DOE/SC-2024

Lessons Learned from Ecosystem-Scale Experimental Field Studies

Workshop Report

U.S. DEPARTMENT of ENERGY | Office of Science
Biological and Environmental Research Program

Lessons Learned from Ecosystem-Scale Experimental Field Studies

January 14, 16, and 17, 2025

Convened by
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About BER

The Biological and Environmental Research (BER) program supports transformative science and scientific user facilities examining complex biological, Earth, and environmental systems. BER research seeks to understand the fundamental biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecules and genomes at the smallest scales to ecosystems and the Earth system at the largest scales. This research—conducted at U.S. Department of Energy national laboratories and research institutions across the country—is contributing to a future of energy and infrastructure security, independence, and prosperity for all Americans.

Front Cover Image Credits

Clockwise, from top: **(1)** Oak Ridge National Laboratory (ORNL) scientists use 3D modeling to assess long-term flooding hazards and population risks. [Courtesy ORNL] **(2)** A researcher installs a snow pillow at the Rocky Mountain Biological Laboratory in Gothic, Colo. [Courtesy Emilio Mateo, Aspen Global Change Institute] **(3)** An Earth system model shows a representation of the coastal interface [Courtesy Coastal Observations, Mechanisms, and Predictions Across Systems and Scales—Field, Measurements, and Experiments. Reprinted with permission under a Creative Commons Attribution 4.0 International License from Ward, N. D., et al. 2020. "Representing the Function and Sensitivity of Coastal Interfaces in Earth System Models," *Nature Communications* **11**, 2458. DOI:10.1038/s41467-020-16236-2] **(4)** An aerial view shows Spruce and Peatland Responses Under Changing Environments 26-foot octagonal enclosures in the Marcell Experimental Forest north of Grand Rapids, Mich. [Courtesy ORNL] **(5)** A scientist samples soil in Blodgett Forest near Georgetown, Calif. [Courtesy Lawrence Berkeley National Laboratory]

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Preface and Acknowledgments

Ecosystems are composed of complex biotic and abiotic components interacting in time and space through biogeochemical cycles, energy flows, and ecological dynamics. The vast majority of ecosystem studies are relatively short term (less than 10 years, typically less than 3 years) and modest in spatial scale. Experiments that are long term (e.g., 10 years or longer) and large in scale (e.g., spatial extent or complexity) are relatively rare. However, they are necessary to achieve a holistic, integrated, and scale-aware understanding of naturally variable systems and are crucial to developing and testing predictive models. Long-term studies also provide greater statistical power and more nuanced insights than short-term studies into the factors that give rise to temporal variability. Moreover, large-scale ecosystem- or watershed-level studies provide necessary insight to better understand dynamic biogeochemical interactions by accounting for spatial heterogeneities and transitional gradients that studies with more restricted footprints often overlook. Together, long-term and large-scale experiments enable greater understanding of ecosystem function and simultaneously facilitate accurate process representation in site-specific, regional, and global models.

Despite their advantages and documented successes, several challenges can limit the realization and success of long-term and large-scale studies. For example, funding uncertainty and high costs can constrain study continuity and outcomes, while lack of planning for robust data management and the evolution of project science and teams over time can hamper effectiveness and impact.

The research community is poised to use lessons learned from past and ongoing ecosystem manipulation studies to inform the design and implementation of future experiments. In January 2025, the U.S. Department of Energy's (DOE) Lessons Learned from Ecosystem-Scale Experimental Field Studies workshop brought together academic and national laboratory community leaders who have been integral to the planning, implementation, maintenance, and successful production of datasets and publications of several long-term and large-scale ecological research projects. The workshop aimed to understand what contributed to the successes and challenges of these studies and to provide an ecosystem experiment primer that defines key attributes the broader community should consider when designing and launching future ecosystem studies.

DOE is a recognized leader in long-term, large-scale, and manipulative ecological experiments, such as Scientific Focus Areas, the Free-Air CO_2 Enrichment (FACE) experiment, the Spruce and Peatland Responses Under Changing Environments (SPRUCE) studies, and the Next-Generation Ecosystem Experiments (NGEEs) in the Arctic and Tropics (see Appendix C: Represented Projects, p. 63). As such, this

Lessons Learned from Ecosystem-Scale Experimental Field Studies Workshop Goals:

- **Understand the factors contributing to the successes and challenges of previous studies**
- **Provide an ecosystem experiment primer that defines key attributes to consider when designing and launching future ecosystem studies**

workshop presented a unique opportunity to reflect on the lessons learned from designing and operating Big Science projects. Learning from these examples will ensure future research efforts can prevent unnecessary mid-course corrections that can negatively impact predictive understanding, data management, safety, outreach efforts, scientific community and societal support, and budgets. In using past lessons to inform future endeavors, DOE and other funding agencies can ensure the highest scientific return on investment. Ultimately, useful insights from this workshop will enable the research community to strategically prepare its next high-impact, large-scale, long-term research efforts.

The Biological and Environmental Research (BER) program at DOE appreciates the tireless efforts, vision, and leadership of workshop organizers Elizabeth Borer, Aimée Classen, Paul Hanson, and Tim Scheibe.

Appreciation and acknowledgment are extended to all the workshop attendees, co-writers, and contributors who vigorously participated in workshop discussions and generously gave their time and ideas to this important activity.

This report would not be possible without the workshop writing teams and chapter leads who diligently worked with participants to draft this document: Vanessa Bailey, Ben Bond-Lamberty, Elizabeth Borer, Aimée Classen, Amy Goldman, Paul Hanson, Colleen Iversen, Charlie Koven, Nate McDowell, Alistair Rogers, Tim Scheibe, Ben Sulman, and Peter Thornton. Finally, BER acknowledges the outstanding efforts of the staff from Oak Ridge National Laboratory's Biological and Environmental Research Information System, who helped create the workshop visuals and edited and prepared this report for publication.

Executive Summary

Efforts to understand and predict ecosystem responses to environmental change require long-term, large-scale, spatially representative experiments and observations that capture natural variability, test predictive models, and generate transferable knowledge. Such studies are indispensable for unraveling the complexities of terrestrial ecosystems and their responses to disturbances and evolving environmental conditions, while generating the data necessary for developing mechanistic models and predictive tools that inform decision-making processes.

Having a rich history of designing and executing large-scale ecosystem experiments, the U.S. Department of Energy's Environmental System Science program convened a workshop in January 2025 that brought together leaders in the field to distill critical lessons from decades of experience in large-scale experiments. The workshop aimed to (1) provide an ecosystem experiment primer for best practices, thus ensuring a high scientific return on investment for funding agencies, and (2) offer a robust framework for the design and management of future research initiatives.

This report synthesizes insights and experiences from workshop participants and is structured to capture the entire research life cycle, from goal setting and design to operations, adaptive management, team dynamics, collaborations, and the often overlooked aspect of decommissioning. By synthesizing decision-making and lessons learned across diverse research approaches, the report aims to provide a template of essential factors to consider when designing successful long-term, large-scale ecosystem experiments.

Core Lessons Learned: A Research Life Cycle Approach

Design and Planning (Chapter 2)

The design and planning phase of experiments is critical for all ecological domains; however, it is particularly crucial for experiments that are large, complex, longer in duration, and expensive.

The importance of the design and planning phase is true whether an experiment is a single-site manipulation, multisite comparison, or a broadly distributed network. Experimental designs benefit from using theory, models, and observations to generate hypotheses around which the project revolves. Site selection criteria are driven first by scientific needs, but experiments must also address financial and logistical constraints. Common hurdles include site access and permitting, infrastructure availability, safety and security concerns, and pretreatment variability. Engagement with landowners and local communities should occur during this phase to address relevant logistical challenges and maximize co-benefits, which help to maintain an experiment's long-term sustainability.

Experimental design should consider multiple factors to maximize the study's long-term impact.

The statistical design must not only be as rigorous as possible across all disciplines and scales in the study but also stay within budget and balance plot size with replication. Regardless of whether the study is a field manipulation or a distributed network, planning for flexibility in goals, treatments, measurements, and collaborators provides a strategic advantage and can support the long-term sustainability of the project. Experiments frequently experience unexpected challenges, such as infrastructure damage and funding or personnel changes. Projects can generate unexpected discoveries that lead to new research ideas, and new collaborators can become engaged in the project. Each of these mid-stream changes will be smoother if an initial flexible design has considered how to maximize benefits from such changes during the design phase. Best practices to benefit from unanticipated opportunities include designing experiments with the ability to test alternative hypotheses and reserving space for future measurements or treatments.

Data management strategies and within-project data-sharing mechanisms should be identified before the project starts to ensure integration across team members, disciplines, and collaborators.

Consideration of comprehensive and standardized data management, metadata, and accessibility during and after project completion is essential. Similarly, protocols for storing code and model output should be developed to maximize efficiency in the transfer of model output to team members (see also Ch. 4: Project Management and Productive Teams, p. 29).

Data–Model Integration (Chapter 3)

Data–model integration should inform experimental design; enable more integrated, impactful, and robust conclusions; and provide an improved capacity for scaling understanding.

Model needs and results should guide data collection throughout the project while experimental results should inform model development, calibration, and testing. Projects with successful data–model integration are characterized by clear communication, mutual understanding between disciplines, and experimental designs that address both empirical and modeling uncertainties. Proactive and consistent effort is necessary to prevent communication barriers between disciplines. Developing a shared vocabulary, conceptual framework, and research goals can take time but will aid communication and project effectiveness in the long run. Transparent, consistently formatted, and timely shared data, metadata, and model code throughout the project accelerates experimental insights, model development, and benchmarking. High-quality data, clear documentation, standardized formats, and public release of data and model code ensure long-term impact on the broader community and utility for society.

Project and Data Management (Chapter 4)

Effective project management should be guided by the project's scientific questions and a shared vision.

Successful large-scale and long-term scientific endeavors, particularly in field-based environmental system science, depend on robust, adaptive project management and the cultivation of productive and collaborative teams. Effective management requires generating a shared set of questions, developing an experimental design that supports those questions, and setting clear deliverables. Balancing project control with flexibility needed for scientific evolution and adaptation to unforeseen events builds resilience (see also Ch. 2: Identifying Science Questions, Design Methodologies, and Site Selection, p. 11). Collaborative leadership and the development of leadership skills across career levels within the team eliminates the risk of single points of failure and helps build an enduring project leadership.

Effective data management is essential for collaborative research and long-term impact.

Data management is more straightforward when projects establish data-sharing protocols early and invest in data hygiene—basic quality assurance, high-quality metadata, and model-friendly formats—that support integration and interpretation across disciplinary boundaries. Automated data processing, quality assurance tools, and clear metadata standards reduce barriers to continuous data–model integration. Project data should aim to be "AI-ready," enabling easy combination of multiple datasets for data-driven analyses and synthesis studies. Implementing FAIR (Findable, Accessible, Interoperable, and Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles supports clear communication, trust, and standardized workflows.

Productive teams have clear and effective communication, clear expectations, and a sense of belonging.

Best practices include regular structured meetings, shared collaborative platforms, and periodic in-person gatherings that enable relationship building. Leadership should prioritize team building and communication, conflict resolution, and a positive collaborative atmosphere to create and maintain a cohesive project culture. Open and regular communication among all interested parties—including project personnel, sponsors, and site access providers—enhances transparency and efficiency while building trust. Clear protocols for physical and psychological safety and a code of conduct protect team members and safeguard the project's integrity. Finally, strong mentoring at all career stages enhances both individual performance and team cohesion.

External Collaborations and Engagement (Chapter 5)

Modern ecosystem science encompasses the core research team but also includes distributed collaborators, local communities, land managers, and other interested parties.

A shared culture of trust and mutual benefit maximizes the productivity and benefits of external collaborations. Successful external engagement follows three guiding principles: (1) co-developing research goals and methods, (2) focusing on mutual benefit, and (3) listening with an open mindset. Project teams should develop and distribute clear governance plans, data-sharing protocols, and expectations for collaboration. Such engagement strategies increase impact and responsiveness to project and collaborator needs.

Scientific advisory boards extend project impact, provide resilience during challenging periods, and create pathways for integrating expertise and knowledge into research outcomes.

Well-balanced scientific advisory boards complement team expertise, providing independent evaluation and facilitating connections across agencies, industries, and communities. These boards offer diverse perspectives and create pathways for knowledge integration, enhancing project impact and resilience.

Decommissioning (Chapter 6)

Responsible project completion is crucial for long-term community relationships and scientific credibility.

Historically, little attention has been given to the conclusion of research projects, leading to ecotrash—infrastructure and equipment left behind after scientific projects—that can harm the environment, endanger individuals, damage equipment, and undermine the reputation of scientific teams and their funding bodies. Conscious planning, dedicated budgeting for decommissioning, explicit land-use permits with clear closeout plans, and robust accountability mechanisms from funding agencies should be implemented. Project leadership should ensure that decommissioned sites are safe and hold themselves, their team members, and their institutions accountable. Beyond physical site restoration, other activities should include scientific communication with stakeholders; site documentation; and archiving environmental samples, data, and code. Carefully planned decommissioning preserves the long-term scientific value of the research, ensuring its accessibility and reusability for future inquiry.

Success Indicators

Overall, a successful ecosystem-scale experiment has several key aspects that drive success at each stage of a study, including its design, implementation, operations, and completion. The report recommends the following key success indicators for ecosystem-scale experiments:

Design Phase

- Scientific goals are recognized as meaningful and important by the scientific community.
- Research life cycle planning is conducted carefully with flexibility built into the design at the outset and planned through decommissioning.

Implementation Phase

- Management is flexible, collaborative, communicates effectively, and develops capacity for current and future leadership, enabling nimble responses to changing circumstances and unexpected events.
- Projects address core scientific goals but also embrace thoughtfully planned high-risk, high-reward endeavors.

Operations Phase

- Leadership makes careful and intentional investments in all project participants and across the collaborative team, from students and technicians to senior investigators.
- Projects build a supportive culture where physical and psychological safety are protected for all team members.
- Clear and open communication is established, allowing external partners and communities to effectively engage with the project.
- Research findings are communicated to the entire team, interested parties, the public, and funding sponsors.

Completion Phase

- Papers, data, knowledge, and collaborative teams produced through the project represent significant advances that persist beyond the project.
- Decommissioning minimizes negative long-term impacts to communities and the environment.
- The intellectual impact and legacy of these projects—and the well-trained project teams—extend beyond papers and datasets, fostering new collaborations and leading to follow-on research led by the next generation of scientists.

1 Introduction

1.1 Long-Term and Large-Scale Ecosystem Experiments: Past, Present, and Future

Large-scale and long-term studies provide society with the quantitative and generalizable results that are needed to understand the complexity of terrestrial ecosystems and their responses to disturbance and changing environmental conditions. Studies that generate long-term data across continental and global scales allow researchers to identify alternative system states driven by combinations of weather and longer-term forcing, as well as other environmental, edaphic, and Earth system drivers. When the range or variance of independent variables to be modeled exceeds what can be observed naturally or through archived data, experimental approaches involving manipulations of environmental conditions (e.g., temperature, water levels, and atmospheric composition) or ecosystem structure become critical for addressing important and societally relevant research questions. Experimental manipulations also allow for causality testing in ways that observational approaches do not. Finally, long-term studies can uncover rare phenomena that shorter studies miss (Viblanc and Muller-Landau 2025). Ultimately, through the collective work of large-scale, long-term experiments, which span diverse research platforms of various sizes and durations, the scientific community can better understand complex multivariate interactions within ecosystems.

The DOE Biological and Environmental Research (BER) program is a recognized leader in designing and operating long-term, large-scale, manipulative ecological experiments and observational networks needed to address important research questions using fundamental science principles and approaches. For decades, DOE has invested considerable resources into studying ecosystems to better understand the impacts and feedbacks of energy production and determine legacy effects from Manhattan Project activities. Additionally, in a shift from many past environmental research studies that focused on identifying and defining the statistical significance of variables that drive environmental stresses, more recent DOE-sponsored environmental research aims to represent complex ecological interactions in high-resolution models that improve predictive understanding and future projections. This new research direction requires robust quantitative field data to parameterize, analyze, and improve predictive capabilities used for human, environmental, and national security decision-making. Environmental manipulation studies, such as DOE's Free-Air CO_2 Enrichment (FACE) studies, Throughfall Displacement Experiments (TDEs), and the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment, have provided unparalleled insight into the responses and feedbacks for hypothesized future environmental conditions not extractable from past human experience.

Another key advance in DOE ecosystem-scale experiments over the last 20 years is the coupled model-observation-experiment, or ModEx, paradigm (see Fig. 1.1, p. 2), a central research approach of DOE's Environmental System Science (ESS) program. The ModEx paradigm, used in notable experiments such as FACE and the Next-Generation Ecosystem Experiments (NGEEs) in the Arctic and Tropics, has transformed understanding of biomes in state-of-the-art models. This research approach redefines experimental design by coupling targeted field data collection that informs and is informed by the development and refinement of model structures, such as those found in the Energy Exascale Earth System Model (E3SM). Additionally, network-based science approaches, such as those used by AmeriFlux, continue to provide data and

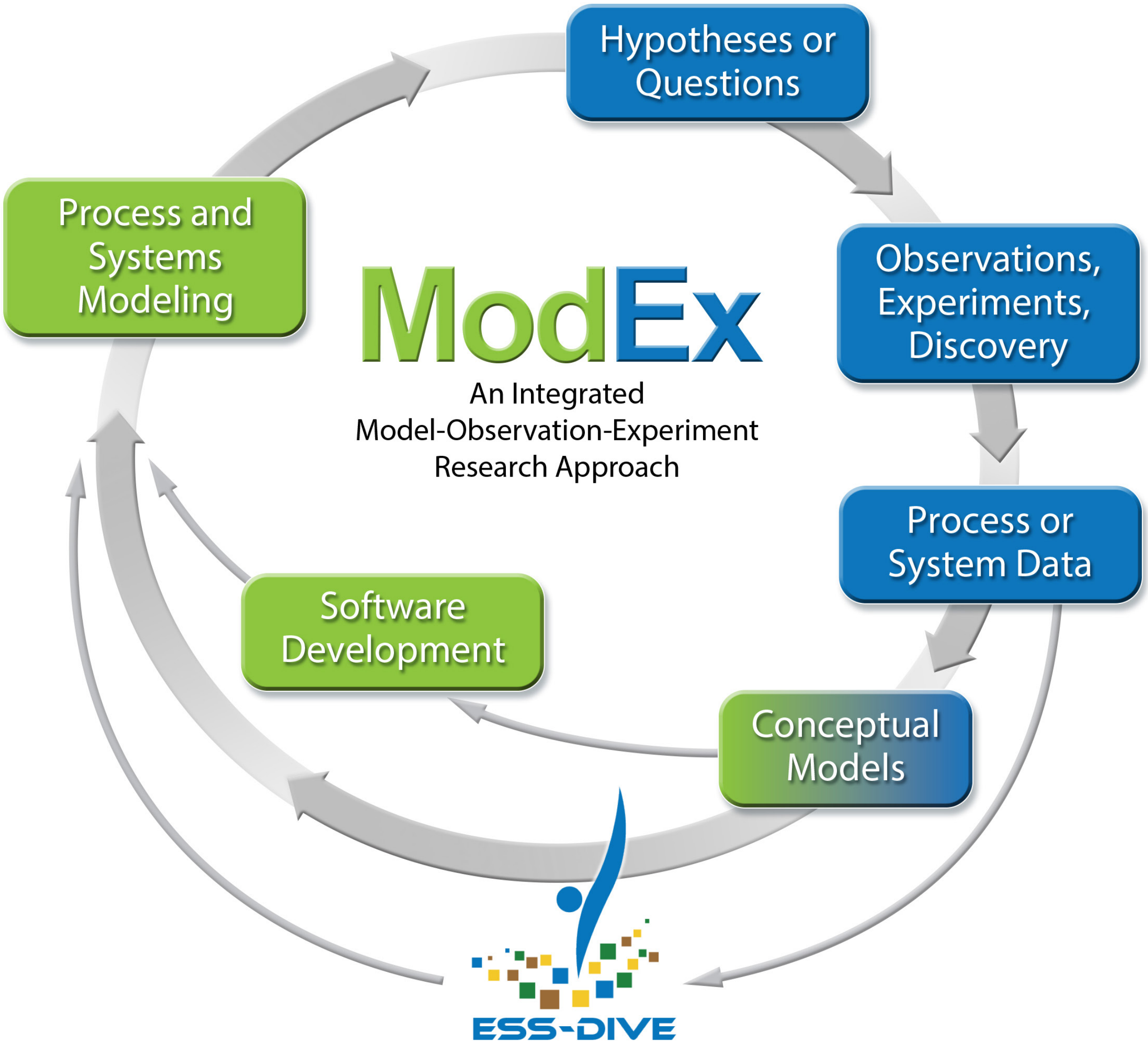

Fig. 1.1. Integrated Model–Observation–Experiment (ModEx) Paradigm. The BER program's ModEx approach integrates process research, which involves observations, experiments, and measurements performed in the field or laboratory, with modeling research, which simulates these same processes. This integrated loop ensures that models incorporate state-of-the-science knowledge about critical systems, and the resulting improved models can be used to guide field and laboratory research to inform future decisions.

