Belowground Biogeochemistry Science Focus Area

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Developing predictive understanding of belowground biogeochemistry and improving terrestrial ecosystem modeling capabilities

The world's soils and their cycling of carbon and nutrients play a critical role in ecosystem productivity, maintaining atmospheric carbon dioxide (CO_2) concentrations and terrestrial carbon sinks. Carbon cycling involves microbial, plant, and abiotic processes responsible for soil organic matter (SOM) chemistry, transformation, and loss, which are also intimately coupled to nitrogen availability to plants and microbes.

Accurate understanding of these soil biogeochemical processes is critical for predicting ecosystem responses to changes in climate, but current gaps in understanding of soil-plant-microbe interactions make estimates of ecosystem-climate feedbacks highly uncertain. Moreover, subsoils contain twice as much carbon as surface horizons globally, yet their contribution to soil-atmosphere feedbacks has largely been ignored.

To address these challenges, the Environmental System Science (ESS) program of the Department of Energy's (DOE) Biological and Environmental Research (BER) program is supporting the Belowground Biogeochemistry Science Focus Area (SFA) led by Lawrence Berkeley National Laboratory.

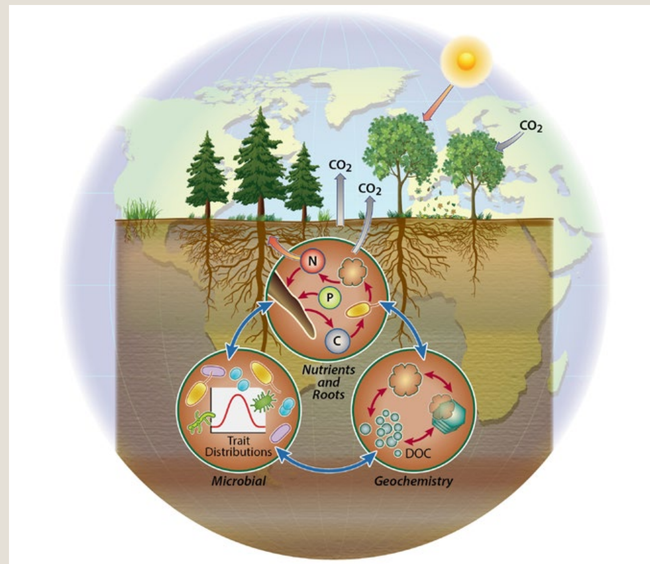
This SFA aims to develop a predictive understanding of belowground biogeochemistry in the soil-plant-microbe-climate system, with an emphasis on the whole soil profile, and to improve capabilities for modeling terrestrial ecosystems and their role in the climate and Earth systems. To accomplish these goals, this SFA integrates a team of experts in biogeochemistry and ecosystem ecology, microbial ecology and genomics, geochemistry, and ecosystem modeling.

A critical part of the integrated model-experiment research is developing robust, generalizable tools for understanding and predicting soil biogeochemical responses to global change across spatial and temporal scales. This research will also inform other fundamental and DOE-mission relevant questions regarding the future role of soils in bioenergy, nutrient provision, and the water cycle.

Key Science Questions

The overarching challenge driving the Belowground Biogeochemistry SFA is developing predictive understanding of the role of soils in terrestrial feedbacks to atmospheric and climate changes over the next 100 years. Specific science questions to address this challenge include:

- How do biotic and abiotic processes and properties interact to control soil organic matter (SOM) cycling and its response to environmental change over depth?
- How do SOM cycling and coupled soil-microbe-plant biogeochemistry respond to warming over time and space?
- What is the potential for whole-profile soil organic carbon loss and change in ecosystem-carbon balance due to environmental changes over the twenty-first century?
- What is the best way to represent a generalized set of principles governing soil carbon dynamics and nutrient cycling to improve ecosystem models for Earth system analysis?



Belowground Biogeochemical Cycles. *The plant-soil-microbe system. Key: CO_2, carbon dioxide; N, nitrogen; P, phosphorus; C, carbon; DOC, dissolved organic carbon.*

Research Approach

Scientists are employing a coordinated set of field and laboratory experiments, combined with advanced analytical techniques and process-rich modeling, to characterize controls on organic matter cycling and how ecosystem responses to climate change are shaped by interactions between soils, plants, microbes, and nutrient cycling. Model uncertainties guide the experimental design and observational priorities, while empirical results and theory inform model development to address the challenges of spatial and temporal scaling. Research focuses on the whole-soil profile, and whole-soil warming experiments serve as an integrating platform to study belowground biotic and abiotic processes governing ecosystem biogeochemical cycles.

