbon feedbacks and progressing environmental predictability.

Using Root and Soil Traits to Forecast Woody Encroachment Dynamics in Mesic Grassland

- **Principle Investigator:** Jesse Nippert (Kansas State University)
- **Collaborators:** Lydia Zeglin (Kansas State University); Kate McCulloh (University of Wisconsin-Madison); Kevin Wilcox (Consultant)
- **Award:** $998,261 over 3 years

Grasslands are a widespread and globally important biome providing key ecosystem services including carbon (C) storage and regulation of the water cycle. Grasslands face multiple threats, including changes in drought intensity and woody encroachment - a process that results in increased woody plant abundance corresponding with decreased herbaceous plant abundance. The combination of reduced soil moisture and shifts in plant dominance from herbaceous to woody are likely to alter C pools in the soil profile. We currently do not have the capacity to predict either the magnitude or rates of change in these C pools. In order to predict changes in grassland vegetation structure and the associated impacts on C cycling, we require a better understanding of the distribution of soil C pools at multiple soil depths, and the responses of these pools to changes in precipitation. The Land Surface Model (LSM) component of Earth System Models has the ability to capture these dynamic changes in ecosystem function, but currently lacks the data to accurately parameterize these processes at multiple depths within the soil profile. To support and perform this parameterization, we will undertake a detailed investigation of root and soil traits at varying soil depths, to capture the belowground impacts of changing dominant plant growth forms (grasses to shrubs) and the impacts of frequent drought.

We have developed a set of objectives that combine observational, experimental and modeling approaches to improve our ability to predict ecosystem consequences of shrub encroachment and drought in the US Great Plains region. These objectives are: (1) Quantify differences in aboveground (stem and leaf biomass) and belowground C pools (root C, microbial C, bulk soil C) using detailed excavations of entire mixed shrub-grass assemblages. We will also subsample portions of the rhizosphere for detailed root physiological and microbial activity measurements, to provide information on rates of change in soil C pools; (2) Using rainout shelters built over mature shrub-grass communities, we will experimentally reduce the amount of precipitation. Comparing responses between shrubs and grasses, we will measure differences in source-water use, above and belowground productivity, canopy water stress, soil C pools and microbial C-cycling activity, and changes in plant cover and community dynamics; (3) Using a global demographic LSM (CLM FATES), we will forecast the impacts of available water on shrub-grass cover in the central Great Plains region, and the resulting effects of these dynamics on ecosystem services (aboveground production, above- and belowground C budgets).

Results from this project will define the depth-resolved feedbacks of drought and dominant vegetation on belowground root architecture, soil microbial C cycling, and ecosystem C balance. The observation-experiment-modeling framework used here will improve our understanding of interactions and feedbacks between aboveground and belowground processes, by specifically measuring plant-soil-microbial traits at various depths in the soil profile. The details of these coupled interactions (plant-soil-microbial) will improve the representation of subsurface processes in LSMs and will improve forecasts of dynamic changes in ecosystem structure in grassland ecosystems.

Effects of Hurricane Disturbance and Increased Temperature on Carbon Cycling and Storage of a Puerto Rican Forest: A Mechanistic Investigation of Above- and Belowground Processes

- **Principle Investigator:** Tana Wood (USDA Forest Service)
- **Collaborators:** Molly Cavaleri Michigan Technological University); Sasha Reed (U.S. Geological Survey); Jennifer Pett-Ridge, Lawrence Livermore National Laboratory); Karis McFarlane (Lawrence Livermore National Laboratory); Xaiojuan Yang (Oak Ridge National Laboratory)
- **Award:** $999,997 over 3 years

Hurricanes affect nearly every continent in the world and are among the most intense weather disturbances in forest ecosystems. In 2017, the coastal United States (US) and Puerto Rico were devastated by a series of major hurricanes that caused more than $200 billion in damages, which will have long-lasting implications for the economics and natural resources of US forests. At the same time, models project that temperatures in the tropics and subtropics will increase by 3-5ºC within the next 20 years. The combined effects of hurricane disturbance and warmer temperatures could fundamentally alter the trajectory and duration of forest recovery following disturbance, resulting in altered ecosystem states that are difficult to predict from historical data alone. Despite the immediate and significant effects of hurricanes on forest carbon and nutrients, as well as the potential to affect the long-term trajectory of forest recovery, hurricanes are not currently represented in Earth System Models, and no studies have captured the potential interactions of hurricanes within the context of a changing climate. To address this major knowledge gap, we will take advantage of a once-in-a-century opportunity to investigate the recovery of forest structure and function following a major hurricane disturbance under experimentally warmed conditions. We will leverage an already established field warming experiment in Puerto Rico (Tropical Responses to Altered Climate Experiment [TRACE]), funded by the USDA Forest Service and the US Department of Energy, to capitalize on the experiment's wealth of pre-hurricane baseline data, including microclimate data before and during Hurricanes Irma and Maria, as well as multiple aspects of forest response following these major storms. TRACE is uniquely positioned as the first and only experiment in the world able to evaluate the combined effects of hurricane disturbance and increased temperature in a field setting. We will assess soil carbon, nutrients, and microbial processes along with plant physiology and chemistry in established warming plots impacted by hurricanes in order to address the following research questions: 1. Are there legacy effects of pre-hurricane experimental warming that persist after hurricane disturbance, or does the system "re-set" itself to new baseline conditions? 2. Will hurricane disturbance and increased temperature interact to generate soil and plant responses that fundamentally alter the trajectory of forest recovery?

We will explore these issues both above- and belowground, drawing on a suite of research approaches. With this project, we would collect and synthesize some of the only data in existence that directly inform quantification, evaluation, and modeling of tropical forest responses to the interactive effects of disturbance and warming. Results would directly address DOE's mission to improve our understanding of globally important and environmentally sensitive processes in understudied ecosystems and to improve the quality of complex Earth and environmental model projections.

Terrestrial Ecosystem SCIENCE

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

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