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improved understanding of the changing world across continental gradients.

In addition to transforming experimental design, many long-term and large-scale ecological experiments, including DOE-sponsored studies, have significantly advanced understanding of Earth system dynamics. Along with DOE's large flagship experiments (e.g., FACE, NGEEs, TDE, and SPRUCE), other examples include the Survival-Mortality Experiment (SUMO), the Tropical Responses to Altered Climate Experiment (TRACE), and the Watershed Function Science

Focus Area (SFA). While these experiments focus on a limited set of prioritized environmental variables, their results contribute valuable insights for developing mechanistic models of ecosystem functions, which are necessary for addressing spatial, temporal, and environmental variability.

Additionally, several long-term, large-scale observational and experimental networks—supported by DOE, other federal agencies, and the research community—have been established both nationally and globally. Examples include the AmeriFlux network, the National Ecological Observatory Network (NEON), the Long-Term Ecological Research (LTER) Network, Long-Term Agricultural Research (LTAR), Critical Zone Observatories (CZOs), the Molecular Observation Network (MONet), the Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (WHONDRS), and research coordination networks such as the Nutrient Network (NutNet) and the U.S. Geological Survey's National Streamgaging Network (NSN). Additional examples include the Forest Global Earth Observatory (ForestGEO), the Disturbance and Recovery Across Grasslands Network (DRAGNet), Warming and (species) Removal in Mountains (WaRM), the Detrital Input and Removal Treatments (DIRT) network, as well as other large-scale regional efforts, such as NASA's Arctic-Boreal Vulnerability Experiment (ABoVE), and the Large-Scale Biosphere-Atmosphere Experiment (LBA).

Collectively, the full catalog of federally funded research initiatives provides the global research community with essential data on biogeochemical and ecological processes, covering spatial scales from individual plots (cm^2 to m^2) to subregional areas (km^2). By combining and summarizing data from multiple sites over many years, researchers can derive insights and a predictive understanding across regional to continental scales, contributing to a broader understanding of ecosystems globally. For more information about site locations, project duration, study approaches, funding types, and infrastructure needs of some of the research projects that were represented at the workshop, see "Studying Ecosystems at Scale," p. 4.

Important scientific questions remain for researchers to address with large-scale and long-term studies, but challenges persist for DOE and other agencies to fund the most effective and efficient future research with finite resources. Key challenges include: (1) reliance on short-term funding cycles, typically made up of 3-year grants; (2) limitations of single-investigator or small-team awards; (3) requirements for near-term (less than 3 to 5 years) documented accomplishments necessary for career advancement to scientists in many institutions and agencies; (4) various mixes of funded and unfunded collaborations; (5) gaps in data collection; (6) disruptions due to funding interruptions, geopolitics, and pandemics; and (7) lack of standardization in methodologies.

1.2 Workshop Goals and Structure

Recognizing the importance and value of previous investments in these large-scale research initiatives, DOE and the broader federal and research community convened a 3-day virtual workshop to consider key challenges and extract wisdom from past research activities. Held on January 14, 16, and 17, 2025, the Lessons Learned from Ecosystem-Scale Experimental Field Studies workshop provided a space to discuss, evaluate, and understand the factors that contributed to the successes and challenges of past research. The meeting's goal was to distill key characteristics for consideration when designing and launching future collaborative, large-scale ecosystem studies.

Recent feedback from the NGEE Arctic Science Advisory Board included a clear recommendation that DOE should share the "magic recipe" for how the NGEE program was designed so that other collaborative, large-scale and long-term studies could adopt best practices and avoid known challenges. This retrospective exercise served as the foundation of the workshop and allowed BER to identify and characterize insights from these experiments, particularly when they succeeded or even when they failed

Continued on p. 6

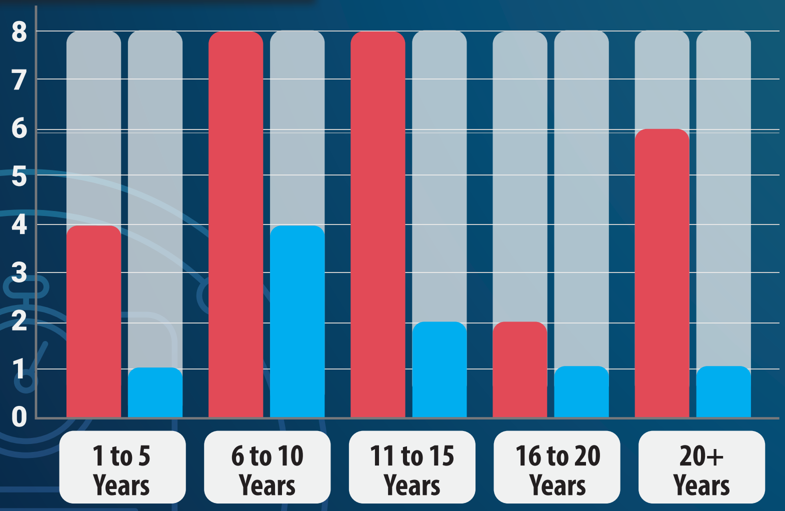
STUDYING ECOSYSTEMS AT SCALE

Projects represented[1] at the Lessons Learned from Ecosystem-Scale Experimental Field Studies workshop varied in design, location, duration, funding, approaches, and infrastructure, but all shared in their efforts to advance understanding of ecosystem functions and improve process representation in models. The different research approaches of these projects, along with their successes and challenges across the research life cycle, provide valuable lessons that can inform the future of large-scale, long-term ecosystem experiments.

PROJECT LOCATION

Ecosystem-scale projects represented at the workshop span the globe, advancing critical knowledge of Earth's ecosystems. To see this information visualized in ArcGIS, visit https://arcg.is/0GraX51.

PROJECT DURATION



Active and completed projects demonstrate the sustained effort required for ecosystem-scale experimental studies. Projects vary in length, but together they provide insights across short- and long-term timescales.

🟥 Active Projects

🟦 Concluded Projects

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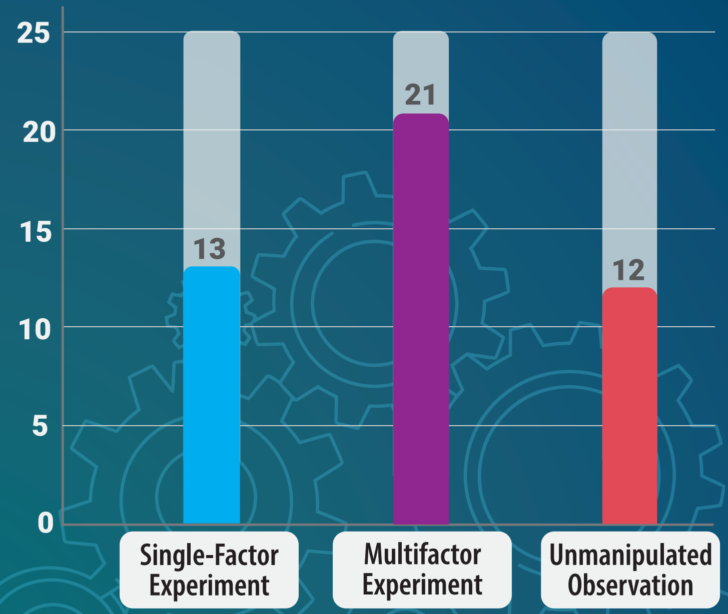
[1] Data for this infographic was collected for 37 projects represented at the workshop. Participating projects are marked with an asterisk in Appendix C: Represented Projects, p. 63.

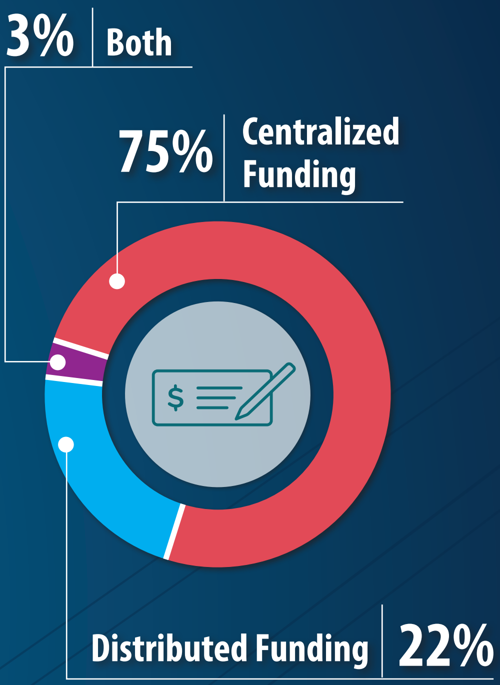
STUDY APPROACH

Research strategies vary, with projects employing experimental manipulations or observational designs to assess ecosystem processes.



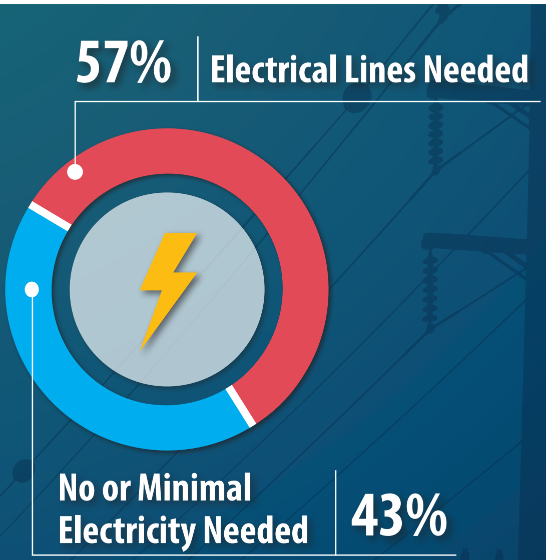
FUNDING TYPE

Most projects (75%) represented at the workshop were supported by centralized funding from a single government agency (e.g., DOE, the National Science Foundation, or the National Institutes of Health), 22% by distributed funding from multiple stakeholders, and 3% by both.

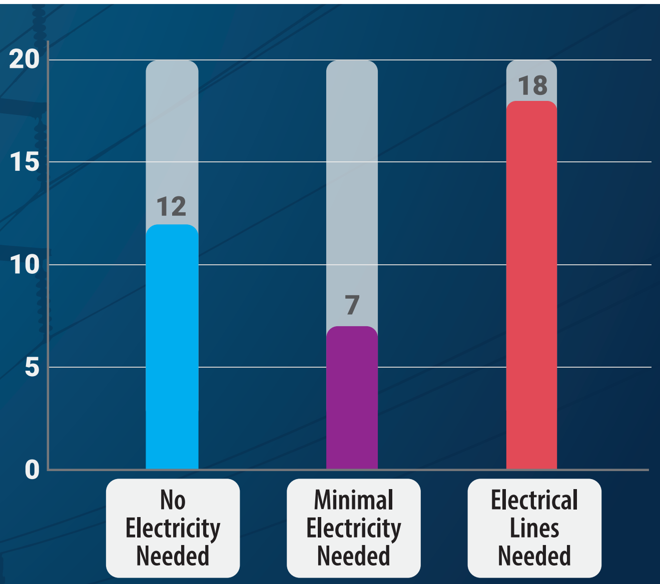


INFRASTRUCTURE NEEDS

Infrastructure needs, such as electricity requirements, differ considerably across projects, reflecting varying goals and objectives. Some require no electricity, and others need extensive systems to power treatments, measure response variables, and operate instrumentation.



Electrical power required to measure response variables and operate instrumentation



Electrical power required for treatments to achieve their original design goals. While each experiment is unique and driven by specific scientific questions and approaches, they share common design principles, such as operations, team management, and engagement.

Careful reflection on elements that drive successes and challenges is essential to understand what worked, what teams could do differently, and, in some cases, how to avoid unanticipated pitfalls. Missed opportunities and successes experienced by past projects must be assessed to best position next-generation studies to ensure the highest return on available investments.

The virtual workshop was organized into five breakout sessions: (1) science questions, design, methods, and site selection; (2) management and operations and collaborations and data sharing; (3) interested party engagement and pitfalls; (4) decommissioning and wrap-up; and (5) what hasn't been discussed? Each breakout session included a questionnaire, summary report-out, then a panel discussion, followed by several smaller breakout discussions with 10 or fewer people. These smaller groups gave participants a better chance to engage in virtual discussions. After each breakout discussion, group representatives presented briefings to the larger group. A final session at the end of the workshop on January 17 mapped out the next steps for creating this report (see Appendix A: Workshop Agenda, p. 59).

To achieve workshop goals, organizers brought together 41 leaders from the research community—18 from DOE national laboratories, 21 from universities, and two from other organizations (see Appendix B: Workshop Participants, p. 62). Many of these participants have stewarded the experiments and networks mentioned in the previous section and have thus been integral to the development, operation, analysis, and completion of several major long-term, large-scale ecological research projects. Many were also scientific leaders of the first-generation experimental and observational networks or participants in transformational ecological studies (see Appendix C: Represented Projects, p. 63). With a number of these leaders having retired or considering retirement, this workshop was a unique and timely opportunity to capture their knowledge and insights. As such, participants were tasked with reflecting on their experiences and the lessons they learned with the goal of advancing scientific rigor and creativity, improving and refining methodology, avoiding past mistakes, and identifying where new efforts can be most impactful in driving knowledge forward. This workshop report seeks to highlight these critically important experiences, insights, and takeaways to produce a template for future researchers to consider when new research initiatives are planned.

1.3 Workshop Questionnaire and Contributors

Workshop organizers developed a pre-workshop questionnaire (see Appendix D: Pre-Workshop Questionnaire, p. 92) that was sent to numerous scientists with leadership roles in (primarily) DOE, NASA, and large-scale ecosystem research projects funded by the National Science Foundation (NSF). Forty-four respondents provided 64 individual responses to the questionnaire (some respondents answered in regard to multiple experiments). Most respondents were principal investigators or in a leading role for the experiment discussed in their questionnaire responses. Most projects represented in the questionnaire fell into three categories: warming projects (12 responses), NGEE projects (11 responses), and distributed networks (6 responses). However, a variety of other projects were also represented, including CZOs, FACE, LTER, AmeriFlux, precipitation and drought studies, SFAs, and biological research stations. Ten projects categorized themselves as other. Project start dates ranged from 1971 to 2024. Over 40 participants (60%) indicated that their projects are still ongoing. Primary funding sources for projects came from DOE (59%) and NSF (31%), but a few received funding from the U.S. Department of Agriculture, NASA, or other sources. Many projects established processes for data management and sharing, although the timing varied among projects. Over 85% of projects are still synthesizing data.

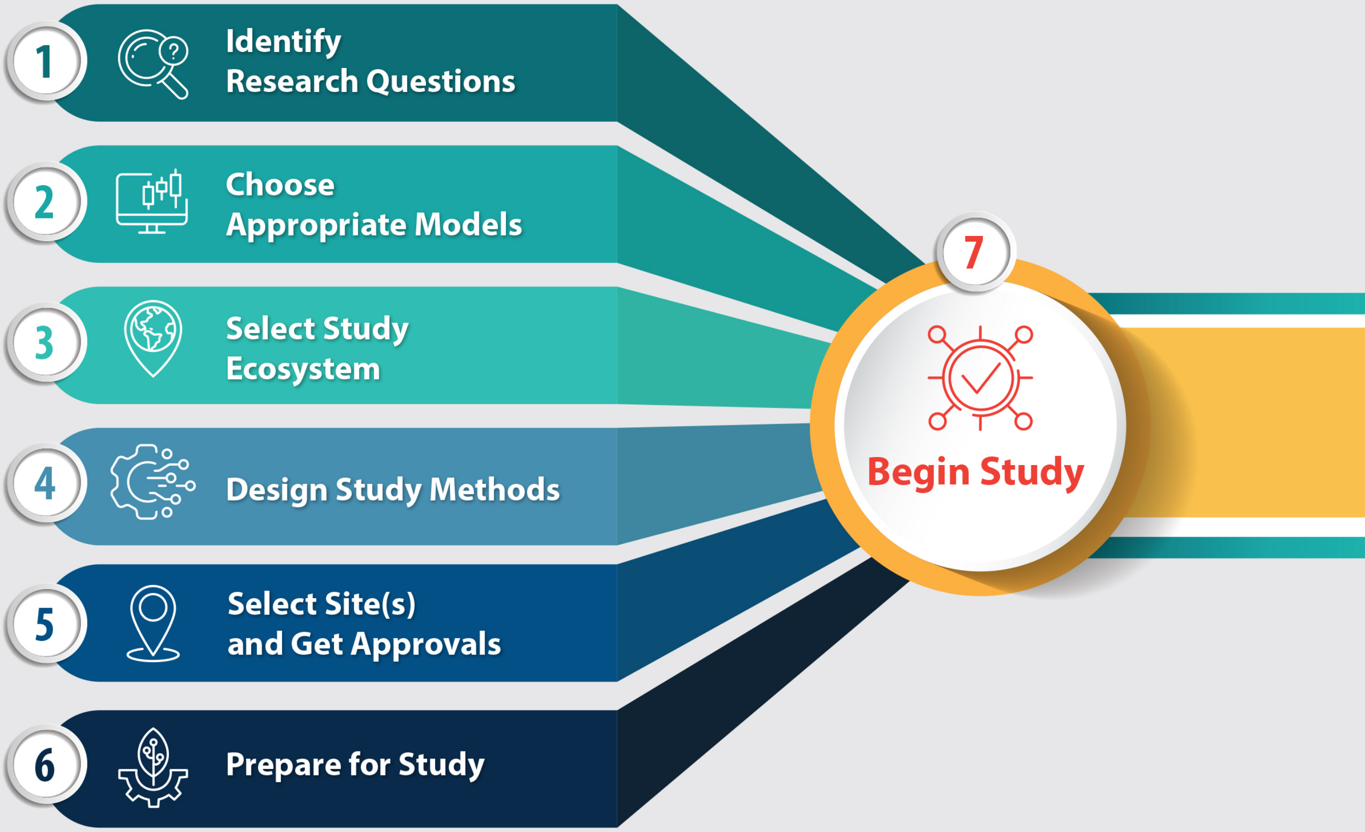
The questionnaire also sought to determine whether the ultimate goals of the project were met. Fifty-three percent of responses indicated that the goals were met. The other 47% indicated that some questions remain unanswered, the study generated additional questions, or work is still ongoing. The rest of the questionnaire was split into seven topics: (1) study design and methodology; (2) site selection, study management, and operations; (3) collaborations and data sharing; (4) interested party engagement; (5) risks, constraints, and opportunities; (6) decommissioning and wrap-up; and (7) an "Other" category to discern whether the questionnaire missed any critical topics. The perspectives and lessons learned extracted from this questionnaire, as well as insights from workshop participants, are included in this report and provide a broad representation of experiences.

