U.S. Department of Energy Office of Science
Office of Biological and Environmental Research
Climate and Environmental Sciences Division

Environmental System Science

Summary of projects awarded in summer 2015 under Funding Opportunity Announcement DE-FOA-0001172.

Funding Opportunity Announcement Overview

The Office of Biological and Environmental Research's (BER) Terrestrial Ecosystem Sciences (TES) program seeks to improve the representation of terrestrial ecosystem processes in Earth system models thereby improving the quality of climate model projections and providing the scientific foundation needed to inform DOE's energy decisions. The Subsurface Biogeochemical Research (SBR) program seeks to advance a predictive understanding of the biogeochemical structure and function of subsurface environments to enable systems-level environmental prediction and decision support. TES and SBR programs use a systems approach to understand ecosystems over multiple scales that can be represented in models (e.g., single process models, watersheds models, ecosystem models, and the CESM). This emphasis on the capture of advanced understanding in models has two goals. First, it seeks to improve the representation of these processes in coupled models, thereby increasing the sophistication of the projections from those models. Second, it encourages the community to exercise those models and to compare the results against observations or other data sets to inform future research directions.

The Funding Opportunity Announcement **DE-FOA-0001172**, was jointly issued by the Terrestrial Ecosystem Sciences and Subsurface Biogeochemical Research programs and was released in the summer of 2014. The goal of this FOA was to improve the representation of terrestrial ecosystem and/or subsurface processes, with a view towards advancing sophistication and accuracy of Earth system models, thereby improving the quality of climate model projections and providing the scientific foundation needed to inform DOE's energy decisions. 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 Community Earth System Model and the Accelerated Climate Model for Energy). This emphasis on the capture of advanced understanding in models had two goals. First, it sought to improve the representation of these processes in coupled models, thereby increasing the sophistication of the projections from those models. Second, it encouraged the community to understand and use existing models and to compare model results against observations or other data sets to inform future research directions. It also sought to encourage an iterative dialog between the process and modeling research communities such that research objectives would be designed to address model needs and that modeling efforts are designed to inform process research.

While the TES and SBR programs 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 Science Areas:

- The role of belowground processes and mechanisms across scales (e.g., microbial process including soil carbon transformation/stability, root dynamics, mycorrhizal interactions, and plant mediated (e.g. root exudates, priming, hydrological, biogeochemical transformations) associated with a changing climate;
- New or improved understanding of carbon relevant biogeochemical pathways, fluxes and ecosystem function with particular emphasis on Arctic tundra and tropical ecosystems;
- New or improved understanding of critical carbon processes at the terrestrial-aquatic interface which have the potential for direct feedbacks to the climate system (e.g., soil carbon transformation, methane biogeochemistry), and;
- Synthesis activities that draw broad insights into, and improve our understanding of, terrestrial ecosystems and their role in forcing climate change will be considered. These lower cost activities should leverage existing models, sites and datasets.

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.

The Regional and Global Climate Modeling (RGCM) program within BER's Climate and Environmental Sciences Division (CESD) decided to jointly support one application that strongly linked between the their program objectives and TES.

Eleven awards (four of which were exploratory awards) were made through this Funding Opportunity Announcement totaling $9,684,404 over three years.

Funded Projects

Terrestrial Ecosystem Sciences (TES)

Understanding Mechanistic Controls of Heterotrophic CO_2 and CH_4 Fluxes in a Peatland with Deep Soil Warming and Atmospheric CO_2 Enrichment

- **Principle Investigator:** Jason Keller (Chapman University)
- **Collaborators:** Scott Bridgham (University of Oregon); Qianlai Zhuang (Purdue University)
- **Award:** $1,495,783 over 3 years

