Environmental System Science Program

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Advancing foundational ecological and hydro-biogeochemical process knowledge across scales to predictively understand Earth's terrestrial, watershed, and coastal systems

The terrestrial environment—from bedrock to atmosphere—encompasses dynamic, diverse environmental systems that are interacting with a changing climate. Terrestrial, watershed, and coastal systems face increased temperatures, more extreme weather events, and rising levels of atmospheric carbon dioxide (CO_2) as well as expanding urbanization and other environmental disturbances. Predicting how these systems might respond to such stresses requires understanding their complex biological, chemical, ecological, hydrological, and physical processes as well as their interactions with one another and with human activities from molecular to global scales. While scientific understanding of these processes continues to improve, persistent knowledge gaps limit the ability of scientists to understand and predict the response of environmental systems to a changing environment.

To address these gaps, the U.S. Department of Energy's (DOE) Environmental System Science (ESS) program supports research to improve foundational scientific understanding of physical, chemical, and biological processes of environmental systems and their interactions, with a particular focus on understudied regions and system interfaces. Within DOE's Biological and Environmental Research (BER) program, ESS integrates observations with process research to advance ecosystem models that enable predictions of ecological, hydrological, and biogeochemical processes affecting terrestrial environments. As these systems evolve, ESS is advancing a richer understanding of their processes, functions, and feedbacks and developing improved scale-aware capabilities to predict their behavior. These foundational insights and capabilities will enable DOE and the nation to plan and develop energy infrastructure, better manage natural resources, steward the environment, and identify equitable solutions to Earth's most vulnerable communities.

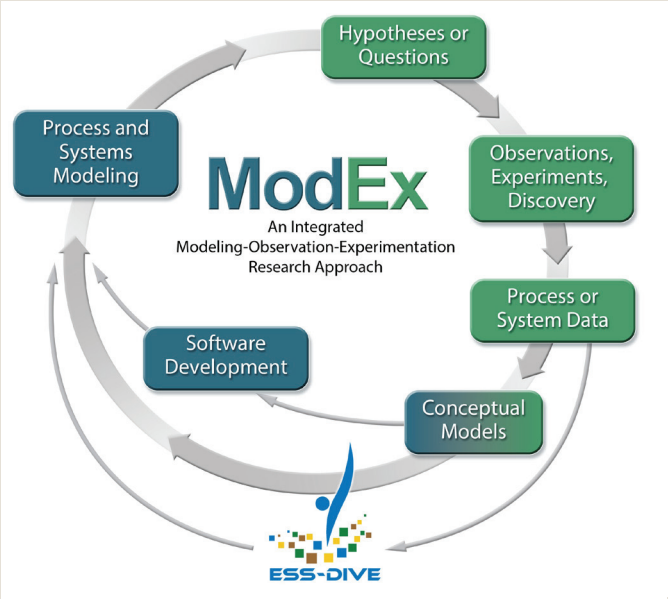
Collaborating Across Environmental Science Domains. Terrestrial, watershed, and coastal systems sciences make up the three domains of BER's Environmental System Science program. [Courtesy Lawrence Berkeley National Laboratory (top left), Pacific Northwest National Laboratory (top right, bottom left)]

Research Approach

ESS supports research across a wide range of disciplines, such as microbial ecology, plant ecology, biogeochemistry, hydrology, -omics, and model development to investigate inherent and emergent properties of changes to Earth and environmental systems across different spatial and temporal scales. This multifaceted research—which includes observation, experimentation, field manipulation, and simulation—produces new knowledge that enhances understanding of the current functioning and future dynamics of terrestrial processes.

ESS Research Emphasis Areas

- Understanding the role of disturbances in ecosystem processes and functions.
- Gaining a mechanistic understanding of how belowground processes affect carbon flux and key elemental cycling and their coupled feedbacks to Earth and environmental systems.
- Expanding emphasis on understudied Arctic, boreal, tropical, and coastal systems and the role of their critical biogeochemical stocks and fluxes in a changing environment.
- Addressing key ecological and biogeochemical gaps in the understanding of terrestrial-aquatic interfaces at local to global scales.
- Quantifying and predicting the hydrological mechanisms driving fine-scale biogeochemical processes and water exchange in coupled surface-subsurface systems.
- Quantifying how biological behavior, feedbacks, and abiotic-biotic interactions leading to molecular transformations influence the mobility, transformation, and fate of key nutrients.
- Identifying, quantifying, and predicting watershed responses to natural and anthropogenic perturbations and shifts to new states; translating the resulting predictive understanding across scales to underpin environmental and energy strategies.
- Analyzing long-term ecosystem observational records to inform and evaluate models.
- Supporting large-scale coupled modeling and process research projects and large-scale, long-term ecosystem manipulations to understand environmental variability and response to change.
- Exploring unrecognized or innovative research topics.