1.4 Report Structure

Organized around key components of the research life cycle, this report reflects on past studies, evaluates management practices, and synthesizes best practices from project successes and challenges across a range of research approaches to inform and improve planning for next-generation experiments (see Research Life Cycle of Ecosystem-Scale Experimental Field Studies, p. 8). The report begins with a consideration of study goals, scope, design, and data–model integration (Chapters 2 and 3), then tackles considerations and approaches to operations and adaptive management of experiments, teams, and collaborations (Chapters 4 and 5). The final research life cycle topic on decommissioning (Chapter 6) is one that frequently receives less attention than it should. The report ends with a summary of lessons learned across a wide range of studies and key criteria for considerations that may support successful design of future long-term, large-scale ecosystem experiments (Chapter 7). Ultimately, this report will help inform future BER experiments and long-term SFAs, including successor experiments that will evolve from the NGEE and SPRUCE studies. It will also be useful to the broader global ecological research community and enable safe, sustainable, and transformative research for decades to come.

Research Life Cycle of Ecosystem-Scale Experimental Field Studies

The research life cycle of long-term, large-scale ecosystem projects involves multiple phases from experimental design (steps 1-4) to site preparation (steps 5-6), which includes funding and approvals, prototyping, constructing site infrastructure, contracting for ongoing services, and evaluating safety and environmental concerns. This extensive preparation is followed by collecting and archiving response data (step 7), publishing results (step 8), improving models (step 9), and finally decommissioning a completed study (step 10). Knowledge gained through data and modeling analysis ultimately leads to the identification of new research questions and hypothesis development (step 11). Successful ecosystem-scale research experiments recognize that these different phases of the research life cycle must be considered from a project's inception to inform and improve planning and design, integrate data and models, develop management practices, foster external collaborations and engagement, and create decommissioning strategies.



1 **Identify Research Questions**

2 **Choose Appropriate Models**

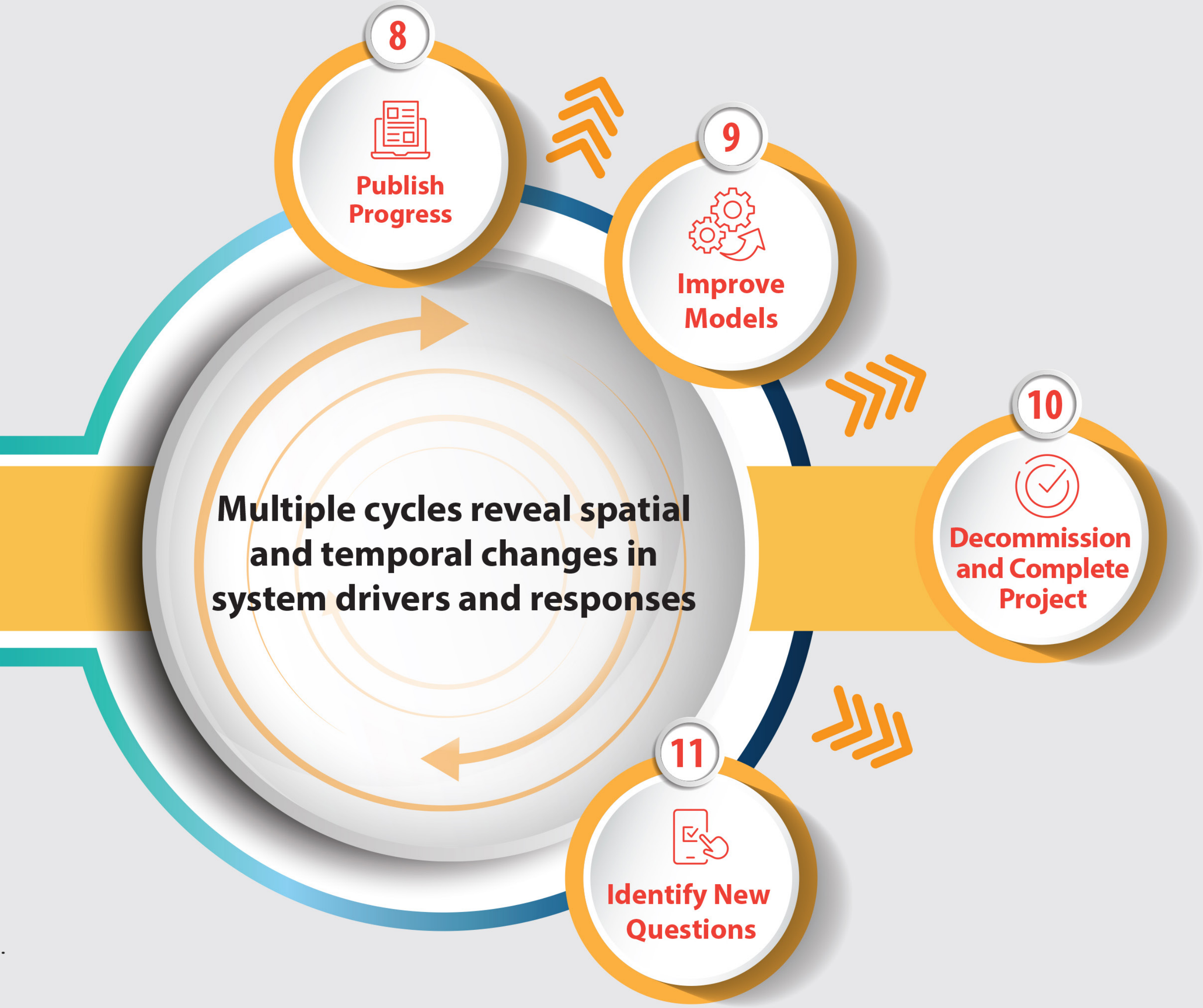
3 **Select Study Ecosystem**

4 **Design Study Methods**

5 **Select Site(s) and Get Approvals**

6 **Prepare for Study**

7 **Begin Study**


8
Publish Progress
9
Improve Models
10
Decommission and Complete Project
11
Identify New Questions
Multiple cycles reveal spatial and temporal changes in system drivers and responses

Chapter 2

Identifying Science Questions, Design Methodologies, and Site Selection

Key Takeaways

- Ecosystem-scale experiments generate new transferable knowledge by offering access to sufficiently large or replicable plots that can support changes and additional treatments.
- Long-term ecological experiments should be supported by finer-scale experiments in both the laboratory and the field to optimize scientific discovery. Complementary modeling experiments and simulations can inform experimental design and guide adaptive decisions.
- Statistical design and data management should be planned before any work begins to ensure robust comparisons and support model–experiment integration within the project and across the community.
- Site selection must balance financial and logistical constraints with managing pretreatment variability and targeting science questions. Engaging with local communities before and throughout experiments is essential.

2 Identifying Science Questions, Design Methodologies, and Site Selection

Bold, manipulative ecosystem experiments and observational studies can accelerate discovery of ecological interactions and responses. Effective experimental design is a key element to the success of these experiments and observations. The design phase offers numerous opportunities—identifying science questions, determining design methodologies, and selecting appropriate sites—for researchers to not only set up their experiments for success but to also plan for potential challenges that may occur throughout the course of the research life cycle. This chapter outlines challenges, considerations, and opportunities identified by workshop participants and questionnaire respondents to guide the future design of interdisciplinary field experiments for ecosystem science.

2.1 Considerations and Challenges in Experimental Design for Large-Scale, Long-Term Experiments

Workshop participants and questionnaire respondents had considerable experience designing and implementing ecosystem studies. Consistent with DOE BER's history of successful ecosystem experiments, they found that effective design strategies emerge through collaboration between computational scientists focused on enhancing predictive understanding and empirical scientists focused on recognizing, manipulating, and measuring system processes (Kyker-Snowman et al. 2022). They also noted that replicating treatments, taking baseline measurements (aboveground and belowground), and archiving samples are key to a site and experiment's utility beyond the immediate needs of investigators. In addition, site selections for large studies must consider access controls (both permissions and physical access) and have features that make it a good model system, representing key processes and properties of other landscapes, regions, or ecological settings. Furthermore, without clear, testable hypotheses and statistical forethought, an experiment can be limited by oversampling, inadequate controls, and lack of appropriately archived samples. The sections that follow elaborate further on these and other lessons about experimental design.

Identifying Science Questions

Long-term studies and experiments endure when the motivating questions are carefully considered, experimental designs are robust and adaptable, funding is secured for continued site maintenance, preparations are in place for continued access to project sites, and a clear communication and outreach plan is developed. The design of ecosystem experiments and observations is intimately linked to the scale and scope of scientific questions that the research seeks to address. These questions typically involve complex interactions and feedbacks between environmental variability and ecosystems, and large-scale, long-term studies provide crucial datasets and fundamental process knowledge to build and test predictive models (see Fig. 2.1, p. 13). Additionally, science questions developed for extensive or large-scale research investments must focus on critical areas of uncertainty in ecosystem forms and functions and aim to provide the research community with new knowledge that can be used as an information source for policymakers and society.

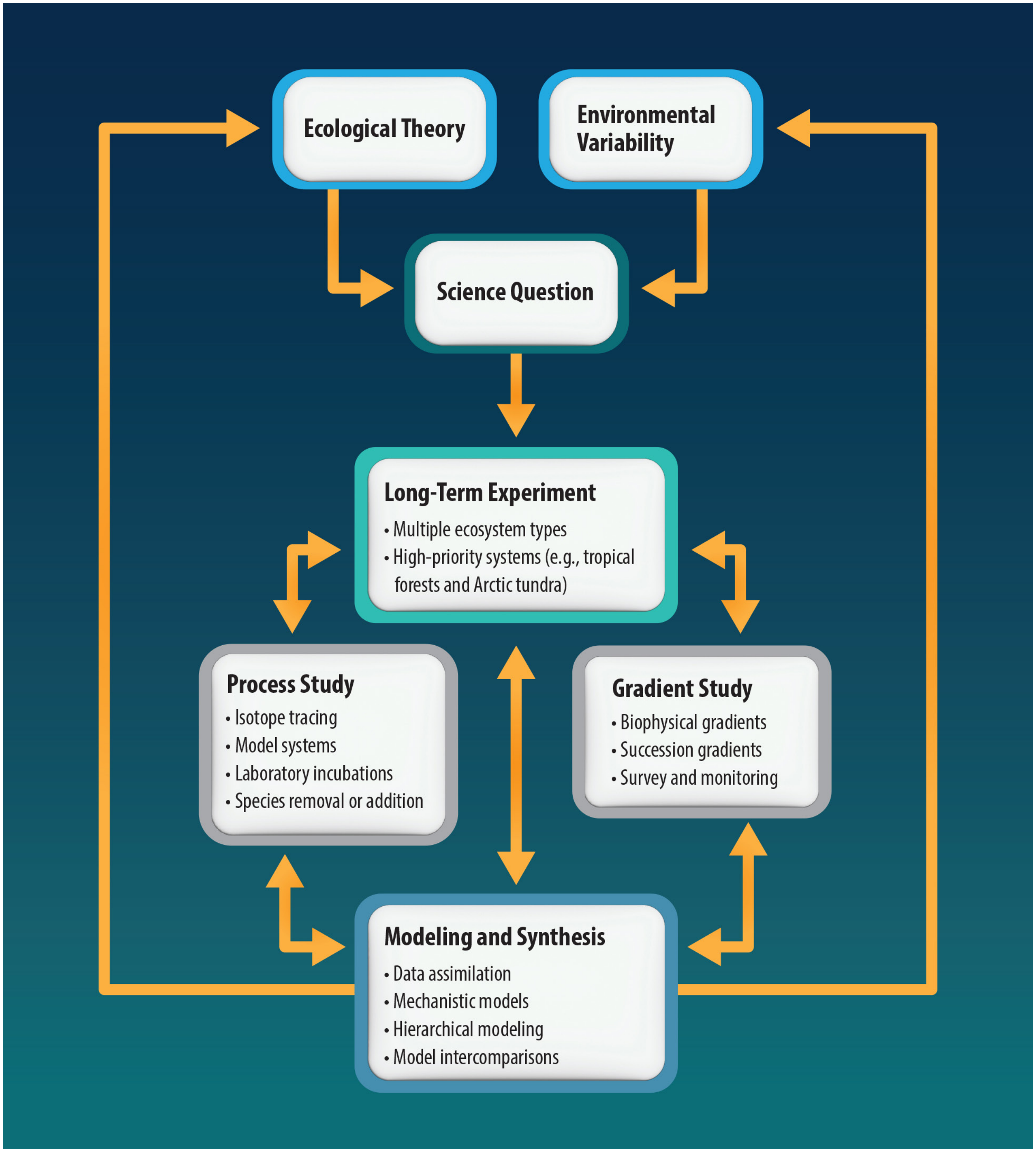


Fig. 2.1. Coordinated Approaches To Studying Large-Scale, Long-Term Ecosystems. Long-term ecological experiments begin with defining questions that are informed by ecological theory and environmental variability. The resulting experiments are supported by process studies and observations along environmental and ecological gradients. Model uncertainty helps to prioritize selection of study location (e.g., understudied or underrepresented systems). Modeling can also synthesize multiple data sources for improved predictions and advance ecological understanding. Each of these elements works independently and collectively to optimize scientific discovery. [Adapted from Luo, Y., et al. 2011. "Coordinated Approaches To Quantify Long-Term Ecosystem Dynamics in Response to Global Change," *Global Change Biology* **17**(2), 843–54. DOI:10.1111/j.1365-2486.2010.02265.x]

Planning for Unexpected Challenges and Opportunities

Effective experimental design for addressing critical research questions requires adaptability, rigorous planning, and strong collaboration. Indeed, the most effective experimental designs prioritize hypothesis-driven research with clearly defined response variables while remaining adaptable to future needs and unexpected events or findings. Flexibility is also a key ingredient to successful experimental design. Large-scale experiments can be designed from the outset to accommodate unforeseen logistical challenges, unpredictable natural conditions, unanticipated treatment responses, emergent opportunities, or alternative hypotheses.

Flexible designs such as adopting a regression approach to treatments (e.g., multiple temperatures or nutrient supply rates), ensuring sufficient replication, reserving plot space for new treatments, and using a nimble distributed approach with variable sites can enhance a team's ability to respond to unforeseen issues. For example, BER's Coastal Observations, Mechanisms, and Predictions Across Systems and Scales—Field, Measurements, and Experiments (COMPASS-FME) project leads the Terrestrial Ecosystem Manipulation to Probe the Effects of Storm Treatments (TEMPEST; Hopple et al. 2023; see Fig. 2.2, this page). The TEMPEST study, established in 2020, is a long-term experiment seeking to understand the effects of freshwater flooding and seawater intrusion on upland forests and to facilitate deeper explorations into the early mechanisms of ecosystem transition. When forest stress occurred more rapidly than predicted in the third year of the 10-year research design, the project's adaptive experimental design allowed BER researchers to pause the manipulative treatments for a season.

Additional recommendations for anticipating unplanned challenges and opportunities during the design phase include:

- Carefully considering the balance between plot size and replication level to provide the necessary statistical power helps projects achieve robust results (via replication) while maintaining project longevity (via sufficient plot size for long-term sampling).
- Generating model simulations in tandem with collecting and analyzing pretreatment data can efficiently guide design to avoid or prepare for unexpected observations.
- Combining intensively sampled sites with distributed networks of less intensively instrumented or sampled sites can support scalability, generalizability, and cost-effectiveness.
- Leveraging existing sites, such as the Long-Term Ecological Research (LTER) Network, Long-Term Agricultural Research (LTAR), Long-Term Research in Environmental Biology (LTREB), National Ecological Observatory Network (NEON), and Critical Zone Observatories (CZOs), along with field stations, infrastructure, networks, and datasets can reduce costs, build collaboration,

Fig. 2.2. Terrestrial Ecosystem Manipulation To Probe the Effects of Storm Treatments. TEMPEST is a decade-scale experiment designed to test the effects of seawater and freshwater flooding on ecosystem state and function. Throughout the year, over 1.4 million observations are captured every month, spanning weather conditions, vegetation dynamics, soil conditions, and groundwater and open water chemistry. During the treatment events, soil and water sampling and soil and plant trace gas measurements are manually conducted. [Courtesy Nick Ward, Pacific Northwest National Laboratory]

and scale insights (e.g., through integrating remote sensing data).

- Collecting, preserving, and archiving key samples (e.g., soil and plant tissue) in multiple formats (e.g., dried or frozen at –80°C) allows for unplanned new measurements and additional analyses to investigate unexpected results or new questions, sometimes years after the experiment was initiated.
- Communicating between teams with a range of scientific expertise, including modeling, identifies key variables for measurement and may lead to modified designs before and, in some cases, during implementation.
- Working from the project's outset to ensure financial stability for long-term data continuity—widely recognized as a main challenge of long-term experiments—will support extended data collection and instrument maintenance and replacement.

Selecting Research Sites

Research site selection requires balancing scientific objectives with practical, financial, and logistical constraints. Surprisingly consistent challenges influenced site selection for the research projects represented in the questionnaire despite the projects' wide array of questions, ecosystems (e.g., forests, grasslands, tundra, and saltmarshes), and manipulations (e.g., elevated CO_2, nutrient additions, warming, drought, and snow removal). These challenges included: site access and permitting, site security, infrastructure availability (e.g., data-communication service), sufficient plot sizes to reserve protected within-plot space for future manipulations and new collaborations, consideration and quantification of key existing biotic and abiotic characteristics, and overall site heterogeneity. Budgetary constraints can force trade-offs, such as short-term, high-investment activities versus long-term infrastructure or modeling and high replication versus sufficiently large plot size. For field manipulations, investing in pretreatment environmental and soil sampling of every plot was recommended as a valuable tool to avoid or mitigate pretreatment conditions from confounding treatment responses. Logistical considerations like transportation, wireless data transfer, electric power availability, and housing also influenced site selection (see Fig. 2.3, this page). Permitting delays, as reported by several respondents, underscored the need for early planning and flexibility.