Peatlands are among the most important terrestrial ecosystems in the global carbon cycle. These wetlands currently store roughly one-third of the terrestrial soil carbon and are a significant source of the potent greenhouse gas methane (CH_4) to the atmosphere. The overall objective of this project is to expand our mechanistic understanding of how deep warming of peat and CO_2 enrichment in a bog affect carbon mineralization and CH_4 dynamics and to incorporate that understanding into Earth system models. Using the ongoing SPRUCE experiment and complementary laboratory experiments, we will test the following hypotheses: H1: Warming will have a substantial positive effect on CH_4 production in surface peat but will have a smaller positive effect in deep peat due to its chemical recalcitrance. H2: Warming will cause a larger increase in anaerobic CO_2 production than CH_4 production due to stimulation of 'upstream' microbial processes, and this ratio will increase with depth. H3: Both warming and CO_2 enrichment will increase the prevalence of acetoclastic methanogenesis (production of CH_4 from acetate) over hydrogenotrophic methanogenesis (production of CH_4 from CO_2 and H_2) as a result of increased labile substrates and an increase in homoacetogenesis (acetate production from H_2 and CO_2). An increase in the importance of acetoclastic methanogenesis will be coincident with increased overall CH_4 production. H4: Both treatments will lead to transient accumulations of low-molecular-weight organic acids, including acetate, due to the slow growth of methanogens. H5: Anaerobic CH_4 oxidation will be an important process below the water table, adding to CH_4 consumption from aerobic CH_4oxidation in surface soils as an important sink of CH_4. Our results will be incorporated into ongoing modeling efforts, and in particular will be used to improve algorithms associated with anaerobic processes and CH_4 cycling within the Terrestrial Ecosystem Model (TEM).

Coastal Wetland Carbon Sequestration in a Warmer Climate

- **Principle Investigator:** J. Patrick Megonigal (Smithsonian Institution)
- **Collaborators:** Matt Kirwan (Virginia Institute of Marine Sciences); Paul Dijkstra (Northern Arizona University)
- **Award:** $1,499,952 over 3 years

Coastal wetland ecosystems remove carbon dioxide from the atmosphere and store it in soils at high rates. Marshes, mangroves, and seagrass meadows occupy just 2.5% of Earth's land area, yet they hold about half of the planet's carbon stored in estuaries and oceans, and they bury about the same amount of carbon as all terrestrial forests. High rates of carbon sequestration are attributed to high rates of plant growth, low rates of decomposition, and sea level rise. As rates of sea level rise accelerate, coastal wetlands have the potential to store soil carbon at increasingly fast rates provided that the plants can survive flooding. Coastal wetlands have only recently been recognized as important carbon sinks, and therefore the response of carbon cycling to global change in this ecosystem is virtually unexplored. The future stability of these ecosystems is uncertain because global change drivers such as temperature and elevated CO_2 perturb the complex ecological feedbacks that drive carbon storage. Despite the leverage these ecosystems exert over the global carbon cycle, the dynamics of coastal wetland carbon pools are not presently represented in earth system models. Our objectives are to quantify how warming affects the stability of coastal wetland soil carbon pools, the ability of coastal wetlands to maintain current rates of carbon sequestration, and to quantify interactions between temperature, elevated CO_2 and inundation frequency on soil carbon storage. To address our hypotheses, we will build the first in situ, active aboveground and belowground warming experiment in a coastal wetland, and examine the interaction between warming, elevated CO_2 and inundation frequency on soil carbon storage rate. We will then modify a well-established ecosystem-scale model of marsh carbon dynamics to include new insights from the field experiment. Finally, we will extrapolate our experimental data further by linking the ecosystem-scale model to the global-scale Community Land Model.

Extrapolating Carbon Dynamics of Seasonally Dry Tropical Forests Across Geographic Scales and into Future Climates: Improving Simulation Models with Empirical Observations

- **Principle Investigator:** Jennifer Powers (University of Minnesota)
- **Collaborators:** Bonnie Waring (University of Minnesota); David Medvigy (Princeton University); Forrest Hoffman (Oak Ridge National Laboratory); Xiaojuan Yang (Oak Ridge National Laboratory)
- **Award:** $1,500,000 over 3 years