The ModEx Approach: Integrating Modeling, Observations, and Experiments. Within the ModEx framework, researchers combine process research (including observations, experiments, and measurements performed in the field or laboratory) with modeling activities that simulate these same processes in an iterative fashion.

The ESS program supports a diverse research portfolio, with investments in small-scale, near-term university-led projects and large-scale, long-term national laboratory-led projects, such as Science Focus Areas (SFAs) and the Next-Generation Ecosystem Experiments (NGEEs). The longer-term national laboratory projects often include collaborative opportunities with universities, DOE user facilities, and other national laboratories.

Terrestrial ecosystem, watershed, and coastal processes exhibit considerable uncertainties in their functions, feedbacks, and dynamics and thus are difficult to represent in models. The ESS program seeks to improve model representations of these processes to more accurately project how they will respond to a changing climate and environment. Using integrated process research, the coupled modeling-experimental (ModEx) approach championed by ESS examines complex environmental system properties and generates open-source and community models that incorporate state-of-the-science knowledge about critical systems. The resulting improved models can then be used to guide field- and laboratory-based research and inform future responses to complex energy and environmental challenges.

Key Environmental Science Domains

Interdisciplinary, multidomain science is a hallmark of ESS research, which is comprised of terrestrial, watershed, and coastal systems science. The program also has a growing focus on ecological and watershed processes in urban systems.

Terrestrial Ecology

Understanding ecosystem functions is essential for improving the ability to predictively model terrestrial ecosystems and their feedbacks to the Earth system. To achieve this understanding, ESS terrestrial ecology research focuses on ecosystems and ecological processes that are globally or regionally significant, sensitive to climate and environmental change, and insufficiently understood or inadequately represented in models. Through hypothesis-driven observations, experimental manipulations, and large-scale, long-term field studies, this research area aims to explain the mechanisms and processes controlling primary production and carbon cycling, biogeochemistry, and the impacts of disturbance on terrestrial ecosystems. Insights into these areas will improve model projections and better inform the development of resilient U.S. energy strategies.

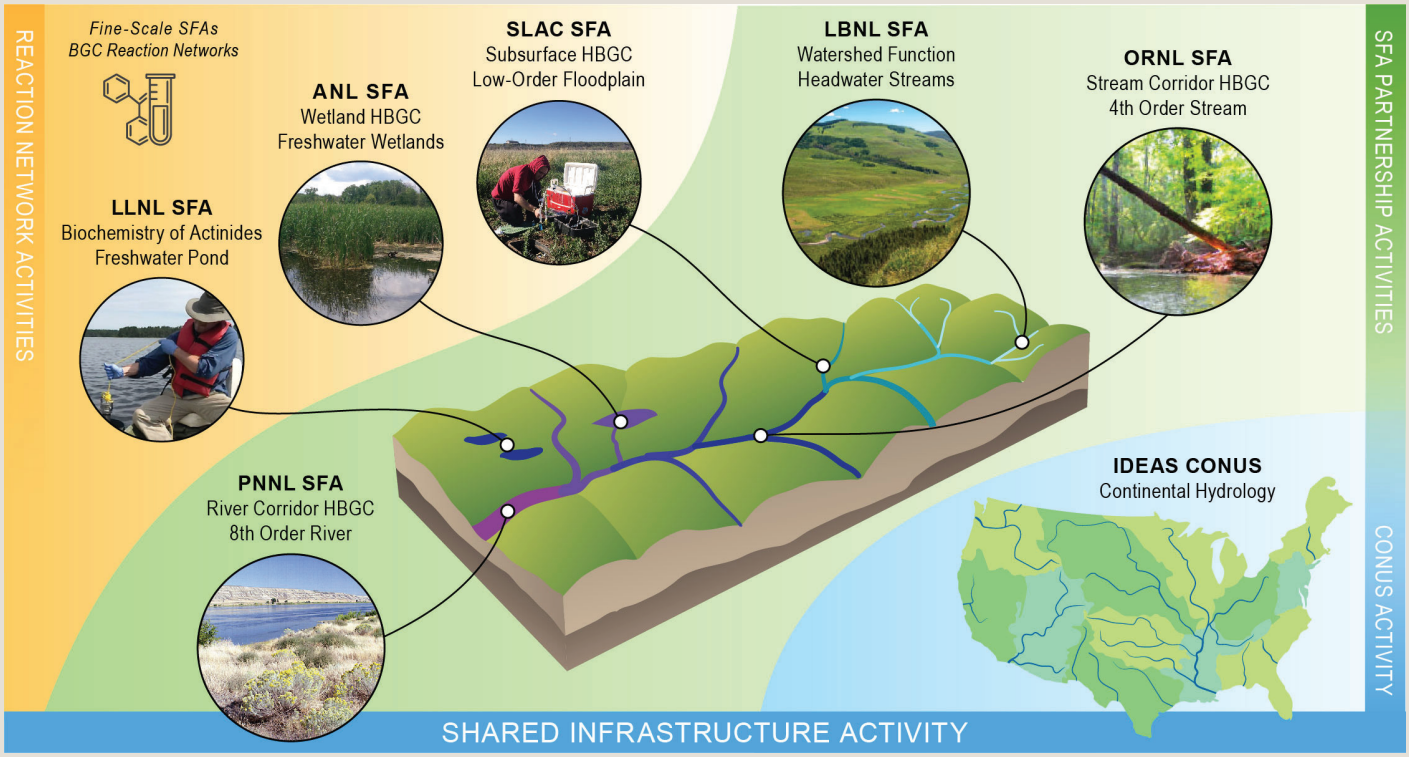
Current and future ESS investments in terrestrial ecology research include BER's innovative concept for coupling models with experimental and observational campaigns, such as the NGEE projects in the Arctic and Tropics. ESS supports additional investments in large-scale ecosystem manipulations in the Spruce and Peatland Responses Under Changing Environments (SPRUCE) project in northern Minnesota.