Fig. 2.3. Gathering Continuous Ecological Data Demands Energy Infrastructure and Data Logging. Solar panels (left) supply power to sensors and dataloggers at one of the COMPASS-FME wetland research sites in Ohio. The pole (right) includes sensors for photosynthetically active radiation, temperature, relative humidity, wind, and precipitation. The datalogger in the white box (center) collects these data as well as data from unseen belowground and aboveground sensors such as tree sap, soil moisture, temperature, and other environmental conditions. [Courtesy Nick Ward, Pacific Northwest National Laboratory]

For example, the Climate Change Across Seasons Experiment (CCASE) at the Hubbard Brook Long-Term Ecological Research site was originally planned for a forest dominated by sugar maple (*Acer saccharum*). However, due to lack of access to electricity for warming soils in the growing season and creating soil freeze/thaw cycles in winter, the experiment was ultimately established in a lower-elevation red maple (*Acer rubrum*) forest close to an existing electric transformer (Templer et al. 2017). Flexibility in site use—whether by allocating space for future experiments in the design phase or by adapting existing infrastructure—helped projects pivot their focus in response to new information or opportunities, though some limitations (e.g., fixed infrastructure and plot size) posed significant challenges to such pivots.

Determining Research Scales

Bridging the gap between small-scale experimental findings and large-scale Earth system models is essential for accurate understanding and predictions of future ecosystem processes and structure (U.S. DOE 2008; Kyker-Snowman et al. 2022). A persistent issue is the need for cross-scale integration, both in space and time, to account for the complex interactions and feedbacks between fine-scale processes and those occurring at increasingly larger scales. Connecting advanced sensor networks with remote sensing is a promising approach going forward.

Decadal experiments such as the Free-Air CO_2 Enrichment (FACE) experiment and the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment have led to new insights about plant, microbial, and soil responses (e.g., species interactions, adaptation mechanisms, and biogeochemical reactions) and points of vulnerability to changing environmental conditions over long periods (Hanson and Walker 2019). Controlled field manipulations are particularly useful when the key environmental drivers are at levels outside contemporary or historical observations and measurements. Such studies are often complex and expensive and therefore are likely to be reserved for research on key science uncertainties established by model projections and scientific consensus.

Research investments in large multidisciplinary ecosystem experiments can successfully be complemented by smaller-scale and shorter-term laboratory experiments and collaborations to target mechanisms that underpin the larger experiment (see Fig. 2.4, this page). Advantages of small-scale experiments are that they can often be better controlled, replicated, modified, and repeated with fewer resources; their disadvantage is that they may not capture landscape-level processes important for predictive modeling and ecosystem-scale insights. Similarly, short-term experiments may not account for long-term ecological responses and feedbacks. Both types of experiments are useful for model development and calibration to provide consistent results when upscaled from detailed site-level characterizations or when downscaled from continental or regional scales. Suggestions for future directions include landscape- and regional-scale studies, experiments that endure for decades, cross-ecosystem comparisons

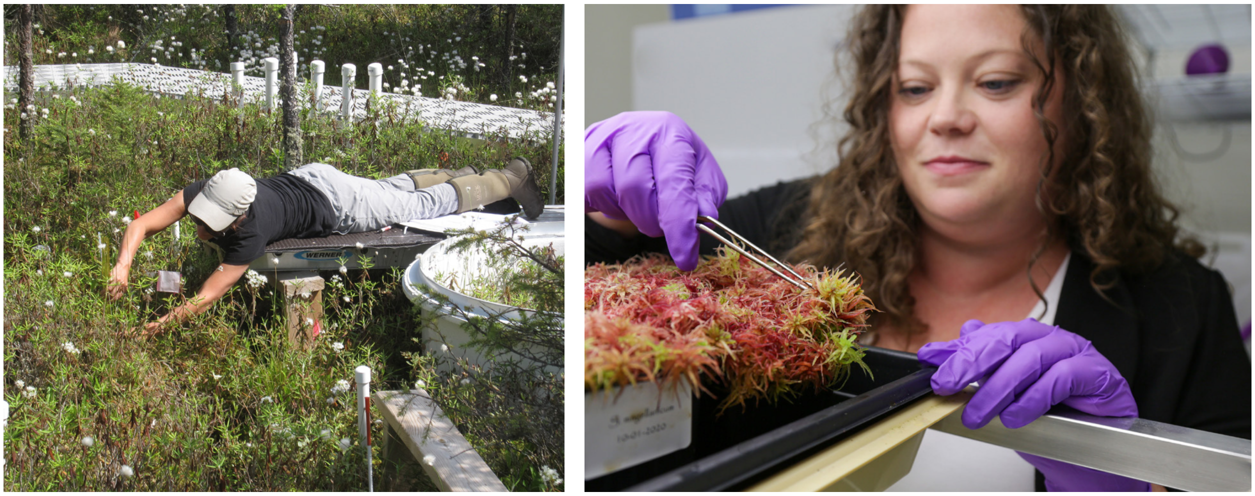


Fig. 2.4. Sampling *Sphagnum* Moss in a SPRUCE Chamber and in the Laboratory. *Sphagnum* moss was sampled from the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment where ecosystem-scale *Sphagnum* productivity was observed to decline in response to warming treatments (left). These samples were studied in laboratory microcosms to determine the mechanisms through which the microbial community influenced *Sphagnum* productivity (right). [Images courtesy Oak Ridge National Laboratory.]

using standardized protocols, and investigations that combine multiple biogeochemical and environmental factors to capture multiplicative and interactive effects (Hanson and Walker 2019).

Considering Community Engagement and Logistics

Logistical and community considerations are an extremely important part of site selection and project design. Engaging with knowledgeable members of the local community and site managers, co-creating a shared vision, building trust with landowners and communities, and fostering partnerships with local institutions can streamline permitting, site selection, and access. This engagement can also reduce operational costs and provide a roadmap for meeting ethical responsibilities, such as minimizing environmental impacts of the research. Researchers can leverage the proximity and knowledge of local scientists and other community members to reduce experimental risk, seek assistance for year-round site support, and build capacity while ensuring that scientific results can be communicated in ways that bring value to host communities.

Modular project designs, alternative hypotheses, and contingency plans can help ensure progress despite financial or logistical roadblocks. Dedicated project management personnel can help manage logistics by maintaining local relationships, project continuity, and permit compliance. Ethical and environmental responsibility, such as protected species management and long-term planning for decommissioning, should also be part of the project design phase. For a deeper exploration of community engagement, see Ch. 5: External Collaborations and Engagement, p. 37. For more on decommissioning, see Ch. 6: Completing Experiments and Decommissioning Sites, p. 45.

Managing Data

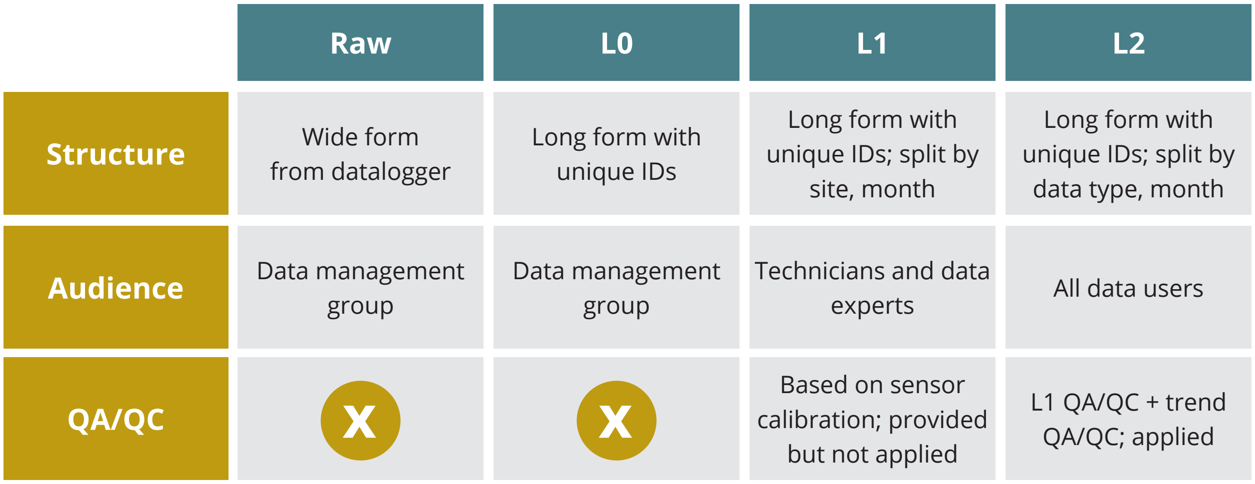
Long-term, large-scale, collaborative research initiatives require effective data management to maximize project impact, improve field experiment quality, and enable future work at the sites beyond the project's duration (see also Ch. 3: Integrating Data and Models, p. 23). This is especially true for distributed experimental research (Lind 2016; Myers-Pigg et al. 2025) and for model–experiment, or ModEx, designs where quality-controlled data must be shared rapidly between empiricists and modelers. Comprehensive and integrative research requires standardizing data formats, collection protocols, and accessibility (see Fig. 2.5, p. 18). Collaborative networks demonstrate the potential for unified data management to enhance the success of distributed ecological experiments. Examples of such networks include AmeriFlux (Chu et al. 2021), Nutrient Network (NutNet; Borer et al. 2014), LTER (Harms et al. 2021; Jones et al. 2021), Organization for Biological Field Stations (McNulty et al. 2017), International Tundra Experiment (Henry and Molau 2003), the Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (Stegen and Goldman 2018), and NEON (Donnelly et al. 2024).

Choosing Experimental Design Approaches

Intensive field efforts have a wide range of experimental designs and funding models. They tend to be focused on either experimental data or observational data and arise from both large top-down investments from a single agency and small bottom-up investments by researchers with different sponsors and common interests.

The SPRUCE experiment is an example of one primary project funded by a single agency (BER) to assess the response of northern peatland ecosystems to increases in temperature and elevated atmospheric CO_2. Initiated in 2009, this experiment has drawn in additional researchers from multiple institutions seeking to explore specific aspects of the experiment ranging from microbes (Kolton et al. 2022) to canopy integrity (Jensen et al. 2021).

BER's Atmospheric Radiation Measurement (ARM) user facility and the NGEE Arctic project are examples of projects funded by a single agency (BER) that have taken a different approach by providing consistent measurements in a variety of land types and systems. Specifically, ARM's fixed sites provide continuous atmospheric data streams in important ecosystems, while their mobile facilities operate in a campaign



	Raw	L0	L1	L2
Structure	Wide form from datalogger	Long form with unique IDs	Long form with unique IDs; split by site, month	Long form with unique IDs; split by data type, month
Audience	Data management group	Data management group	Technicians and data experts	All data users
QA/QC	X	X	Based on sensor calibration; provided but not applied	L1 QA/QC + trend QA/QC; applied

Fig. 2.5. Collecting, Curating, Sharing, and Storing Data Requires Pre-Planning and Communication Between Project Members and Data Repositories. An example of this coordination involves the Coastal Observations, Mechanisms, and Predictions Across Systems and Scales—Field, Measurements, and Experiments (COMPASS-FME) project and the Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE). To assemble, check, and distribute data at multiple levels, the COMPASS data management team collaborates with both project scientists and ESS-DIVE, a data repository for Earth and environmental data. Raw data from instruments are used only by the stewards of those sensors. The team reviews the data for an initial quality check and produces Level 0 (L0) data. As calibration information is provided to inform the dataset, technicians and data experts develop Level 1 (L1) data, which enables users to use the raw or corrected data. Finally, all data users are engaged in applying quality checks and calibration adjustments for the Level 2 (L2) dataset and its extensive accompanying metadata. L2 data applies all calibration and quality corrections, and these data are fully curated to project needs. Both L1 and L2 data are available for broad community use.

mode that allow community scientists to leverage guest instruments to tackle specific research questions. Similarly, NGEE Arctic uses a larger, coordinated campaign approach that works at multiple scales to address major model biases and uncertainties. This approach uses a single, coordinated project and project team focused on a common question but is not limited to a single site or experiment type.

A third approach, based on community engagement and distributed science strategies, can facilitate the detection of generalizable principles that may be difficult to discern from single-site endeavors. This approach brings together existing networks where possible. An example of a project using this core experimental design is NutNet (see Fig. 2.6, p. 19), a grassroots global research cooperative with over 170 independently supported grassland sites. NutNet experimentally studies productivity–diversity relationships and their nutrient drivers, developing knowledge that is not exclusive to a particular location or region.

Each of these approaches can be equally successful in conducting large research endeavors, and integrating these approaches can lead to highly translatable discoveries. Choosing which approach or combination of approaches is best for a particular challenge depends on the overarching research question, the availability of research support, and the team needed to conduct the research.

Assessing Financial and Institutional Resources

Regarding aspects of experimental design, long-term observations and experiments vary widely in their abilities to observe spatial and temporal variation, manipulate variables of interest, generate publications, and manage data. Despite these variations, their scale of research is tightly coupled with financial or institutional resources.

Financial resources constrain the choice of specific variables and ecosystems that are manipulated. For

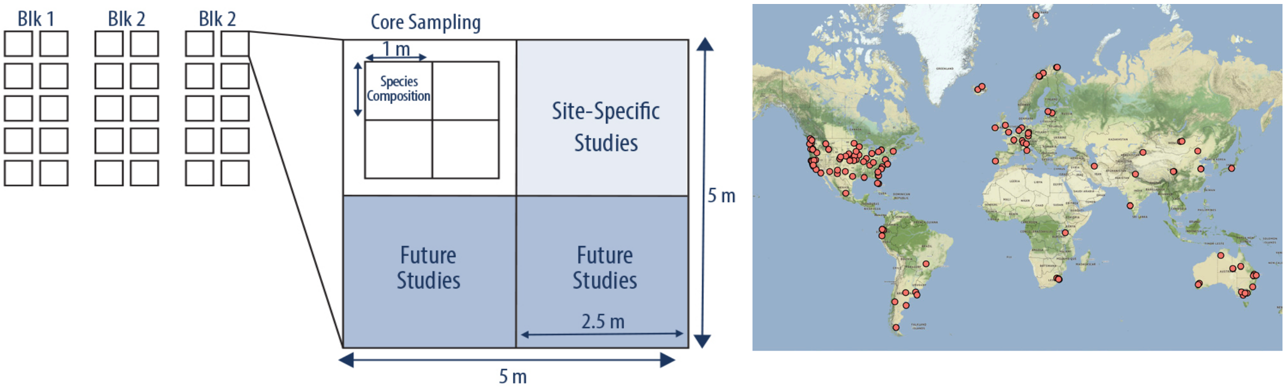


Fig. 2.6. Common Experimental Design Generates Transferable Knowledge of Nutrient Cycling in Ecosystems. The Nutrient Network (NutNet) global research cooperative has a standardized experimental design that is easily deployable. The design (left) consists of three blocks of 10 plots. Each plot requires a core sampling subplot with identical treatments at all sites (top left; species composition), which provides powerful experimental linkage across locations and investigators. Each plot also leaves room for site-specific treatments (one subplot) and future experimental opportunities (two subplots) for greater experimental flexibility and individual research priorities. This experimental design has been applied at more than 170 independently supported grassland sites around the world, seen in the map (right). [Images courtesy NutNet and Elizabeth Borer, University of Minnesota]

example, early field manipulations of atmospheric CO_2 in intact ecosystems were in Arctic tundra, tidal marsh, and native prairie ecosystems, in part because their low-stature vegetation is easily accommodated in open-top chambers. The cost of engineering, building, and operating these experiments was small compared to FACE technology that eventually allowed CO_2 to be manipulated in large-stature forests. Relatively inexpensive manipulations, such as nutrient additions, litter manipulations, species manipulations, and passive warming, tend to be more common, more widely distributed, and operate longer than designs that demand ongoing and expensive investments in consumable supplies (e.g., CO_2 or electricity). On the other hand, expensive experiments are more likely to fill important knowledge gaps about specific ecosystem types and apply more realistic manipulations.

Different team sizes have different roles and strengths (Wu et al. 2019). Designing and implementing complex, multifactor or multisite experiments with large collaborative teams requires significant resources, but such projects are often positioned to generate high-density data and publications at a faster rate than low-resource or multisource-funded experiments and collaborative networks. These projects also tend to have more well-defined workflows for data and metadata management, sharing, and publication and are more likely to be formally coupled with modeling goals and workflows.

Experimental scale and financial resources do not directly determine a program's success, as both high-resourced and low-resourced designs have proven to be productive; success and scientific productivity are driven by team engagement as well as funding and resources (see Ch. 4: Project Management and Productive Teams, p. 29 and Ch. 5: External Collaborations and Engagement, p. 37).

The range of scales reflected in the varied experimental designs of ecosystem-scale experiments is a strategic asset toward the ultimate goals of understanding and forecasting terrestrial and aquatic ecosystem dynamics and global change. Collaborative networks, such as NutNet, DroughtNet, and TreeDivNet, arise from the individual investigator's interests that leverage a wide variety of resources and opportunities to maintain continuity. The National Science Foundation (NSF) invests in low-, medium-, and high-resourced designs through programs such as Research Coordination Networks (small-scale funding, limited to 5 years), LTREB (small-scale funding, 5 years, renewable up to 10 years), LTER (relatively long-term funding, 6 years, renewable indefinitely), and CZO networks (large-scale funding, 5 to 10 years, non-renewable).

DOE, NSF, NASA, and the U.S. Forest Service have historically made possible some very large-scale designs that fill major knowledge gaps in specific ecosystems or Earth system components, often requiring very large upfront investments in engineering, logistics, and engagement with the scientific community. A number of long-term experiments have succeeded with a hybrid approach to long-term financing in which a large initial award supports the design, construction, and initial years of treatment and data collection, then funding transitions to smaller awards from different sources in later years (see sidebar, Extending Long-Term Ecosystem Insights with Hybrid Funding, p. 21). A well-designed study will anticipate changes in sponsors by identifying a set of core data and observations to be collected on minimal resources across financial transition periods.

In terms of institutional resources, Ecosystem Research Centers (www.ecosystemresearch.org/) play a major role in the success of long-term ecosystem-scale research programs. The 30 member organizations of the Association of Ecosystem Research Centers are universities and nonprofit organizations that maintain the physical and field infrastructure required for long-term ecosystem research (Ward et al. 2004). These institutions and others provide access to terrestrial and aquatic ecosystems that are often unique and ideal for meeting siting requirements, such as security, power, and access. Many of the long-term studies cited in this report are located at such research centers and therefore benefit from the financial support, data access, and collaborations that motivated the centers.

2.2 Conclusions and Recommendations

Long-term success of experimental and observational ecosystem projects arises from decisions made during the design phase. Combined experiences from workshop participants and questionnaire respondents show that flexible, rigorously planned, collaborative designs lay the groundwork for enduring, impactful projects. While research hypotheses and goals should be the focus of experimental design, researchers should also be prepared to address unexpected challenges and opportunities that emerge along the way. Approaching these challenges individually and in small steps can help overcome even the largest design barriers with minimal disruptions to the pursuit of the research vision. Additional characteristics of effective experimental design for ecosystem-scale initiatives include (1) balancing exciting, immediate, answerable questions against big-picture, long-term goals; (2) engaging and empowering early career scientists; (3) producing and publishing valuable new data; and (4) investing in infrastructure to extend data life cycles.

Further recommendations from workshop participants and questionnaire respondents include using the project's design phase to:

- Invest in careful, pretreatment characterization of biota, soil, and environmental conditions in experimental plots to minimize or mitigate confounding effects on treatment responses.
- Use post-treatment analysis of an experiment's data archives to identify opportunities for sustained evaluation and data modeling.
- Construct experimental plots large enough to allocate free footprints for future measurements or to modify planned treatments and measurements. This consideration allows flexibility to accommodate unforeseen research objectives at a later date and provides space for new collaborators to join as long-term experiments proceed.
- Collaborate across disciplines and funding agencies and plan in phases (e.g., designing pilot studies

Continued on p. 22

Extending Long-Term Ecosystem Insights with Hybrid Funding

Initiated in 1987, the Global Change Research Wetland (GCReW) is home to the world's longest-running elevated CO_2 experiment dedicated to unraveling the complex ecological processes that confer stability on coastal marshes as they respond to global environmental change. Nearly four decades after its inception, the experiment continues to produce high-impact insights on ecosystem responses to global change.