Seasonally dry tropical forests (SDTFs) experience a pronounced dry season lasting 3 to 7 months, and once accounted for approximately 40% of all tropical forest. Throughout the last several centuries, the area covered by SDTFs has been dramatically reduced through conversion to grazing and croplands, and they are now considered the most threatened tropical biome. However, in many regions STDFs are now growing back. These forests are valuable because they are reservoirs of unique biodiversity and store large stocks of carbon in biomass and soils. Despite their global importance, assessing the responses of SDTF carbon dynamics to ongoing global changes is extremely challenging. Many ecosystem models have not resolved SDTFs from wetter tropical rainforests or drier savannahs. Moreover, model improvements are strongly limited by availability of empirical data, especially for belowground processes such as root production and nutrient dynamics. Therefore, the central objectives of this project are to quantify how belowground processes mediate the responses of SDTF carbon dynamics to environmental change, and incorporate that understanding into two state-of-the-art models, ED2 and ACME. To do so, we will use an interdisciplinary approach that integrates: 1) field observations of ecosystem processes and plant functional traits across a range of dry forest sites in Costa Rica, Mexico, Puerto Rico, and Colombia, 2) forest-scale experiments that manipulate water and nutrient availability in Costa Rica, and 3) model simulations that quantify sensitivity of ecosystem carbon cycling to external forcings. Ultimately, our combined measurement and modeling approach will elucidate controls on C cycling in SDTFs, leading to better understanding of atmospheric carbon dioxide dynamics, nutrient deposition, and climate change feedbacks, and improved models for the global change research community.

Multifactor Experiment and Model Integration to Determine the Regional Vulnerability of Permafrost Carbon to Climate Change

- **Principle Investigator:** Edward Ted Schuur (Northern Arizona University)
- **Collaborators:** Yiqi Luo (University of Oklahoma); Charlie Koven (Lawrence Berkeley National Laboratory)
- **Award:** $1,499,666 over 3 years

Sustained and substantial carbon release from the Arctic is a wildcard with the potential to alter the future trajectory of climate change. A key societal question is whether there are tipping points, global carbon cycle surprises that will make climate change effects such as sea-level rise, extreme weather, droughts, and impacts on agriculture occur faster than currently projected by models. The overarching goal of this project is to determine the susceptibility of carbon in permafrost (perennially frozen) ecosystems to climate change. The project addresses this goal using a combination of field and laboratory experiments to measure isotope ratios and carbon fluxes in a tundra ecosystem that has been exposed to experimental warming and drying. The measurements are designed to develop a mechanistic understanding of the ecosystem sources contributing to carbon losses following warming and permafrost thaw, and how these dynamics change over time. Field results will be used to derive parameter values for large scale Earth System Models using data assimilation techniques, which can then project the response of permafrost ecosystem carbon balance to a range of future climate scenarios. The data sets and modeling simulations generated by this project will help outline the potential magnitude of Arctic carbon release to the atmosphere in a warmer world.

Effects of Fine-Root Senescence Upon Soil Communities and Nutrient Flux into Soil Pools

- **Principle Investigator:** Alan Strand (College of Charleston)
- **Collaborators:** Seth Pritchard (College of Charleston); Daniel McGlinn (College of Charleston)
- **Award:** $149,933 over 2 years

Soils represent one of the largest carbon pools on the planet and the most significant mechanism for carbon movement into soils is through fine-root production and subsequent mortality (turnover). In addition to their importance in carbon dynamics, fine root pools also have been shown to impact cycling of nitrogen in terrestrial ecosystems. The interaction between carbon and nitrogen cycling mediated by fine root dynamics is a critical component of modern climate models and Improving our understanding of this linkage is an obvious way to improve model accuracy and predictive power. Unfortunately, the study of fine root senescence and death, a critical step in both soil carbon and nitrogen dynamics lags significantly compared to study of above ground soil carbon inputs as well as belowground processes such as fine root production. This knowledge gap is potentially very significant; recent model improvements that include physiological processes associated with leaf senescence have greatly improved model performance. It is likely that adding the impacts of root senescence, particularly upon nitrogen dynamics, will significantly improve climate models as well. The main reason that root senescence is understudied is due to the technical difficulty of working with roots in situ. In this project we will test the feasibility of inducing and detecting root senescence in the field using the widespread and sylviculturally important species, Pinus taeda. Two methods will be deployed for inducing senescence in intact root systems: physical and steam girdling. Once treatments (including a handling only control) are imposed, we will examine several techniques to assess senescence. Senescence will be evaluated through internal anatomical, external morphological, and transcriptional changes through time subsequent to treatment. The main outcome of this project will be a detailed examination of the feasibility of inducing senescence in fine roots, the timing of root responses to induction, and the metabolic and anatomical changes that occur during senescence. These results will be used to plan large-scale studies of the role that fine root senescence plays in nutrient cycling and its role in improving global climate models.