Research Tasks and Recent Results

SFA research is organized into five main tasks: (1) ecosystem experiments and biogeochemistry, (2) microbial responses and feedbacks, (3) organic geochemical controls on SOM, (4) soil biogeochemistry and carbon cycle modeling, and (5) impacts of wildfire and warming on soil biogeochemistry and forest regeneration.

Task 1 creates and maintains long-term, whole-soil warming experiments in the field and measures emergent ecosystem responses to warming, such as soil CO_2 respiration and nutrient availability. Results are showing that soil temperature has a large effect on

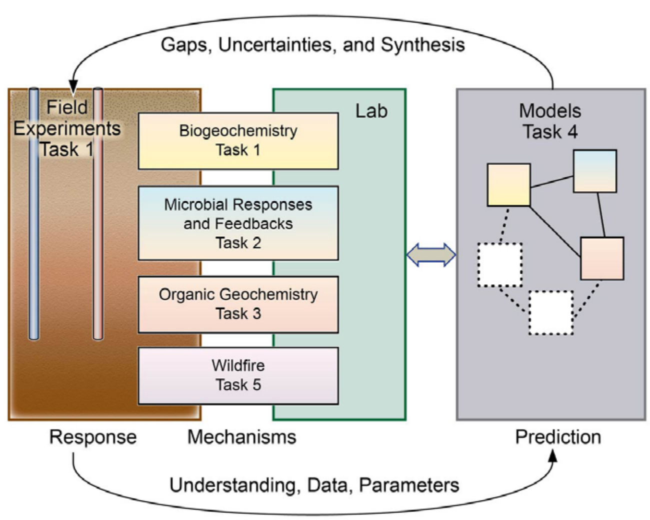
Blodgett Forest Whole-Soil Warming. *In the central experiment of the Belowground Biogeochemistry SFA, the whole profile of a forest soil is warmed by 4°C year-round to look at decomposition pathways, microbial processes, and long-term stabilization. Scientists measure the effect of warming on carbon losses and microbial activity* **(left)**. *The SFA is starting a comparison whole-soil warming experiment in a grassland, where the effect of soil warming on plant processes and nitrogen cycling will be studied* **(right).**

Model Integration

The Belowground Biogeochemistry SFA employs process-rich, fine-scale models as well as representations for global applications. This approach enables the exploration of mechanisms at the scale of observations and the extraction of efficient process representation for integration into DOE's Energy Exascale Earth System Model (E3SM) Land Model (ELM). The long-term vision is a modeling capability that can be applied across temporal and spatial scales, providing insights into transient results such as soil response to warming and other manipulations and the effect of altered nutrient cycling on plant carbon inputs to soil. The SFA will test the models across a wide range of soil types, chemistries, plant inputs, climate regimes, and manipulations.

decomposition and SOM composition at all depths. Warming by 4°C increased respiration by about 35%, a temperature sensitivity higher than that predicted by most Earth system models. To study temporal responses, the SFA added additional experimental plots seven years after the original started.

Task 2 determines how soil microbial traits, physiology, and community properties vary over the soil profile and in response to environmental changes and investigates how they affect SOM mineralization rates, pathways, and products. SFA research indicates that warming results in a significant decline in microbial biomass in subsoils. Although warming stimulated microbial growth, subsoil microbes had lower carbon use efficiency, which contributed to greater carbon loss and decreasing biomass.



SFA Research Organization. *The Belowground Biogeochemistry SFA is organized into five main tasks with field and laboratory experiments tightly coupled with modeling to enable predictive understanding of belowground processes governing terrestrial biogeochemical cycles.*

Task 3 examines how SOM chemical composition and the interactions of organic molecules with minerals and metals influence SOM availability to soil microbial transformations or leaching. In recent results, mineral stabilization explains long-term persistence of even the most labile substrates. Decomposition of labile substrates was effectively stopped when they were sorbed to mineral surfaces.

Task 4 improves modeling of decomposition, nitrogen cycling, and plant growth. New process representations, including for microbial activity, nutrient limitations, and the effects of moisture and temperature on organo-mineral interactions, are being incorporated into DOE's Energy Exascale Earth System Model (E3SM) Land Model (ELM). This is important for benchmarking model performance against perturbation experiments and for exploring ecosystem responses to warming at site to global scales. An international data synthesis activity co-led by the SFA will use results from similar warming experiments around the world to build understanding and evaluate models, thereby improving confidence in assessments of ecosystem carbon storage under twenty-first century climate.

Task 5 explores the impacts of wildfire and soil warming on soil biogeochemistry and forest regeneration. The SFA is developing a novel rapid-response approach to experimental warming and plans to deploy it postfire in a proof-of-concept experiment focused on belowground biogeochemistry and tree seedling establishment in a mid-elevation Sierra Nevada Forest.

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