An example of a project using a hybrid funding strategy, GCReW's construction and operation was funded by an initial DOE grant to gain insights into the possibility that C3 vegetation would be an increasingly large CO_2 sink as concentrations rose. The study addressed this and related questions for 20 years by competing for renewal awards at 3-year intervals. When the DOE program ended, the National Science Foundation (NSF) stepped in to fund the experiment to answer related, but different, questions about the resilience of coastal wetlands to accelerated sea level rise.

Aerial Image of Four Long-Term Experiments at the Global Change Research Wetland Operated by the Smithsonian Environmental Research Center. The experiments were initiated either by DOE alone or by DOE in partnership with the U.S. Geological Survey. The two shorter-term experiments (4 and 9 years) remain DOE-funded at present while the two longer-term experiments (39 and 20 years) are sustained by the National Science Foundation and Smithsonian funding. [Courtesy Shelley Bennett, Smithsonian Environmental Research Center]

The NSF Long-Term Research in Environmental Biology (LTREB) program provides more modest levels of funding to the project but commits to doing so for 10-year periods, thereby significantly extending the usefulness of the experiment and the initial DOE investment. The Smithsonian Environmental Research Center (SERC) provides GCReW with additional investments in infrastructure and salaries. The nearly 40 years of key institutional support from DOE, LTREB, and SERC that has ensured GCReW's continued success demonstrates the importance of hybrid funding and highlights these institutions' ongoing commitment to efficacious long-term environmental observations and experiments.

followed by scaling up) to ensure that experimental projects are designed to remain scalable, impactful, and adaptable over time.

- Develop and deploy a clear and consistent project message (i.e., elevator pitch) to convey study importance and goals to funding agencies, sponsors, and the community.

Finally, one of the most important indicators of success of any project is its intellectual impact and legacy on the next generation of scientists. Decade-scale experiments are long enough that individual researchers may advance through multiple career stages (e.g., graduate student, postdoctoral fellow, staff researcher, task lead, and principal investigator) through the same project. The attendees of this workshop represented many of these career stages, and several attendees are examples of this career growth. Such knowledge and experience are the foundation for future discovery.

Chapter 3

Integrating Data and Models

Key Takeaways

- Frequent collaboration between empiricists and modelers throughout a project can guide experimental design, generate model-informed hypotheses, and align data collection with modeling needs.
- Targeted efforts to define and bridge language gaps and expertise help project participants from different disciplines and research backgrounds understand the language and concepts of both sides of the model–experimental fields.
- Ongoing sharing of data, metadata, and modeling approaches throughout the project leads to advances in model development, benchmarking, and experimental insights.

3 Integrating Data and Models

Integrating experimental data with model simulations is a key part of achieving outcomes that reach beyond the scale of individual field sites (Hanson and Walker 2019). Computational models synthesize current scientific knowledge in mathematical forms and function as a tool for extrapolating scientific results in space and time, simulating different treatment scenarios, and generating hypothetical experiments. Experimental results that are not integrated with model frameworks can be difficult to relate to other places and times, thereby challenging the transferability of knowledge gained from one project to more general needs. At the same time, models that are not well integrated with experimental measurements can suffer from errors and unrecognized uncertainties (Wieder et al. 2019).

A major challenge in linking models with large-scale field and experimental projects is ensuring that observational data and models correspond closely in terms of scales, processes, and boundary conditions. An important early step is to establish criteria to decide the fitness-for-purpose of one or more potential models. For example, the Next-Generation Ecosystem Experiments in the Tropics (NGEE Tropics) and Arctic (NGEE Arctic) both sought to develop state-of-the-art, process-rich models to improve representation and predictive understanding of these complex terrestrial ecosystems. However, each project had different fitness-for-purpose criteria and adopted different data–model integration strategies to meet those needs. To accurately represent forest structure and function and provide robust projections of hyper-diverse tropical forest responses to global change, NGEE Tropics decided early to focus on a single core modeling platform. This platform, the Functionally Assembled Terrestrial Ecosystem Simulator (FATES), was coupled to the E3SM Land Model (ELM)—the land component of the DOE's Energy Exascale Earth System Model (E3SM). ELM-FATES best suited the needs of NGEE Tropics because it was based around a vegetation demography approach that allowed representation of individual plants competing for light and other resources within forest stands of different ages, which together comprise an ecosystem, with distinct scaling methods between each of these elements. For NGEE Arctic, the project's aim to simulate how surface and subsurface processes and properties are interconnected across permafrost-dominated tundra ecosystems was better served through a broader portfolio of models to represent different processes at different scales. As such, the project developed approaches in ELM to bridge between these scales. Ultimately, these decisions about integrating data and models involve tradeoffs that need to be balanced in the overall project organization, a task which benefits from a thoughtful and intentional approach to designing a project-wide data–model integration strategy.

This chapter synthesizes the insights of workshop participants and questionnaire respondents on best practices for effective data–model integration in ecosystem experiments. While effective communication was identified as the most critical challenge to data–model integration, communication also offers the strongest potential for solutions. These solutions, described in detail in the sections that follow, center on collaboration between empiricists and modelers throughout the project—from initial design, to implementation, to synthesis. Frequent communication focused on data–model deliverables helps to prevent the formation of disciplinary silos and ensures mutual understanding of the distinct approaches and terminology of empiricism and simulation. Finally, clearly defined mechanisms and schedules for sharing data and model output ensure a concrete workflow across disciplines. These include boundary condition, parameterization, and benchmarking datasets (and associated clear metadata) for modeling and new model-generated hypotheses for subsequent empirical testing.

3.1 Best Practices for Effective Data–Model Integration in Ecosystem Experiments

Early and Collaborative Engagement

Effective data–model integration in large-scale ecosystem projects requires early and collaborative engagement between modeling and experimental scientists. Such engagement should happen not only with individual modelers but also, crucially, with the larger modeling programs and their development roadmaps. For example, a large Earth system modeling project like E3SM develops its own model development roadmaps focused on project scientific goals, such as improved representation of land–atmosphere coupling and large-scale atmospheric dynamics, as well as technical goals, such as model codes that take advantage of new computing technologies.

Targeted communication across projects can help (1) identify where the ecosystem-scale measurement and modeling goals of projects align with the structure and goals of larger modeling and software development projects and (2) determine how planned efforts, including improvements to model parameterization or representation of ecosystem processes, can be aligned across projects. By involving both groups from the initial stages—such as brainstorming and project design—projects can ensure that data collection aligns with immediate model requirements, improving the accuracy and utility of simulations. This approach also ensures that the ecosystem project's design accounts for the the model's longer-term roadmaps for science, software, and hardware (e.g., changes in central processing and graphics processing units).

Mapping ecosystem project data collection and model developments into the long-term development plans of larger modeling projects can help to enable more rapid integration and long-term use of ecosystem project outcomes by the broader scientific community. Hosting workshops during the proposal and project design phases fosters alignment by refining integration pathways, optimizing model inputs, and promoting cross-disciplinary understanding.

Frequent and Clear Communication

Clear communication and a shared conceptual framework are also essential for bridging disciplinary gaps within a project. Developing a common vocabulary and conceptual understanding of complex numerical land–surface models reduces misinterpretations and ensures that observational data collection and modeling needs complement each other. This open dialogue is critical for identifying and prioritizing which variables are essential for models and distinguishing them from those that can be supplemented by existing datasets. Equally important is identifying the appropriate scale and level of complexity for modeling activities that are suitable to the project scope and research questions. Fine-scale, detail-oriented models may be appropriate for some projects (or project components) while large-scale land surface models or fully coupled Earth system models may be warranted in other areas. A proactive and collaborative approach enhances the ability of models to represent ecosystem change and resilience more effectively, ultimately leading to more robust scientific insights and better-informed decision-making.

Common understanding of differing goals and needs of empirical and modeling components of a larger project helps to align expectations. For example, model simulations often need to start with essential inputs—such as environmental or weather forcing data, boundary conditions, parameter datasets, and evaluation datasets—that may seem less exciting but are crucial for generating meaningful simulations. Without early discussion of these needs, project members' expectations of what they hope to gain from model simulations may not match up with what models can realistically deliver. Similarly, expectations of data that can feasibly be collected for model forcing, parameterization, or evaluation may not be realistic without early communication. This disconnect can hinder effective collaboration and integration.

Experiential learning can help avoid disconnects and misunderstandings and ensure effective communication across model-empiricist disciplinary boundaries. This approach allows both modelers and empiricists to gain hands-on familiarity with other components of the project. For modelers, participation in fieldwork, field site visits, and hands-on experience with experimental methods facilitate a deeper understanding of where model parameterization and evaluation data come from as well as the major sources of uncertainty. Setting foot in a field site provides an intuition for the characteristics, spatial layout, and scale of a field site that benefits setup and interpretation of model simulations.

Opportunities for empiricists to gain hands-on experience with models are just as important. Exploring model structures, assumptions, and approaches allows empiricists to better understand how data will be used in model configuration, parameter estimation, and evaluation, as well as the types of questions that can be usefully answered with models. Unfamiliarity with computer programming and complex model code structures can be mitigated with carefully designed model tutorial workshops. For example, the NGEE Arctic project organized a “Field to Model” workshop for which ELM was packaged in a user-friendly format that each participant could run on their own laptop without reading or writing model code. In another example, the NGEE Tropics project held a FATES tutorial with the primary aim of teaching international colleagues working at tropical forest census sites how to use and apply ELM-FATES at their site locations.

Clearly Defined Data-Sharing Strategies

Data sharing is a key component of data–model integration, and measurement data from repeated iterations of a project’s model–experiment loop must be shared quickly. As such, this data often requires frequent communication before it is fully analyzed or published, so even preliminary results can be incorporated into model simulation planning and interpretation. Similarly, preliminary model results can help inform experimental design and interpretation before model outcomes are ready for publication. At the same time, effective data–model comparison requires data quality that supports integration and interpretation. Data hygiene, including basic quality assurance checks, high-quality metadata, and data formats that can be easily processed into model-friendly forms, helps to reduce barriers to continuous data–model integration. An active and well-integrated data management team, automated data processing and quality assurance tools, and a project culture of communication and data sharing all help to support effective model–experimental data connections. Similar considerations apply to model code: clearly explained and documented model approaches allow experimentalists to better understand how data collections can be used with models and how experimental design can benefit from model insights.

Sharing data and model code outside the project is also important for facilitating longer-term and broader-scale impacts of project results. Timely public data releases, with detailed metadata and contact information for data contributors, allow other projects to integrate modeling approaches and experimental results beyond the scope of an individual project. Contributing to broader-scale data availability is invaluable for supporting synthesis and modeling approaches that draw insights from measurements going beyond the scale of individual field sites and experimental manipulations. Additionally, public code releases are beneficial for translating new model approaches into lasting scientific progress. Finally, models’ long-term impact can be ensured through active collaborations across projects (e.g., between a large-scale experiment and a model development project such as E3SM) via designated cross-project liaisons and project deliverables tied to model code integration tasks. For more information about the role of data sharing in the success of ecosystem-scale experiments, see Ch. 5: External Collaborations and Engagement, p. 37.

3.2 Conclusions and Recommendations

An overall theme of workshop discussions was that communication across empirical and modeling team members is crucial across all stages of a project, starting with initial conceptual planning and continuing through experimental design, analysis, and decommissioning phases. Successful communication depends

What Does Success Look Like?

Projects with successful data–model integration build knowledge that is reflected in both novel empirical results and improvements to model frameworks, parameterization, and interpretation (potentially including improved understanding of major predictive uncertainties).

A hallmark of projects with successful data–model integration is clear communication and understanding across project members with modeling and empirical expertise. Modelers understand how and why data were collected, and empiricists understand how data were integrated with model simulations. In addition, teams work together to identify the appropriate modeling approach, scale, and level of complexity for the project's research questions. Experimental design and publications address both empirical and modeling uncertainties and provide benefits for both approaches.

on close interactions between team members that allow project participants with different expertise and research backgrounds to understand the language and concepts of both sides of the model–experimental fields. Example strategies for overcoming communication barriers included hands-on workshops, organized materials such as glossaries and model documentation, and frequent communication across disciplinary boundaries. As lines of communication are established, they must be used starting at the experimental conceptualization and design phase to make sure planned measurements and experiments fit with identified model uncertainties and capabilities. Early communication will also ensure that modeling approaches are consistent with the state of knowledge and the questions being addressed with empirical methods.

During the data collection and analysis phase of a project, frequent interaction between field data and model simulations can enhance both sides of the project by informing continual model improvement and identifying new measurements or experimental approaches that can address identified predictive uncertainties. Archiving data and model simulations as well as model code during an experiment, and during decommissioning phases, should use clear and consistent documentation, standardized formats, and open sharing approaches to facilitate lasting value and future utility for data–model integration. Ultimately, efforts to incorporate early and collaborative engagement, frequent and clear communication, and clearly defined data-sharing strategies will help ensure successful data–model integration in ecosystem-scale research endeavors (see sidebar, What Does Success Look Like?, this page).

Chapter 4

Project Management and Productive Teams

Key Takeaways

- Effective management and operations are guided by a clear shared vision and top-level science questions.
- Space created within the project and team can help manage new opportunities that arise and build resilience for unplanned events.
- Clear and effective communication, a commitment to common collaborative tools, and clear expectations promote a sense of belonging that fosters innovation and builds productive teams.

4 Project Management and Productive Teams

Successfully managing and operating a long-term experiment or ecosystem-scale field effort relies on two key elements: a shared vision for success and a compelling top-tier science question. These components serve as the foundation for making difficult decisions. Also critical for program success is a team with varied expertise, perspectives, and backgrounds that works together with open and effective communication. As the complexity of a program, site, or project grows, control over certain aspects of the project—such as physical sampling in an experiment, project safety, and deliverable timelines—must be balanced with the flexibility needed to allow scientific evolution and project growth as new opportunities emerge. In this way, multidisciplinary science can maximize the potential of long-term observational or manipulative experiments that are done safely and responsibly. This chapter highlights what workshop participants and questionnaire respondents identified as key challenges in project management, operations, and team dynamics. It also offers examples of how effective management approaches can be used to manage field sites; guide the evolving scientific goals of long-term observation or manipulation experiments; and nurture productive, supportive scientific teams.

4.1 Effective Approaches for Managing Large-Scale, Long-Term Projects and Fostering Productive Teams

Establishing A Project Vision

A high-level vision that includes top-tier science questions and key deliverables is necessary to motivate and justify the investments required to achieve large-scale and long-term projects. This vision informs where a project needs to build capabilities, invest in equipment or infrastructure, prepare for adversity, and seek collaboration. It also provides clarity when making inevitable hard decisions, such as choosing between competing priorities under flat or shrinking budgets or deciding which competing idea gets to destructively sample valuable experimental material. Objectives and goals must be effectively communicated internally to the project team and externally to multiple audiences including reviewers, program managers, land managers, and the general public. This vision aligns and motivates team members, provides clear expectations, and offers a path for engagement among team members and collaborators.

Designing the management plan for large-scale research projects builds off the core science questions, advanced design methods, and site selection covered in Ch. 2: Identifying Science Questions, Design Methodologies, and Site Selection, p. 11. Ultimately, visions for project management should guide and provide proper motivation for the location, scale, participation types, and infrastructure support capabilities that can be leveraged by a larger community of scientists.

Considering the Research Life Cycle

Project management begins with conceptualizing science questions, research concepts, and experiment design. This extends throughout the entire research life cycle—from selecting sites and securing funding and approvals to prototyping, collecting pretreatment data, constructing site infrastructure, contracting for ongoing services, evaluating safety and environmental concerns, and ultimately to sustaining operations, collecting and archiving response data, and publishing results and decommissioning (see Fig. 4.1, p. 31). New research efforts must consider this continuum of complex and interrelated activities from the beginning to adequately plan for the needs of project personnel and financial resources. Successful large research efforts

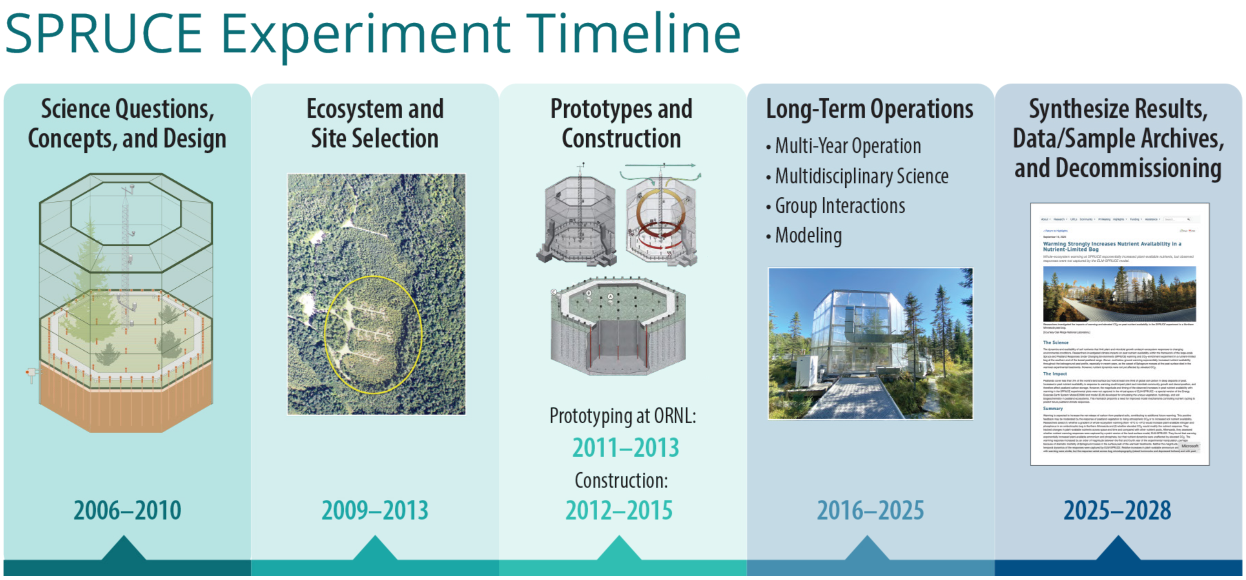


Fig. 4.1. The Research Life Cycle's Role in Project Management for Long-Term and Large-Scale Ecosystem Experiments. The Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment management approach demonstrates the complexity and commitment needed in long-term and large-scale research experiments. A whole-ecosystem experiment in an ombrotrophic bog located in the Marcell Experimental Forest of northern Minnesota, SPRUCE assesses the response of northern peatland ecosystems to increases in temperature and exposures to elevated atmospheric CO_2 concentrations across multiple spatial scales—including microbial communities, moss populations, various higher plant types, and some insect groups. Science questions, concepts, and designs were developed from 2006 to 2010 and refined in a 2008 workshop. Ecosystem and site selection occurred from 2009 to 2013 concurrent with construction of a prototype at Oak Ridge National Laboratory (ORNL) using laboratory development funds, and an Environmental Assessment for the Marcell site under the National Environmental Policy Act. Construction in the Marcell began in 2012 and extended to 2015, with long-term operations from 2016 to 2025. In 2025, synthesis of results began with an international workshop and is expected to continue until at least 2028. Data archiving has occurred throughout the lifetime of the project, and formal sample archiving for samples from the entire project began in 2025. Decommissioning as required under the Environmental Assessment is expected to begin in 2026 and conclude by 2028. [Images courtesy SPRUCE]

recognize that different phases of the research life cycle (e.g., project development, construction, operation, and synthesis) require a range of expertise and resources and incorporate plans to meet these varying needs throughout the project.