Benchmarking and Improving Microbial-Explicit Soil Biogeochemistry Models

- **Principle Investigator:** William Wieder (University of Colorado, Boulder)
- **Collaborators:** A. Stuart Grandy (University of New Hampshire); Rich Phillips (Indiana University); Ben Sulman (Indiana University); Steve Allison (University of California, Irvine); Jim Randerson (University of California, Irvine)
- **Award:** $497,780 over 2 years

Earth system models that are designed to project future carbon cycle–climate feedbacks exhibit notably poor representation of soil biogeochemical processes. This weakness is associated with highly uncertain projections about the fate of the largest terrestrial carbon pool on Earth (i.e., soil carbon). Given these shortcomings there has been intense interest in the development of soil biogeochemical models. However, efforts to create analytical tools to characterize, improve and benchmark these models have thus far lagged behind. This project will develop a framework to compare, evaluate and improve the process-level representation of soil biogeochemical models that could be applied in global land models. This work will provide a critical framework to understand, evaluate and benchmark soil biogeochemical models that are applied at global scales. Moreover, products from the project will be made publicly available to facilitate continued development and evaluation of these models with data across scales. These products will include synthesized data, a newly developed data assimilation framework, a global model test bed, and model simulation results. The results are expected to provide broad benefits to a wide range of stakeholders by improving the accuracy of soil carbon projections to environmental change.

Regional and Global Climate Modeling (RGCM)/ Terrestrial Ecosystem Sciences (TES)

Multiscale Land-Atmosphere Interaction in Tropical Ecosystems

- **Principle Investigator:** Allan Denning (Colorado State University)
- **Collaborators:** Michael Pritchard (University of California, Irvine); James Randerson (University of California, Irvine)
- **Award:** $1,199,964 over 3 years

The future behavior of tropical forest ecosystems is arguably the largest contributor to uncertainty in the strength and even the sign of carbon-climate feedback. Some coupled carbon-climate models predict massive dieback of tropical forests as climate warms, which then results in greatly increased CO2 emissions as forest carbon decomposes and amplifies global warming. Other models don't show this effect of warming. The difference between the two scenarios rests on the degree of resilience of tropical forests to persistent drought in climate models.

We have developed a strategy for evaluation of drought responses of tropical forests using a special Multiscale version of the Community Earth System Model. We perform three model experiments with CESM, in which land-atmosphere interactions are performed with subgrid-scale sampling at different spatial scales. Forest drought stress in these simulations is evaluated against four metrics: (1) seasonal and interannual variability at a series of eddy covariance records along a transect from the very wet NW Amazon to the very dry SE Cerrado; (2) the climatological position of the forest-savanna border is evaluated against global vegetation maps; (3) the response of two five-year experimental droughts imposed on forest plots in the Brazilian Amazon; and (4) the response of the simulated forest to two "100-year droughts" in 2005 and 2010 using solar-induced fluorescence.

After quantifying the responses of CESM (in its three Multiscale configurations), we will also perform decadal time slice experiments of mid- and late-21st century climate across a range of scenarios to evaluate likely carbon-climate feedback in light of hindcasting results. Finally, we will work closely with our collaborators at UC Irvine and Oak Ridge National Laboratory to incorporate these new metrics into an existing software package for climate model evaluation.