Watershed Sciences

Watershed sciences research seeks to advance a predictive understanding of how watersheds function as integrated hydro-biogeochemical systems and how they respond to disturbances, such as changes in water recharge, availability, and quantity; nutrient loading; land use; and vegetative cover. Using a systems approach, ESS researchers probe the multiscale structure and functioning of watersheds and capture this understanding in mechanistic models that represent both the complexities of the terrestrial subsurface and ecohydrological interactions with surface waterbodies and vegetation at multiple spatial and temporal scales. These models provide the basis for testing hypotheses, guiding experimental

Aerial View of SPRUCE Project Site. SPRUCE research is conducted on an 8.1-hectare peatland of the Marcell Experimental Forest in northern Minnesota. Ten open-topped aboveground enclosures simulate various levels of warming and CO_2 exposure. The remote landscape includes a mix of uplands, bogs, fens, lakes, and streams. [Courtesy Oak Ridge National Laboratory]

Enhancing the Science of Coastal Zones. The COMPASS project will help dramatically improve predictive understanding of coastal systems, including their response to short- and long-term changes. [Courtesy Pacific Northwest National Laboratory]



Watershed Science Testbeds. ESS supports a network of watershed testbeds within the contiguous United States where national laboratory, university, and interagency partners work in interdisciplinary teams to advance watershed system science for energy. ESS watershed science funds six national laboratory–led Science Focus Areas that represent a network of complementary testbeds for tackling a range of DOE energy and environmental challenges. [Courtesy Los Alamos National Laboratory]

design, integrating scientific knowledge on multiple environmental systems into a common framework, and translating this information to support informed decision-making and policies.

Coastal Systems

Terrestrial-aquatic interfaces and transitions along coastlines and shorelines are dynamic areas of great complexity and uncertainty regarding their response to a wide range of natural and anthropogenic influences, including sea level rise, hydrologic intensification, land-use and land-cover change, and urbanization. Through holistic, hypothesis-driven studies, ESS coastal research seeks to address key uncertainties in the fundamental and predictive understanding of integrated coastal environmental systems and to improve their representation in Earth system models. Understanding the physical, biological, and ecological dynamics of coastal environments will enable evaluation of their response, feedback, and vulnerability to future climate, environmental, and human pressures, as well as the implications for intersecting environmental and societal interests.

A major ESS investment in coastal science is the Coastal Observations, Mechanisms, and Predictions Across Systems and Scales (COMPASS)–Field, Measurements, and Experiments program that focuses on field studies and associated process and ecosystem modeling of two coastal interfaces in western Lake Erie and the Chesapeake Bay.

Urban Integrated Field Laboratories

Urban regions encompass interdependent environmental, ecological, infrastructure, and human components. These densely populated areas have high degrees of heterogeneity and are often located in climate-sensitive locations. Fundamental systems-level research aimed at identifying the foundational principles of dynamic physical, biogeochemical, and human processes and interactions is necessary to (1) improve the science underpinning understanding of climate and environmental predictability in urban systems and (2) address major gaps in scientific understanding of their two-way interactions with the climate system. This knowledge is essential to inform equitable climate and energy solutions that can strengthen community-scale resilience across urban landscapes.

Supporting Equitable Climate Science. Urban Integrated Field Laboratories (IFLs) focus on understanding complex urban environments and their impacts on disadvantaged communities. For example, the Southeast Texas Urban IFL represents the climate adaptation needs, population diversity and vulnerability, and ecological richness characterizing many urban centers along the Gulf Coast.