Site management is a critical component in the research life cycle of large-scale and long-term projects. Successful sites balance rigid protocols for safety and project activities with flexibility to attract collaboration and cooperation. Project and site access approval systems can help manage activities, requirements, and hazards as well as provide a record of project locations and personnel. Keeping track of such site elements and closely monitoring project timelines ensures safety and minimizes project overlap. Furthermore, maintaining institutional knowledge of legacy projects is important; for example, a project manipulating soil nutrient resources in a specific location could bias the sampling of future projects conducted at the same location.

Additionally, successful ecosystem-scale field sites, including many manipulative plot-based experiments or decadal-length measurements, require infrastructure that can support both short-term and long-term field experiments of varying intensity. Balancing between support for infrastructure that spans projects and between support for individual scientific projects maximizes the stability of site maintenance and operation. For example, the site might maintain buildings, roads, vehicles, and a set of instrumentation for all participants to use for measurements, but individual participants would maintain and operate their unique project-specific instrumentation. Having experienced technicians as part of the project team to provide critical instrument repair and site-specific knowledge greatly increases the likelihood of a site's success. Furthermore, site management supported by multiproject, varied funding streams (i.e., agency support, user fees, state support, and private donations) helps minimize fiscal emergencies when one source of revenue is reduced. Ultimately, maintaining stability within site management and support staff will ensure a field experiment's efficient operation and successful conclusion.

Evolving Science Goals

Long-term experiments almost always encounter unexpected events or new discoveries that require scientists to consider shifts in their project goals. Unexpected events can arise from disturbances such as wildfires, ice storms, and floods that can dramatically alter an ecosystem's composition, structure, and function and destroy experimental infrastructure. Additional challenges, such as loss of funding or personnel changes, can alter what manipulations and measurements can be maintained. However, unanticipated results, new findings, or technological advancement (e.g., the evolving role of artificial intelligence) could require shifts in resource allocation and thus trade-offs in achieving a project's objectives. Planning for flexibility in science goals—such as intentionally protecting a portion of an experiment for unplanned manipulations, sampling, or measurement—will enable a project to better manage unforeseen events. Furthermore, lessons learned from past field studies highlight the importance of designing for scalability (big and small) and adapting to emerging needs and opportunities. For more information on how to plan for unexpected events or new discoveries during the design phase of large-scale, long-term ecosystem experiments, see Ch. 2: Identifying Science Questions, Design Methodologies, and Site Selection, p. 11.

Implementing Collaborative, Flexible Leadership

Management and operational roles in ecosystem-scale experiments require leadership skills that often differ from the technical expertise that first drives individuals into leadership positions. Critical soft skills such as team building and communication may be underdeveloped in these leadership teams. However, investing time in learning how to lead and contribute effectively as a team member will support smooth management and communications (Daniels and Lavallee 2014). Mentoring is critical for building leadership capacity within the team and preparing individuals for increasingly complex roles while also fostering connection, trust, and a sense of community among team members.

Successful leadership provides clear pathways for collaboration, articulates a clear vision, prioritizes data–model integration through team coordination, handles conflict resolution and personality management, and makes a long-term investment in both the project and the research team. All these factors are important for motivating people to invest in the hard cross-disciplinary relationships that are hallmarks of large-scale experiments. Additionally, leadership needs to deliberately use and model active listening to make it part of the team culture, as this approach gives a wider range of people time to be heard. Furthermore, workshop participants noted that collaborative leadership reduces the risk of single points of failure. Developing leadership skills in junior scientists through training, increased responsibility, and distributed leadership will ensure that experiments continue to run smoothly and project teams receive adequate support throughout the research life cycle.

Building and Supporting Productive Teams

High-quality, innovative research is driven by teams at various career stages, with a range of backgrounds and expertise from different disciplines. Multidisciplinary, integrated team environmental system science is essential for identifying and answering novel and complex research questions, developing new methods to achieve co-created goals, and enabling discoveries that can lead to broader understanding and application. Decades of literature on team science highlights that collaborations among individuals with differing experience, perspectives, or expertise can accelerate progress and discovery (e.g., Mâsse et al. 2008;

A History of Success Through Team Science

Several DOE Environmental System Science projects highlight the imperative of team science. Projects such as Free-Air CO_2 Enrichment (FACE; U.S. DOE 2020), established in the 1980s, initially focused on plant physiological responses of crop plants but evolved to encompass multiple ecosystems and sites, with teams examining whole-ecosystem processes and a strong data–model interaction.

The 1990s saw the emergence of FLUXNET (Baldocchi et al. 2001) and AmeriFlux (Novick et al. 2018), which started with a few meteorological towers at sites across the globe to quantify carbon sources and sinks across ecosystems. AmeriFlux has since grown to include over a thousand towers worldwide and now engages teams of ecologists, meteorologists, atmospheric chemists, modelers, educators, and big data scientists.

DOE research efforts developed in the early 2000s, such as the Next-Generation Ecosystem Experiments in the Arctic and Tropics, conducted research in ecosystems that were poorly represented in Earth system models and often required work with local scientists and community members and spanned multiple national laboratories and academic institutions.

This necessary expansion in observational and experimental approaches over time means that researchers today are working with large, interdisciplinary, and often multinational teams to explore a wide range of environmental questions. Long-term success of these projects depends on transparent collaborative understanding and working with local communities.

Bennett et al. 2010; Hampton and Parker 2011; Holzer et al. 2024). However, building such teams requires intentional effort, time, transparency, trust, and clear communication.

For large-scale field studies at the ecosystem level to succeed, it is important to attract and retain the best team members, collaborators, and advisors. This requires creating an environment in which everyone understands their contributions to the project's goals and feels safe to fully engage. Recent papers have developed protocols for inclusion (e.g., Borer et al. 2023), codes of conduct (Dodds 2024), and the importance of team building (Xenopoulos et al. 2024; Iversen et al. 2020) and in-person collaboration (Lin et al. 2023).

Successful, strong, and sustainable research programs rely on teams working toward a shared vision and set of goals. Field-based environmental system science teams typically consist of two membership categories: research personnel, both internal and external to the primary agency or institution, and external individuals, organizations, or groups that are not part of the core research team (for more on this topic, see Ch. 5: External Collaborations and Engagement, p. 37). Collaborations across these categories reduce barriers to new partnerships, boost efficiency through resource sharing, and create new opportunities rooted in sharing perspectives and information across groups (see sidebar, A History of Success Through Team Science, this page).

However, differences in funding levels, cultural norms and expectations (particularly regarding team hierarchies and publishing), and principles of data management and sharing are all potential sources of friction. Even seemingly simple aspects of science, such as ensuring the use of standardized protocols, can be complicated by language and cultural barriers. Discipline-specific jargon is a common communication barrier, and even terms that appear similar across fields may have different meanings (Knapp et al. 2015). Collaborative teams can often struggle with differing approaches to research design, data analysis, writing, communication, and data sharing. Cross-border and interdisciplinary collaborations are particularly susceptible to these challenges.

Mentoring at all career stages and across roles is a key characteristic of productive, healthy, and empowered teams (Hund et al. 2018; NASEM 2019). Fostering a culture of feedback encourages continuous learning and personal growth, allowing team members to refine their skills and advance in their respective roles (Coutifaris and Grant 2022). This supportive atmosphere not only enhances individual performance but also strengthens overall team cohesion and effectiveness. Training initiatives focused on both physical and psychological safety are paramount in safeguarding the well-being of team members (Edmondson 1999; Newman et al. 2017). By integrating these elements—effective communication, strong governance, dedicated mentoring, and thorough training—research teams create an environment that not only enhances the team's functionality and resilience but also drives scientific innovation by enabling collaborative efforts (Liu and Keller 2021).

Promoting Open and Effective Communication

Across all workshop sessions and survey results, open communication among participants, infrastructure staff, and interested parties was highlighted as foundational for productive, long-term collaborations. Such communication includes providing regular updates to infrastructure staff supporting the field site, participating scientists, potential scientists, and stakeholders. Additionally, regular information exchanges with program sponsors, as well as those who grant site access, are critical for sharing progress updates, informing strategy, and reporting any status changes. Additional unplanned communication may also be necessary to inform sponsors and project participants of unavoidable urgent or unexpected happenings.

Drawing from their management experiences on ecosystem-scale field experiments, workshop participants identified best practices for avoiding pitfalls with collaboration, while noting that some of these challenges are likely unavoidable but can be mitigated with planning. Regular structured meetings that focus on discussion and decision-making and result in clear action items are integral to a project's success. Participants noted that meetings with clear agendas and post-meeting notes fostered openness, collaboration, and trust. Community members who come from different scientific disciplines with different lexicons and cultures may especially benefit from regular, structured meetings. For example, frequent meetings among modelers and empiricists can be used to develop a joint vocabulary, which promotes better project science.

However, project leadership should keep in mind that more frequent team meetings are not always a net positive; the ease with which virtual meetups can be scheduled often results in meetings of low value. In multi-institutional projects, institutes may be tempted to set up regular institute-focused meetings. This strategy should be used sparingly to avoid creating information silos and ensure project-wide communication. In addition, taking time at regular intervals to discuss changes in team member availability and preferences for communication styles or platforms, as well as work styles, supports a culture of collaboration.

Teams should also identify and commit to a set of tools for document sharing, collaborative writing, and communications, rather than individual team members using a variety of tools. Designating a standard set of tools ensures full team access to critical information, regardless of how distributed or remote the team and field locations. Collaborative platforms like Slack, Google Docs, GitHub, and Dropbox facilitate information sharing and increase transparency (Braga et al. 2023; Ram 2013). These tools allow team members to share information across time zones and schedules as well as maintain and access meeting agendas, notes, tasks, and outcomes, reducing the need for excessive whole-project meetings.

Despite the now common use of virtual meeting platforms for communication, no substitute exists for periodic in-person meetings, such as annual all-hands meetings. These in-person gatherings support building trust and a sense of connection that are critical for effective team dynamics. In-person meetings represent a significant investment in personnel time and project expenses but allow for rapid communication, relationship building, creativity and spontaneity, and idea generation. In-person meetings also permit valuable serendipitous exchanges that can be more challenging in virtual interactions, and the spaces for shared experiences provided by these meetings foster trust and collaboration. Therefore, time and space need to be deliberately allocated to enable such interactions.

Ensuring Safety and Accountability

Effective field site safety considers the physical and psychological aspects of fieldwork and requires a clear chain of command and protocols, especially for reporting emergencies (Boon 2022). Safety protocols for both physical and psychological safety must be communicated to staff, scientists, and students, with clear reporting systems and procedures in place (Daniels and Lavallee 2014). For example, call sheets posted in buildings and vehicles are effective for notifying staff and station directors of emergencies, both small and large, and provide information required for post-emergency reporting to agencies and stakeholders. These protocols protect visiting scientists, staff, and the broader site integrity as well as provide standardization to maximize collaboration and data sharing.

Projects also need to consider management approaches when multiple institutions have different methods to ensure safety in the field. In some cases, these differences can offer some beneficial flexibility for multi-institutional field teams where team members from institutes with restrictive approaches can be supported by colleagues with more institutional flexibility. For example, in the early stages of the Next-Generation Ecosystem Experiments in the Arctic (NGEE Arctic), each institution involved in the project had different approaches for dealing with potential bear encounters. Los Alamos National Laboratory was required to provide bear guards for their field teams, the University of Alaska Fairbanks and Brookhaven National Laboratory allowed researchers to carry firearms, and Oak Ridge National Laboratory restricted bear deterrent to bear spray. Ultimately, having a project that included multiple institutes, with different policies, proved to be beneficial. The institutions with a more flexible approach to handling bear safety were able to support other NGEE Arctic project members while in the field.

Furthermore, a code of conduct establishes expectations for all team members, articulates a shared understanding of behavior, and provides a foundation for accountability. Even though disciplinary authority ultimately rests with a scientist's home institution, a project code of conduct provides project leadership with greater agency to maintain a desirable team culture. To delineate institutional codes of conduct from project expectations, some projects define "team norms and expectations" in addition to the institutional codes of conduct. Effective codes of conduct have significantly improved the experience at field stations (Clancy et al. 2014), and resources for developing these codes are now available. Such codes are also increasingly common in the software world and can cover plagiarism, data falsification, co-authorship expectations, and more (Favaro et al. 2016).

4.2 Conclusions and Recommendations

Effective project management and a healthy team culture are crucial for the success of large-scale and long-term field experiments. A clear vision or deliverable and a flexible approach to project management are required to not only ensure that long-term project goals are met, but also to enable the project to adapt to new opportunities, unexpected events, and potentially evolving science goals. Collaborative leadership, open communication, and a sense of belonging are vital for building resilient, productive teams. Investing time in learning leadership skills and fostering connection and trust within the team helps leadership plan for success. Moreover, mentoring at all career stages and promoting a culture of feedback are critical for empowering team members and driving scientific innovation and productivity.

Chapter 5

External Collaborations and Engagement

Key Takeaways

- The productivity and benefits of external collaborations are maximized by establishing a shared culture of trust and mutual benefit that extends beyond the internal project team.
- Project teams should develop and share clear governance plans, data-sharing protocols, and expectations for collaboration.
- Engagement strategies tailored to project approaches increase impact and responsiveness to project and collaborator needs.
- Scientific advisory boards and collaborative networks extend project impact, provide resilience during challenging periods, and create pathways for integrating expertise and knowledge into research outcomes.

5 External Collaborations and Engagement

Decades of research projects and programs in the environmental sciences have demonstrated the power of collaborative teams for understanding and predicting the impacts of changing environmental conditions on ecosystem trajectories (Berner et al. 2024; Keenan et al. 2019; Borer et al. 2017). Successful collaborations across disciplines like ecology, geology, Earth science, statistics, and modeling have taken many forms. Examples include:

- Groups that combine data from many sites with similar sensors, such as AmeriFlux, FLUXNET, and the Global Lake Ecological Observatory Network (GLEON).
- Large collaborative initiatives with centralized data management and funding, such as the Free-Air CO_2 Enrichment experiments (FACE) and the Next-Generation Ecosystem Experiments.
- Collaborative networks with centralized data management but distributed funding, such as the Nutrient Network (NutNet), Disturbance and Recovery Across Global Grasslands (DRAGNet), DroughtNet, Warming and (species) Removal in Mountains (WaRM), and the International Tundra Experiment (ITEX).

In many cases, the core research team—discussed in Ch.4: Project Management and Productive Teams, p. 29—sits within an extended collaborative network. Engaging with an extended network inherently helps project teams meet strategic needs and reduces scientific silos. A cohesive team culture and approach that facilitates interested party engagement (see Key Term, this page) are strong assets for accomplishing research at large scales. Successful external collaborations and engagement with interested parties not only involve clear expectations, strong relationships, and trust but also require research co-development, implementation, and crediting. This chapter summarizes what workshop participants and questionnaire respondents identified as best practices for engaging with integrated teams across a range of interested parties that form this extended network.

Key Term

The term “interested party engagement” is used here rather than “stakeholder engagement” to be open to the many kinds of interested parties, including organizations, agencies, landowners, land managers, rights holders, and the public.

5.1 Best Practices for Engaging Interested Parties in External Collaborations

Approaches to Extended Collaborative Networks

Large-scale, long-term ecosystem projects generally fall along a continuum marked by two main approaches—place-based approaches and distributed approaches—that require different engagement strategies. To be successful across this continuum, projects must be attentive to the people and institutions they collaborate with to facilitate mutually beneficial and impactful engagement.

Place-Based Approaches

Place-based projects focus on a small number of sites to gain deep mechanistic insights. These activities typically span months to decades, creating an opportunity

Learning from Past Project Approaches

Future initiatives can adopt or adapt methods from past projects that have successfully used place-based and distributed approaches.

Place-Based Projects

The Coastal Observations, Mechanisms, and Predictions Across Systems and Scales—Field, Measurements, and Experiments (COMPASS-FME) project built a near-real-time data processing pipeline for a network of hundreds of environmental sensors across tens of sites. This effort produced large, openly available observations (approaching half a billion to date) that have catalyzed internal work, encouraged cross-disciplinary analyses, and fostered external collaborations (Pennington et al. 2024).

The Next-Generation Ecosystem Experiments in the Arctic (NGEE Arctic) faced the challenge of intensive fieldwork based in a northern Alaska community with teams of experimentalists and modelers. The project developed data-sharing and citation guidelines, an online metadata editor, a searchable data cataloging tool with a user interface, and a data tracking system that notified data owners when data was downloaded. NGEE Arctic also intentionally created time and activities for interaction between disciplines (Wullschleger 2019; Iversen et al. 2020).

Distributed Projects

In the Worldwide Hydrobiogeochemical Observation Network for Dynamic River Systems (WHONDRS) collaborative network, researcher and nonresearcher volunteers collected samples at spatially distributed sites using a participatory science approach (Stegen and Goldman 2018; Garayburu-Caruso et al. 2020). WHONDRS used rapid iteration between machine learning guidance and new sampling locations for nimble collaborations and engaged in open, collaborative manuscript efforts through virtual workshops and working groups (Borton et al. 2022).

The Nutrient Network (NutNet) uses a distributed, collaborative model and focuses on long-term experiments. Any scientist who commits to installing the inexpensive experiment, performing annual sampling, and sharing data can join the collaborative NutNet group. Clear expectations are provided for data collection, management, and sharing (Borer et al. 2014) as well as authorship (Borer et al. 2023). NutNet's approach engages people across countries, institutions, and career stages.

for sustained engagement with parties interested in specific locations. In a place-based approach, using existing field stations or institutional connections can facilitate conversations and interactions that can build on trust already established with interested parties. Co-locating the research team with key interested parties, such as the U.S. Forest Service, or embedding projects at a field research station with existing community connections can effectively ease communication and increase co-leadership of projects. Successful place-based approaches in projects such as COMPASS-FME and NGEE Arctic can be implemented in future projects (see sidebar, Learning from Past Project Approaches, this page).