Subsurface Biogeochemical Research (SBR)

Evaluating Trace Metal Limitations on Methane Fluxes in Terrestrial Ecosystems

- **Principle Investigator:** Jeffery Catalano (Washington University)
- **Award:** $100,000 over 1 year

The greenhouse gas methane (CH_4) is produced in terrestrial ecosystems by subsurface microbial carbon cycling under anaerobic conditions. Its formation is localized at terrestrial-aquatic interfaces such as wetlands, permafrost soils, and soil microenvironments where O_2 is limited and organic carbon is available. Global climate models predict higher CH_4 emissions from wetlands in the future because of an increase in inundated area and the enhancement of CH_4 production as temperature increases. Recent work has shown that this relationship over predicts the temperature response of CH_4 production in many systems, suggesting that other substantial limitations on methanogenesis are present. A potentially important limitation that has been largely overlooked is trace metal availability. Methanogens are unique in having high enzymatic requirements for trace metals (e.g., Ni, Co, Zn, and Mo). Our effort will assess the importance of trace metal availability in controlling CH_4 fluxes from wetlands. Specific objectives include to: (1) Determine the extent of trace metal limitations on CH_4 fluxes from temperate wetlands; (2) Identify the effect of chemical speciation on trace metal availability in wetlands and its resulting impact on methanogenesis; (3) Characterize how temperate wetland soil CH_4 fluxes respond to trace metal additions, including the variation in this response as a function of temperature; and (4) Assess future research needs and design potential approaches to account for metal availability in models of regional and global methane biogeochemistry.

High Frequency and Vertical Variations of Soil Moisture and their Impacts on Ecosystem Dynamics

- **Principle Investigator:** Inez Fung (University of California, Berkeley)
- **Award:** $481,352 over 3 years

The vertical distribution of subsurface moisture is a major control on ecosystem dynamics and climate. Moisture at depth may support microbial respiration and sustain ecosystems through dry seasons, while moisture near the surface promotes latent heat cooling of the planetary boundary layer and moisture recycling in the atmosphere. In addition to the slow infiltration of moisture through the soil, there are fast processes that redistribute moisture in the subsurface. Fractures in the weathered bedrock create preferential flowpaths for downward movement of water, while tap roots of trees have been observed to transport moisture to depth after rainstorms, and "lift" the moisture during the day to the fine roots near the surface to support transpiration.

The next generation of ecohydrology and climate models must capture the fast processes that redistribute moisture in order to yield credible predictions. Deep roots and a store of water at depth have been inferred at several AmeriFlux sites with water-limited ecosystems, which show sustained evapotranspiration despite drying of the upper soils. The observations at AmeriFlux sites will be the key to our synthesis analysis and modeling.

The goal of our proposed exploratory project is to develop and test a new subsurface hydrology model that includes a parameterization of stochastic hydraulic conductivity to capture fracture flow, a diagnostic model of rooting profile that depends on the subsurface hydrology, and a representation of hydraulic redistribution by plant roots. The model will yield vertical distributions of moisture that extends to the bedrock, a water store that, albeit small, could be accessible by deep roots. The model will be tested at selected AmeriFlux sites and used to explore the response of transpiration to changes in vertical soil moisture distribution. The proposed work will test hypotheses such as: (i) fractures in weathered bedrock are a significant reservoir of water storage above the water table; (ii) deep-rooted ecosystems are located in regions with weathered bedrock and deep groundwater table; (iii) hydraulic redistribution by plant roots is more important than fracture flow in maintaining a water reservoir at depth; (iv) surface moisture is a necessary but not a sufficient predictor of high-frequency fluctuations in evapotranspiration; (v) changes in the probability density function of extreme weather will have nonlinear impacts on the vertical distribution of soil moisture and ecosystem dynamics. The model, once vetted at the selected AmeriFlux sites, can be applied at all sites and be incorporated into global Earth System Models to investigate the interactions between ecohydrology and climate.