The Urban Integrated Field Laboratories (IFLs)—an initiative spanning programs in BER's Earth and Environmental Systems Sciences Division (EESSD)—are comprehensive projects including field

ESS Community Resources

ESS supports a number of community-based data and modeling resources.

Data Resources

- **ESS-DIVE: Environmental System Science Data Infrastructure for a Virtual Ecosystem** — A data repository for Earth and environmental science data enabling contributors to archive and share data with supporting information in consistent formats that can be cited and tracked. Users, in turn, can efficiently find and obtain data that are easier to interpret, integrate, and analyze.
- **AmeriFlux Network** — A community of sites spanning different climates and ecosystems across the Americas that gathers and shares long-term carbon, water, and energy flux measurements and metadata. AmeriFlux ensures the availability of these continuous, long-term ecosystem measurements (which are necessary to build effective models and multisite syntheses), while maximizing insights through robust, site-specific, independent research programs.
- **Worldwide Hydrobiogeochemical Observation Network for Dynamic River Systems (WHONDRS)** — A consortium of researchers and other interested parties that aims to understand the hydrologic, biogeochemical, and microbial impacts of sustained high-frequency water-level fluctuations in river corridors from local to global scales.

Modeling Resources

- **IDEAS: Interoperable Design of Extreme-scale Application Software** — An extreme-scale scientific software development ecosystem composed of high-quality, reusable computational science and engineering software components and libraries; a collection of best practices, processes, and tools; and substantial outreach mechanisms for promoting and disseminating productivity improvements.
- **ExaSheds**—A synergy between data-driven machine learning approaches and process-based, hydro-biogeochemical high-performance computing simulations that advances the understanding of watershed systems and improves predictive capabilities for watershed and river-basin function.
- **Energy Exascale Earth System Model (E3SM)** — An ongoing, state-of-the-science Earth system modeling, simulation, and prediction project that optimizes the use of DOE laboratory resources to meet the science needs of the nation and the mission needs of DOE.

observations, data assimilation, modeling, and model-data fusion to inform equitable solutions. Covering a variety of urban regions with distinct characteristics, Urban IFLs in Baltimore, Chicago, the Texas Gulf Coast, and the Southwest Urban Corridor face different environmental and climate hazards and have diverse, disadvantaged populations. Urban IFLs include significant participation from local and minority serving institutions and provide new opportunities to inspire, train, and support leading scientists from a variety of organizations who have an appreciation for the global climate and energy challenges of the 21st century.

Research Philosophies

Open and Collaborative Research

The ESS program's open-science and open-data philosophy advances priority research areas by supporting a coordinated mix of investments, including university-led projects, NGEEs, national laboratory–led SFAs, and observation networks that represent short-term projects, decadal experiments, and long-term studies.

ESS collaborates closely with other research programs within BER's EESSD and Biological Systems Science Division (BSSD). Within EESSD, ESS partners with the Earth and Environmental System Modeling program to inform modeling capabilities, including the Energy Exascale Earth System Model (E3SM); the Atmospheric System Research program for understanding the dynamics of land-atmosphere coupling; and the Data Management program's data curation, archiving, and federation activities. Environmental microbiology research within ESS is coordinated with BSSD's Environmental Microbiome program. Beyond BER, ESS activities also are coordinated with research sponsored by other DOE research programs, user facilities, and federal agencies.

Safe, Equitable, Inclusive, and Accessible Research

Belonging, accessibility, justice, equity, diversity, and inclusion are foundational to advancing the U.S. research and scientific innovation enterprise. In line with DOE Office of Science-wide initiatives, BER and ESS are committed to supporting these values in work, research, and funding environments that prioritize mutual respect and personal integrity for people of all backgrounds, as well as the physical and emotional safety of all participants as demonstrated by the Office of Science Statement of Commitment. The program is also focused on pursuing new avenues of engagement with individuals and institutions historically underrepresented in science, technology, engineering, and mathematics fields and careers. Recognizing the need to remove barriers to participation, BER and ESS are involved in new Office of Science initiatives to support broader participation in research and training. These include the Reaching a New Energy Sciences Workforce (RENEW) initiative designed to provide training, mentoring, and activities targeted to build capacity in climate and environmental science-relevant programs at historically black colleges and universities and minority-serving institutions. Additionally, to make science a more welcoming enterprise, the Office of Science will require all applicants to submit a Promoting Inclusive and Equitable Research (PIER) Plan as part of funding proposals beginning in FY 2023. PIER Plans describe the activities and strategies that investigators will incorporate to promote diversity, equity, inclusion, and accessibility in their research projects.

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