Distributed Approaches

Distributed projects spread research activities across space to gain transferable understanding. These projects may cover a defined geographic region or be globally distributed and have potential to engage a broad range of collaborators. Their research activities are more likely to have short temporal engagement and less infrastructure. A distributed approach generates opportunities for collaborators across a wide spatial domain that would be challenging to achieve within a single, intensive location. The team is often working outside their home community, so it is essential to avoid practices such as "parachute science," in which researchers impose their agendas without meaningful collaboration or consideration of local contexts and expertise (Jennings et al. 2023). Often, the scientific objectives driving funding and research priorities will ultimately guide decision-making processes. Nonetheless, distributed approaches offer significant flexibility, allowing teams to navigate these limitations while still promoting broad engagement. The Worldwide Hydrobiogeochemical Observation Network for Dynamic River Systems (WHONDRS) and NutNet adopted effective distributed approaches that can inform the research initiatives of future projects (see sidebar, Learning from Past Project Approaches, p. 39)

Shared Culture and Mutual Benefit

Successful external collaboration requires many of the same trust and team culture tenets that were discussed in Ch. 4: Project Management and Productive Teams, p. 29. Rather than viewing collaboration as a binary between the internal research team and external interested parties, successful projects recognize a spectrum of engagement, with people across the spectrum interacting with the team culture. External collaborators often have perspectives, knowledge, or data that can enrich the project scope, research questions, approaches, and outcomes. Including them early and often in the design and execution of the project can have great benefits. Deliberate efforts to include external collaborators in team meetings, field visits, and retreats can foster deeper engagement and help build a sense of belonging that will benefit research and collaborators. Three guiding principles can promote external collaboration:

- **Co-developing research goals and methods** creates opportunities for deeper understanding and reduces separation between parties (see sidebar, Promoting External Collaborations, this page). This approach also builds awareness for past harms of extractive research behaviors and ensures informed consent (David-Chavez and Gavin 2018).
- **Focusing on mutual benefit** balances the need for technical research goals (e.g., funding agency needs) to be met by creating opportunities that meet priorities of interested parties, such as technical, educational, community, or cultural needs. Even if the goals of each individual are not the same, by following the principle of mutual benefit, the team can align to the same plan of action.
- **Listening deeply and having an open mindset** foster strong collaborations when placed at the forefront of all interactions (see sidebar, Promoting

Promoting External Collaborations

In the WHONDRS project, **co-developing research goals and methods** played a critical role in project design. Globally distributed sampling and sensor deployment have been embedded within open engagement opportunities for study design; public data publishing; and open, collaborative manuscript writing opportunities. These activities are co-developed on a foundation of mutual benefit, in which global collaborators—some of whom are co-located with distributed sampling sites and others who simply heard of the opportunity—share their priorities and interests. In addition, the research team makes changes to studies (e.g., adding metadata fields, modifying methods, and adding data types) and co-designs opportunities (e.g., virtual classroom engagements, trainings, analysis, and writing team activities) to meet those needs while also meeting research objectives.

To cultivate strong collaborations, NGEE Arctic worked from the outset to actively engage in two-way dialogue that focused on **deep listening and an open mindset** with the communities where the team lived and worked. The project team visited the communities that owned the watersheds being considered as intensive field sites and listened to the community's needs and concerns. They also engaged with local and Native communities through an array of interactions and provided regular progress updates for the Native Corporation Boards and reports that summarized the project's scientific findings.

External Collaborations, p. 40). Teams must resist the temptation to jump into collaborations with enthusiasm for their own ideas that may not make space for ideas of external collaborators.

Some common pitfalls can hinder successful external collaborations, such as making assumptions about interested parties' needs or perspectives; rushing the relationship-building process; and eroding trust through inconsistent actions or communication. As noted in Ch. 4: Project Management and Productive Teams, p. 29, strong team culture and safe and effective communication foster success. These requirements also extend to external collaborators.

Expectations for Collaboration

Building on these cultural foundations, projects must also establish governance plans and guidance documents defining the structure and expectations within the project team, and these plans must be shared with external collaborators. When possible, external collaborators should be invited to work with the project team to co-develop these comprehensive expectations or codes of conduct for the project. Such joint efforts contribute to building strong relationships, which are hallmarks of productive collaboration.

These relationships require care, trust, time, and effective communication to thrive. Workshop participants frequently mentioned "operating at the speed of trust" to develop deep relationships that align project goals with the interests of all parties involved, ultimately fostering a sense of shared ownership and commitment. This approach requires patience and genuine investment in understanding different perspectives and priorities.

Facilitating shared experiences, such as conducting fieldwork, traveling to research sites, or engaging in informal social interactions, promotes relationship building while enhancing cross-disciplinary connections. These activities enable deeper conversations, break down barriers, and ultimately strengthen trust in interdisciplinary collaborations. Additionally, implementing principles such as Free, Prior, and Informed Consent, which originated from collaborations with Indigenous peoples, ensures that the rights and voices of all interested parties are respected and upheld (FAO 2016). These principles can guide all external engagement, not just work with Indigenous communities. Ultimately, the strategies to create a collaborative environment discussed in this section seek to empower all team members to contribute meaningfully and generate research that is both scientifically robust and relevant to a breadth of interested parties.

Shared Data and Project Outcomes

Data sharing plays a critical role in accelerating environmental system science–relevant research (Wolkovich et al. 2012; Stall et al. 2019) and enabling scientific collaborations (Lind 2016). Indeed, data sharing is a critical component for the success of ecosystem-scale research endeavors. Effectively sharing data requires set protocols and tools, such as creating standardized workflows for data integration to ensure consistent formatting, metadata, and accessibility. Piloting these workflows before or during the physical experiment, using open-source tools, codes, simulators, and emulators helps (1) emphasize the value of meticulous data documentation and (2) train scientists at all career stages to prioritize well-documented data with clear metadata and units. Careful data management and curation ensures that the legacy of collaborators' efforts remains accessible for continued discovery (see sidebar, Data Management and Curation with ESS-DIVE, p. 42).

Additionally, modelers and experimentalists often have different perspectives on data, such as developing data processing pipelines, quality control procedures, and metadata standards. These differing perspectives can lead to misunderstandings about the availability and usability of data. As one workshop participant noted, "just because data are measured doesn't mean they're available, and just because they're available doesn't mean they are usable."

In addition to data sharing, making other project outcomes available greatly benefits the entire project. For example, many projects have engaged in a wide range of activities that integrate project discovery into education and cultural opportunities across communities, agencies, and organizations. Interested parties

Data Management and Curation with ESS-DIVE

The community data repository ESS-DIVE specifically supports integration within and among BER-supported terrestrial ecosystem and watershed science experiments (Simmonds et al. 2022; Varadharajan et al. 2019). It serves as a centralized location for data storage that provides community access to these data, ensures archiving of project data, and enhances collaboration through data sharing. Looking forward, automated data workflows such as those supported in ESS-DIVE can enhance the quality and accessibility of data, as well as increase opportunities for new modeling and artificial intelligence (AI) applications. Toward this goal, network science provides important opportunities to combine local, regional, and global efforts to address broader scientific questions and confront scaling complexities (Myers-Pigg et al. 2025).

Integrating varied data and perspectives can lead to a more holistic understanding of ecosystem responses. Remote sensing, real-time sensors, and model integration, including AI, are promising approaches for advancing network science to develop predictive models.

often possess local contextual information that can significantly enhance research impact and create an opportunity to increase the value of project outcomes to site-specific collaborators.

However, differences in expectations regarding sharing data and project outcomes can pose challenges when working with external collaborators. While the culture of data hoarding is fading in favor of open data and FAIR (Findable, Accessible, Interoperable, and Reusable) principles (Stall et al. 2019), past negative experiences with data sharing can erode trust. Examples include researchers refusing to share data, even after publishing papers, and researchers demanding co-authorship for access to already-published data. Additionally, early career researchers may be more hesitant to share data compared to more senior researchers due to perceived publish-or-perish imperatives. Collaborators may also have specific concerns around sharing information related to their land, history, community, or organizations based on past experiences or injustices (e.g., the infamous Tuskegee experiment or development of the HeLa human cell line; Lucey et al. 2009).

Addressing these challenges requires both technical protocols and cultural considerations. Such protocols and considerations include:

- Co-locating modelers and empiricists to encourage positive experiences
- Developing relationships and common understandings across disciplines through shared, intentional time together
- Making data sharing safe for early career researchers through the use of embargos, clear policies, and generous co-authorship
- Adopting the Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) Principles for Indigenous Data Governance (Carroll et al. 2020), specifically the principle of "Authority to Control," which speaks to Indigenous data governance protocols and having an active role in stewardship decisions for Indigenous data that are held by other entities
- Explicitly defining time horizon expectations for both sharing and credit with respect to samples and data. Clear, agreed upon data-sharing policies and open cultures are crucial for all science, but particularly larger, interdisciplinary projects.

Experience across the large-scale projects represented in this workshop highlights the importance of clear and regular communication, trust, and data sharing for long-term success. These elements are gained, strengthened, and reinforced through regular interactions. Metrics, timelines, and expectations facilitate the success of all internal and external project participants when communicated clearly and frequently. Beyond addressing immediate needs of data and project outcome sharing, clear communication and collaboration provide strategic advantages for project resilience. Active collaboration and data sharing can be a form of insurance, one that gives a team greater flexibility to anticipate and adapt to changes. These changes may be inevitable or unexpected shocks: For example, costs increased sharply during and after the COVID-19 pandemic, overwhelming pre-existing project contingency planning. Therefore, letting go of some project scope and seeking collaborations (e.g., from nearby institutions, researchers, subcontractors, or local community members), rather than doing things alone as originally designed, can provide efficiencies and flexibilities that ensure continuity towards the project's ultimate objective.

Benefits of a Scientific Advisory Board

The scientific advisory board operates as a link between the project's core team and their extended collaborative network. A well-balanced scientific advisory board can serve many purposes. Ideally, this board would complement the expertise of the project team, be aligned with the project vision, bring a range of expertise and perspectives, and provide connections to other agencies, industries, and communities. An advisory board is an opportunity to add local community representation or land managers, thereby providing a motivated avenue for valuable community knowledge and engagement.

Scientific advisory boards can be useful at all stages of a project, offering valuable, independent evaluation of a project's central vision during ideation, critical proposal reviews, and annual progress feedback. They can also provide different perspectives during challenging phases of the project, such as recovering from natural events like fire or ice storms or navigating uncertain funding periods. In some cases, engaged scientific advisory board members can help open new areas of collaboration and greatly enable collaborative research. For example, the NGEE Arctic team collaborated closely via a formal memorandum of agreement with NASA's Arctic-Boreal Vulnerability Experiment for remote sensing scaling and using remote sensing data products to initialize and evaluate Earth system models in Phases 2 and 3 of NGEE Arctic. The NGEE Arctic Advisory Board facilitated close collaboration across projects and advocated for each in the international Arctic science realm. Ultimately, an effective scientific advisory board extends the network of a project beyond its membership, enabling exchange and access of ideas, data, and resources with a much broader community.

5.2 Conclusions and Recommendations

Well-functioning teams are critical to address large-scale environmental system science challenges, and success hinges on the seamless integration of internal and external team members. Engaging the spectrum of internal and external interested parties is critical for fostering multidisciplinary integration; enhancing research outcomes; and addressing complex, large-scale ecosystem experiments and field studies. Interested party engagement is fundamentally grounded in a collaborative team culture. The outcome is mutually beneficial research and data that support acceleration toward transferable predictive understanding while building trust and creating opportunities with interested parties. Regardless of size and resources, future long-term or large-scale projects can ensure success by prioritizing clear and open communication to break down disciplinary barriers, spark creativity, improve trust and morale, and mitigate risk. Such projects proactively plan for, and actively support, data sharing and cross-disciplinary work. These attributes are crucial to accelerate scientific discovery across ecosystem ecology and biogeosciences.

Chapter 6

Completing Experiments and Decommissioning Sites

Key Takeaways

- Plans for most long-term experiments should include explicit strategies for decommissioning and the resources to do so. These plans should be made at the start of the project and revisited throughout the project lifespan.
- Decommissioning planning should emphasize physical infrastructure removal that minimizes impacts to local communities and the landscape and reduces the project's environmental footprint. Other decommissioning activities should include scientific communication with stakeholders; site documentation; and archiving environmental samples, data, and codes.
- Project leadership in concert with program (i.e., funder) and research institutional administrations are jointly responsible for ensuring that decommissioned sites are safe and therefore must hold themselves, their team members, and their institutions accountable. Proper disposal of ecotrash—infrastructure and equipment left behind after scientific projects—not only helps safeguard communities and the environment but also protects the reputations of scientists, their institutions, and their funding agencies.

6 Completing Experiments and Decommissioning Sites

While much has been written about the design, deployment, and management of long-term, large-scale ecosystem experiments (Hanson et al. 2011, 2017), less attention has been given to the decommissioning of projects. Few studies address when, how, and why projects of varying sizes and durations are decommissioned. Ecology and biogeosciences have increasingly focused on data preservation (Kaplan et al. 2021), but physical infrastructure often goes unaddressed in retrospectives, even in long-term ecological research projects (e.g., Ohnemus et al. 2024; Waide and Kingsland 2021) or planned activities [Delwiche et al. 2024; but see the Jasper Ridge Global Change Experiment ("Jasper Ridge" 2018) and the Shortgrass Steppe Long-Term Ecological Research project (lternet.edu/site/shortgrass-steppe-lter)]. If left in place, physical infrastructure—such as sensors, cables, data loggers, towers, CO_2 vents, infrared heaters, buried cables, and supporting infrastructure like solar panels and boardwalks—has operational, safety, financial, stewardship, and reputational implications.

To recognize the importance of preplanning for experiment decommissioning, workshop participants sought to identify the major challenges to decommissioning and provide recommendations to overcome these obstacles in the future. This chapter summarizes participants' discussion during the workshop, provides specific examples of decommissioning challenges based on their own experiences, and outlines their recommendations for approaching major challenges to help the research community strategically prepare for decommissioning in future ecosystem-scale field research.

6.1 Insights into Decommissioning

Workshop participants largely agreed that decommissioning is not often a priority in pre-project planning. While some projects considered decommissioning early, most did not plan for it until funding was running out (see Fig. 6.1, p. 47). In some cases, scientists assumed funding would continue indefinitely or that someone else would take over responsibility for the project, leading them to neglect decommissioning needs.

Significant discussion and debate surrounded whether the lifespan of a project can, or even should, be predetermined. Some participants highlighted that experimental manipulations provide an important resource to the broader scientific community, even after funding ends, while others stressed the evolving nature of scientific research. Both points indicate the value of documentation and archiving samples, data, and codes as well as the potential value of transferring infrastructure and materials to new ownership for continued science rather than decommissioning. However, others found that prior site custodians had not taken care with infrastructure and the environmental footprint of their activities and that funding streams were not always able to be maintained after project transfer.

While decommissioning plans are rare to date, most workshop participants agreed that scientists should plan future experiments with decommissioning or site transferal in mind at the start of the project and revisit this priority throughout the project lifespan, balancing scientific goals with environmental impact and landowner expectations. Participants further agreed that project leadership must prioritize decommissioning

Fig. 6.1. Developing Decommissioning Plans. As part of the pre-workshop questionnaire (see Appendix D, p. 92), participants were asked when decommissioning plans were developed for their projects. Forty-two responses were collected. Fifty percent (21) of projects made plans for decommissioning during the planning phase, including during final phase planning for the project. Two projects developed plans along the way, and seven began planning for decommission when funding ran out. Twenty-one percent (9) did not plan for decommissioning at all. Three projects are still ongoing and either have not yet started planning or are just starting to plan for decommissioning.

and be accountable for its successful completion and that succession planning should emphasize decommissioning as a priority. Scientists should also consider and plan for remediation, where possible, of landscape impacts (e.g., tree mortality and permafrost degradation).

Decommissioning planning should emphasize physical infrastructure installation and removal that not only minimizes impact to local communities and the landscape but also reduces the project's environmental footprint. Extensive research on decommissioning of man-made platforms (Fortune and Paterson 2020), brownfields, and former nuclear materials sites (Burger et al. 2018) may inform decommissioning strategies. Additionally, the complex logistical considerations of decommissioning may require a project manager who can coordinate activities not directly driven by scientific research questions.

Not all participants agreed that projects needed to be decommissioned. For example, new opportunities may emerge based on technological developments or new cross-disciplinarity collaboration, and some aspects of remaining experimental infrastructure could help identify previously sampled plots or species. In turn, transfer of ownership or responsibility for infrastructure could extend the life of valuable research materials and continue long-term observations while reducing waste, multiplying scientific outcomes, and promoting partnerships with new institutions. However, in this case, the transfer must be handled carefully to prevent safety, environmental, or reputational risks. Long-term projects should evaluate the feasibility of transferring infrastructure early on, with careful attention to safety, landowner agreements, and long-term infrastructure viability. All transfer agreements should be in writing, and contingency plans for decommissioning should be in place in case transfer plans fall through.

Participants drew on their own experiences with long-term observational studies, experimental manipulations, and mobile sites. The Participant Decommissioning Experiences sidebar, p. 51, outlines how some participants navigated the end of project lifespans. For more information about individual projects listed in the sidebar, see Appendix C: Represented Projects, p. 63.

6.2 Decommissioning Challenges and Recommendations

While workshop participants acknowledged that decommissioning is hard, they agreed that it is the right thing to do—for scientists and their science, for landowners, and for sponsors. Indeed, as more scientific teams begin to include decommissioning conversations in their initial scientific planning, this process will become an expected part of the scientific endeavor. Because so few published studies describe critical factors considered when closing out or decommissioning specific field sites, participants developed a list of major decommissioning challenges informed by scientific literature and their own experiences and provided specific recommendations to overcome these obstacles in future ecosystem-scale research initiatives. The challenges and recommendations span eight decommissioning areas: (1) priorities, (2) costs, (3) community needs, (4) project duration, (5) equipment and infrastructure disposition, (6) liability and accountability, (7) sample archival, and (8) data archival.

Decommissioning Priorities

Challenges: Decommissioning has historically not been a priority in ecosystem-scale field science. Short-term projects (less than 3 years) focus more on the immediate science and often have limited time and budgets, whereas long-term projects (decadal) may see continuous infrastructure evolution. This lack of priority is in contrast to other scientific endeavors (e.g., low-Earth satellite missions), which are now required to decommission and de-orbit within 5 years (FCC 2022). Without mandates from funding agencies, decommissioning often lacks dedicated resources or planning.

Recommendations: Incorporate planning for decommissioning into the project design, including estimated labor needs, disposal costs, and reassignment of property to key partners. These plans should be revisited regularly to meet project and mission needs and expectations. Funding agencies can underscore the importance of decommissioning by requiring the inclusion of a project closeout strategy in the original research proposal.

Decommissioning Costs

Challenges: Decommissioning can be expensive and time-consuming, especially for large-scale experimental manipulations, with costs sometimes reaching 20% of initial infrastructure installation costs. Historically, this end-of-life cost has not been considered as a part of the proposal-development or budgeting process, creating tension between the need for additional scientific observations and the funds required for decommissioning.

Recommendations: Estimate decommissioning costs and set this amount of funding aside in the budget at the outset of the project or withhold a small portion of annual funds to achieve this funding amount over the project's lifespan. Also consider the opportunity cost of funding personnel to decommission rather than to collect new observations toward the end of a project's lifespan. Decommissioning costs can also be reduced with foresight, operations, and follow-through.

Community Needs

Challenges: The reputation of science—and the federal governments supporting science—have been tarnished in communities across the world by (1) "parachute science," in which researchers impose their agendas without meaningful collaboration or consideration of local contexts and expertise, as well as the perceived drop in and quickly leave approaches

(Jennings et al. 2023 and Minasny et al. 2020); (2) nuclear testing (O'Neill 2007); (3) lack of communication with interested parties in local communities (Kawerak, Inc. et al. 2024); and (4) legacies of decaying infrastructure or dangerous waste (Hughes et al. 2023). Community relationships must be developed slowly and with care, noting that the need to obtain permission and permits from local communities and their representative agencies can be a time-consuming and lengthy process.

Recommendations: Include a decommissioning plan as part of the permitting process at the project's outset so that environmental stewardship and return of lands to Native, state, and federal organizations are accomplished in a manner that is mutually agreeable to all parties involved. Importantly, funders should support and require such a plan. Notify each land-use permit holder in advance of field closeout and cleanup activities, and schedule site visits with landowners to ensure site closure meets their satisfaction. Make a final report available to partners and landowners to summarize the project's science findings, including before and after pictures of site closure.