A Multiscale Approach to Modeling Carbon and Nitrogen Cycling within a High Elevation Watershed

- **Principle Investigator:** Kate Maher (Stanford University)
- **Collaborators:** Jennifer Druhan (University of Illinois); Corey Lawrence (US Geological Survey); Reed Maxwell (Colorado School of Mines); Carl Steefel (Lawrence Berkeley National Laboratory); Ken Williams (Lawrence Berkeley National Laboratory)
- **Award:** $609,975 over 2 years

Soils, floodplains and shallow aquifers are the least understood components of the carbon cycle, yet they represent the largest reservoir of terrestrial carbon and are highly sensitive to shifts in climate, vegetation, and the resulting water balance. As a result, processes that occur in these environments represent a key knowledge gap in our predictive understanding of nutrient cycling and terrestrial ecosystem function, which in turn limits our ability to model ecosystems over large scales. To provide an approach for developing improved model descriptions, we propose to develop reactive transport descriptions of subsurface carbon (C) and nitrogen (N) transformations and fluxes at multiple scales (soil profile to watershed), using field data collected from a high-elevation catchment in Colorado to constrain the models. The coupling between transport and transformation will be rigorously represented using a new generation of simulations tools, and resulting models will be compared to traditional soil carbon models. These highly resolved simulations offer a new approach for evaluating what information is critical to retain in larger scale models.

Systematic Investigation of the Biogeochemical Stability of Iron Oxide-Bound Organic Carbon: Linking Redox Cycles and Carbon Persistence

- **Principle Investigator:** Yu Yang (University of Nevada, Reno)
- **Collaborators:** Eric Roden (University of Wisconsin, Madison); Daniel Obrist (Desert Research Institute); Annie Kersting (Lawrence Livermore National Laboratory); Baohua Gu (Oak Ridge National Laboratory); Shaomei He (University of Wisconsin, Madison); Yisong Guo (Carnegie Mellon University)
- **Award:** $649,999 over 3 years

A major challenge for Earth system models in predicting the response of the terrestrial ecosystem to climate change is to accurately reflect the biogeochemical processes governing the stability of soil organic matter (SOM). Iron oxide has been suggested as an important mineral phase regulating the SOM stability, and there is an extensive body of literature exploring SOM-mediated microbial reduction of iron oxide. However, the fate of iron-bound SOM in the redox reactions and its response to warming processes, have not been systematically investigated. This has resulted in a significant knowledge gap for predicting the stability of organic carbon (OC) under global climate change. We therefore propose to identify the critical biogeochemical reactions governing the degradation of iron-bound OC and to link the persistence of OC to redox cycles of iron. The central hypothesis is that the degradation rate of soil OC (SOC) during aerobic-anaerobic redox cycles is governed by the amount of iron-bound OC, and the ability of microbial communities to utilize OC as an energy source and electron shuttle for iron reduction that in turn stimulates reductive release of iron-bound OC. In this project, we will integrate micro-scale characterizations, bench scale studies, and mesocosm experiments in the following two major tasks:

1) Analyze coupled iron reduction and OC degradation during aerobic-anaerobic cycles: we will investigate the release and degradation of iron-bound OC during aerobic-anaerobic redox cycles. The development of microbial communities in the reaction systems will be studied using molecular tools.

2) Quantify degradation of OC in forest and tundra soil samples during aerobic-anaerobic cycles: we will analyze the coupled release and degradation of iron-bound OC in bench scale studies using soils collected from a variety of U.S. forest and tundra soils.

We will link the degradation of SOC during aerobic-anaerobic cycles to the reductive release of iron-bound OC and the ability of OC to both fuel and shuttle electrons for iron oxide reduction. Our results will provide data required for development of numerical models that explicitly depict the stability of OC associated with iron oxides. In turn, this project will help the DOE understand responses of terrestrial biogeochemical processes to climate change and improve process-based quantitative representation of carbon stabilization in Earth system models.

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/.

Further information on SBR objectives along with a listing of past and current funding opportunities discussed in this document, is available at http://science.energy.gov/ber/research/cesd/subsurface-biogeochemical-research/

Further information on RGCM objectives along with a listing of past and current funding opportunities discussed in this document, is available at http://science.energy.gov/ber/research/cesd/regional-and-global-modeling/.

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