Additionally, create and respect agreements with local communities and land stewards regarding the condition of research sites after a project has concluded. Permanent infrastructure such as electricity or road installation should only be undertaken in consultation with local interested parties. Even with cleanup, a site that was needlessly disturbed or not adequately restored loses value for local stakeholders as well as future science. At the same time, if cleanup is done well, scientific research projects can provide value to local communities.

Project Duration

Challenge: Many scientific projects evolve over time, often leading to extended durations. For example, a 3-year project may eventually run for 30 years (Melillo et al. 2017; DeAngelis et al. 2015), or prior research may inform a new project phase (e.g., the CiPHER experiment's permafrost borehole; Schuur et al. 2021). This unpredictability complicates planning for decommissioning, since research projects often evolve in unexpected ways (Norby et al. 2010; Wolkovich et al. 2012; Lindenmayer et al. 2010; Knorr et al. 2024) that can generate new questions that can be answered with an existing installation (Melillo et al. 2017; DeAngelis et al. 2015).

Recommendations: Develop a scientific project with explicit timelines, deadlines, and deliverables even if it does not have a scheduled end date. For example, projects may be forced to decommission more quickly than initially planned due to changes in program funding direction, budget cuts, or congressional guidance. As a result, contingency or change management plans are essential to decommission a project appropriately, even in an expedited manner. Such plans may include limited decommissioning to safely suspend the project until alternative funding can be identified.

Equipment and Infrastructure Disposition

Challenge: Field sites often feature complex infrastructure, including sensors, experimental chambers, and access structures like roads and boardwalks. Deciding what can be reused, recycled, or donated while adhering to the expectations of institutions, funding agencies, and local communities can be costly and complicated, particularly in remote areas with limited waste management facilities.

Recommendations: Conscious planning can reduce long-term impacts of equipment and infrastructure without sacrificing the scientific objectives. Physical infrastructure can be designed to do more with less, such as minimizing trail lengths and opting for lighter-weight materials. This approach extends to how research is carried out, such as using biodegradable or recyclable products or adopting more environmentally conscious laboratory chemistry. When possible, rethink transporting equipment (e.g., a hand cart or a backpack in place of an all-terrain vehicle) to reduce trail damage.

Compile and assess a detailed property management inventory, including maps and GPS coordinates of equipment locations, throughout the project lifespan to assess the best methods for property disposition in collaboration with partner scientific institutions and local communities, landowners, and permit holders. Disposition accountable property purchased with project funds according to individual partner institutions and prioritize equipment transfer for new scientific uses or to continue science research and datasets. Property that is no longer useful should be salvaged, recycled in place, or shipped back to home institutions to reduce local landfill impacts, especially in remote communities.

Establish a restoration plan. Replace vegetation to cover trails and other disturbances, and refill and revegetate soil pits and holes. In cases where no established techniques exist for full restoration (e.g., thawed permafrost or subsidence), plan to minimize damage at the project's outset. In addition, a common practice in wetland development is offsetting damage with restoration or preservation of a nearby, but unconnected, parcel of wetland, highlighting a role that restoration professionals could play at the end of a project's lifetime.

Liability and Accountability

Challenge: Infrastructure and equipment (e.g., batteries, buried materials, boreholes, and rebar) that are left behind after scientific projects, often referred to as ecotrash, could not only result in environmental hazards, but also injure people and damage machinery and the environment. Improper decommissioning can also damage the reputation of the project, its scientists, its associated institutions, and its funding agency.

Recommendations: Funding agencies should require all funded projects to include a study conclusion plan and an accountability statement for new proposals that emphasize both logistical and budget considerations, followed by a final report that documents the archiving and decommissioning or transfer of the project. Failure to do so may impact scientists' eligibility for future grants. Sponsor expectations should consider legislation (e.g., the National Environmental Policy Act); risk assessment tools; expectations of other funding agencies (e.g., National Science Foundation); and differing expectations of local communities, institutions, and scientific teams. A succession plan should cover the decommissioning responsibilities assigned to a project director (e.g., permits and relationships), and the project director's institution should be held accountable for the project and decommissioning outcomes.

Sample Archival

Challenge: Long-term experiments sometimes involve unique plant and soil samples altered by treatments over many years. These samples should be archived under controlled conditions, but doing so requires careful planning for long-term storage under controlled environmental conditions.

Recommendations: Provide resources for and develop a long-term sample archival facility to extend investment in long-term experiments and reach beyond existing purposes and technologies. Ideally, the facility should have the capacity to store frozen (4°C and –80°C) and dried samples and be supported by nimble and durable documentation and labeling (e.g., geosamples.org) to make samples FAIR (Findable, Accessible, Interoperable, and Reusable) when linked to metadata through digital object identifiers (DOIs). Custodians and expiration dates should also be a part of the record, enabling future researchers to access and analyze samples to address emerging questions or use analytical methods not currently available.

Data Archival

Challenge: Funding agencies increasingly require timely data archival, which becomes especially important when decommissioning a project. Final observations, harvests, and data must be documented, shared, and preserved to ensure their scientific value is realized (see also the discussion on data sharing and collaboration in Ch. 5: External Collaborations and Engagement, p. 37). Failure to publish resulting observations and data in openly available scientific literature and data archives may be seen as wasted resources.

Recommendations: Proper data management and prompt data publication are as critical as physical decommissioning to ensure research legacies endure, including appropriate metadata for long-term understanding of both observational data and modeling code.

Participant Decommissioning Experiences

Long-Term Observational Sites and Networks

AmeriFlux Management Project (AMP)

At nearly all sites that end operations, lead investigators remove instrumentation and tripod towers. Removal of taller towers and power infrastructure varies, depending on land agreements and ownership, concurrent use by other teams, and capacity of site operators. The DOE-funded AMP supports operations of a set of pre-existing investigator-led core sites with investigator-owned infrastructure. If or when this core-site funding stops, the impacted investigators could continue to use the infrastructure and sites. DOE has limited standing to control this continued use. AMP does have the ability to influence the network culture to promote responsible wrap-up or decommissioning practices.

Critical Zone Observatories/ Critical Zone Clusters

Individual investigators and teams have been responsible for decommissioning sites, and project end dates vary with several 5-year funding cycles. In some cases, instrumentation has been adopted by subsequent, related projects at universities.

FLUXNET Canada

When national support for this network ended, most towers and instrumentation remained in place. Independent scientists continued operations, albeit some with a hiatus in measurements until funding or mentorship were revived.

National Ecological Observatory Network (NEON)

While the network continues, the original idea of relocatable sites—secondary sites within each domain where measurements were not originally intended to be carried out for the entire 30-year duration of the network—was abandoned once the tower design was developed and relocation was determined to be extremely costly.

Next-Generation Ecosystem Experiment in the Arctic (NGEE Arctic)

The NGEE Arctic project spanned remote, cold field sites from Utqiaġvik to Nome, Alaska. To fulfill the promise made by project leadership to its Native Corporation partners, the team removed all equipment and materials from each intensive field site in Alaska at the conclusion of Phase 3 in September 2024. At that time, a team traveled to the communities to share scientific discoveries made in Iñupiat lands. They participated in community-led events, school visits, and radio and newspaper interviews. They also returned to each of the intensive field sites to document cleanup efforts and invited Native Corporation partners to join. They provided partners and landowners with photographs and aerial (drone) videos from before and after equipment removal. Initial listening sessions were key to engaging local and Native communities, developing trust with partners, and planning project decommissioning.

Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (WHONDRS)

Distributed participatory networks of observational sites with minimal or no field-deployed infrastructure have fewer decommissioning implications than other types of observational sites. These networks leverage existing sites and local knowledge of network participants, and data management efforts leverage community data repositories, leading to low costs of deployment and decommissioning. Measurements can be made once or repeatedly but can also be

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flexibly discontinued and restarted as driven by science needs, assuming that the participatory network community stays engaged. Therefore, changes in the status or activity of distributed networks primarily require communication with interested parties that engage with the networks. To maintain mutual benefit, the network must continue to be kept involved in and informed of decisions on network activities and future plans as well as the implications for data access and ongoing and future collaborative opportunities.

Experimental Field Manipulations

Hanford Integrated Field Research Challenge (IFRC)

The Hanford Site in Washington state was the location of a previous weapons production facility, so procedures for well installation and decommissioning were already established. Significant project funds were budgeted and provided to the Hanford Site lead contractor for well installation and closure services. The decommissioning approach for Hanford Site wells is described in annual Hanford Site Groundwater Monitoring reports (hanford.gov/page.cfm/SoilGroundwaterAnnualReports).

Hopland Soil Warming Experiment

Permission from the Hopland Research and Extension Center (Hopland, Calif.) to use the Lysimeter Facility for a soil warming experiment with buried vertical heating cables (e.g., Castanha et al. 2018) did not include a formal agreement for decommissioning. After research concluded, the project director removed all infrastructure and gave the station a short project write-up. Hopland staff have referred scientists interested in using the facility to the project director for more information (e.g., on possible legacy effects). Since the legacy effects in this case will decrease over time, this approach is adequate, but, in general, this type of referral approach depends on the project director being available or keeping long-term records.

Oak Ridge National Laboratory Free-Air CO_2 Enrichment (ORNL FACE)

After the recommendation for phase-out and decommissioning of DOE-supported Free-Air CO_2 Enrichment (FACE) experiments and open-top chambers (BERAC 2006), the CO_2 enrichment community held a workshop to discuss scientific opportunities provided by project decommissioning. However, project decommissioning proceeded in a variety of ways at different sites (U.S. DOE 2020). For example, decommissioning of ORNL's FACE experiment in a sweetgum plantation in eastern Tennessee was not part of the initial project plan. The project director and their sponsor discussed scientific aspects of the final harvest. However, these discussions did not extend to infrastructure or equipment removal, and no funding was set aside for such removal, which was estimated to be quite expensive. Ultimately, the project director decided to fund additional science associated with a final harvest rather than fund the cost of decommissioning, and some infrastructure still remains in place.

Ecosystem-Scale Rainfall Manipulation at the Sevilleta National Wildlife Refuge

Decommissioning of the stand-scale rainfall manipulation and warming experiment in a piñon–juniper woodland at the Sevilleta National Wildlife Refuge (Pangle et al. 2012) was not part of the initial project plan. Some drought plots were removed after trees died, while others were left intact where trees survived. The intact plots were later used for National

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Science Foundation–funded projects (e.g., Thompson et al. 2023). The intact plots were highly valuable, providing a 10-year drought treatment to compare with newly installed treatments.

Smithsonian Environmental Research Center (SERC) Open-Top CO_2 Experiments (OTC)

Formal plans to decommission the tidal marsh elevated CO_2 experiment were not included in the original DOE proposal or subsequent proposals and still do not exist nearly 40 years into the ongoing experiment. Since the research site is part of SERC property, the implicit assumption is that decommissioning responsibilities will reside with the institution. However, the research teams assume that much of the infrastructure (e.g., boardwalks and chambers) will be left in place to support future wetland research activities as well as continual monitoring of key variables such as plant productivity under ambient conditions. Additionally, a similar open-top chamber CO_2 manipulation study focused on a scrub-oak forest at NASA's Kennedy Space Center in Florida also lacked a decommissioning plan. Upon the decision to terminate the FACE and OTC projects in 2006, SERC and NASA staff collaborated to complete final destructive harvests and remove most of the infrastructure. Attempts to fund a legacy CO_2 effect study were unsuccessful; thus, the residual infrastructure stayed until a controlled burn forced final removal of remaining facilities and instrumentation.

South Oyster Site Bacterial Transport

The site was owned by The Nature Conservancy (TNC), and a site closure plan was negotiated with TNC in late 2001 as research was ending (Onstott 2005). The sponsor provided funding after the end of research activities to support site decommissioning. A required subsurface monitoring program was initiated in January 2002 to ensure that the groundwater system returned to its natural state. Following the monitoring period, all wells were removed, and the site was closed in September 2005. As a service to TNC and the local community, the site was replanted with warm season grasses known to scavenge nitrate from groundwater, which was an issue due to nitrate emanating from upgradient farms. Outcomes of the nitrate study were presented to TNC and local community groups.

Spruce and Peatland Responses Under Changing Environments (SPRUCE)

Objectives for decommissioning and removing infrastructure upon study completion were established at the inception of the experiment under a memorandum of understanding between Oak Ridge National Laboratory and the U.S. Forest Service—the landowner of the site where SPRUCE is located. Funding was set aside over time to enable this process to proceed at the end of SPRUCE operations (i.e., the 2025 calendar year). The amount of infrastructure removal, transfer, and recycling of materials and instrumentation are the subject of ongoing discussions.

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Deployed Mobile Facilities

Arctic-Boreal Vulnerability Experiment (ABoVE)

NASA’s Terrestrial Ecology Program supported ABoVE, a larger community field campaign operated in Alaska and northwestern Canada from 2016 to 2025. Additionally, five pre-ABoVE preparatory projects operated from 2014 to 2016. ABoVE was conducted in three phases with Phase 1 operating from 2016 to 2018, Phase 2 from 2019 to 2022, and Phase 3 from 2023 to 2025.

Decommissioning of individual investigator field sites occurred during the phase in which the site was last funded for ABoVE research. Although much ABoVE research leveraged long-term research sites run by NEON, the National Science Foundation's Long-Term Ecological Research program, and Toolik Lake Field Station, and continued operating after ABoVE. In all cases of decommissioning, best efforts were made to remediate the site and return the environment to its pre-ABoVE state.

Decommissioning of the ABoVE Logistics Office in Fairbanks, Alaska, involved the donation of usable equipment to the University of Alaska Fairbanks or to local charities. Key instrumentation and equipment were preserved to support future NASA projects such as Frontlines of Rapidly Transforming Ecosystems, Arctic-Coastal Land Ocean Interactions, and SnowEx campaigns.

The funding agency program manager ultimately decided whether funding for decommissioning was included in individual investigator budgets or as part of the overall budget for the ABoVE Logistics Office. However, it is important to note that decommissioning costs were required budget elements from the outset of the experiment.

Atmospheric Radiation Measurement (ARM) Mobile Facilities (AMFs)

AMFs carry out full-site stand-up and decommissioning every 1 to 2 years. These are frequently relocated, full observatories that host many externally funded small field campaigns at each location. ARM dedicates resources to fixed and mobile sites to ensure each small project has been conducted responsibly and decommissioned appropriately. AMFs provide a starting template for designs to decommission a multipurpose sampling site. One example is the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign, which the AMF2 located near Gothic, Colo., for about 16 months. It hosted 15 small field campaigns with full remediation activities completed months after the end of the field campaign.

Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA-ECO)

LBA-ECO was a NASA-funded component of the Brazilian LBA project. When LBA-ECO concluded, NASA handed off its activities to partners in Brazil to continue ongoing LBA work. The main U.S. investment in infrastructure, including flux towers and a field camp, were passed to Brazilian organizations. Individual investigators mostly donated instrumentation and other equipment to partners at Brazilian universities and government laboratories. A small portion of investigator equipment was exported from Brazil to the United States. Data from LBA-ECO projects was mirrored in Brazilian and U.S. information systems. LBA-ECO held a final science team meeting in Brazil that highlighted the contributions of Brazilian students and researchers who were supported to attend the meeting.

7 Conclusions and Criteria for Success

Ecosystem-scale experimental manipulations provide irreplaceable cause-and-effect hypothesis tests that enable leaps forward in understanding terrestrial processes. However, many challenges to large-scale, multidisciplinary science projects must be addressed to achieve success. The Lessons Learned from Ecosystem-Scale Experimental Field Studies workshop aimed to understand what contributed to the successes and challenges of these studies in an attempt to provide an ecosystem experiment primer that defines key attributes the broader community should consider when designing and launching future ecosystem studies. Workshop participants identified best practices for seven key categories:

- Experimental planning
- Data–model integration
- Project organization and management
- Team communication and culture
- Data management
- Collaboration and engagement
- Decommissioning planning

This chapter summarizes participants' findings in these categories and suggests potential criteria to assess project success.

7.1 Best Practices for Ecosystem-Scale Experimental Field Studies

Experimental Planning

Ecosystem-scale experiments can address complex questions about Earth system processes, ecosystem change, and mechanistic causality, issues that are difficult to study through passive observation alone. Effective experimental designs balance statistical and logistical trade-offs of different approaches, such as regression versus analysis of variance designs, individual site-centered projects, networked studies, and other approaches. Experimental designs are statistically more powerful when integrated with locally and regionally distributed observations and more targeted complementary field and laboratory experiments. Finally, the primary manipulative experiment should be flexibly designed to allow the project to pivot with unanticipated discoveries or challenges.

Data–Model Integration

The ModEx approach, in which information from models and experiments are continuously exchanged, is particularly useful for experimental design. It facilitates identification of key processes that are missing or poorly understood in models. Coupling models with experiments is crucial to guiding site selection, measurements, and sampling designs. Pre-experiment models can suggest what to measure, when to measure, and where to measure key features or processes. For best data–model integration, empiricists and modelers should develop experiments together and have consistent communication to align data collection with modeling needs and vice versa.

Project Organization and Management

Effective management is guided by a clear, shared science vision. Flexible management should balance the project's long-term goals with new opportunities and unexpected events. A collaborative approach to leadership reduces the risk of single points of failure; projects need to pre-plan succession and engage junior scientists. Additionally, project leaders should ensure that teams keep project goals at the forefront throughout the experiment life cycle. Finally, mentoring and promoting a culture of feedback are critical for empowering team members and driving scientific innovation and productivity.

Team Communication and Culture

Successful teams require a strong, team-wide commitment to trust, respect, and safe communication. Clear and transparent communication breaks down disciplinary barriers, sparks creativity, improves trust and morale, and mitigates risk. Fostering collaborative team culture includes setting clear guidelines for credit and authorship along with clearly stated responsibilities and accountabilities. Regular, substantive communication with the funding agency or sponsors is vital to maintain support, excitement, and resource access. Embedding modelers and empiricists into all project teams and creating space, time, and activities for their interactions builds trust across the team and fosters more creative and impactful outcomes. Every participant in a study, from students to technicians to senior investigators, needs to have ownership and an opportunity to contribute to the project's overall success.

Data Management

Large-scale projects need dedicated data teams that are empowered to manage, coordinate, disseminate, and troubleshoot researchers' data. Clearly defined and adaptable workflows for sharing data, metadata, and model output facilitate these collaborations. Consistently used online platforms are valuable for communication, transparency, and trust among research teams scattered across different time zones and disciplines. Additionally, projects should adopt a "document often" and "document centrally" approach to ensure resilient continuity of activities long after individuals depart the team.

Collaboration and Engagement

Local communities and external collaborators are crucial to the success of large ecosystem experiments. Engaging with local communities before and throughout experiments is essential to design and execute experiments with the greatest awareness of the local system and its opportunities and challenges. Tailored engagement strategies—whether for intensive, locally embedded studies or for distributed, broad-scale approaches—maximize technical outcomes and mutual benefit with partners. Finally, maximizing trust by promoting communication with local communities and collaborators is a crucial step.

Decommissioning Planning

Plans for the end of an experiment should be considered at the project's beginning. Effective wrap-up plans are important to ensure data are properly saved in repositories, deliverables are completed, and trust is maintained with local communities. Resources should be explicitly allocated for decommissioning and project wrap-up, with those needs being regularly updated as the experiment evolves. Responsible project wrap-up should include planning and implementation of final sampling; archiving of samples, data, and code; and sharing best practices. Dedicated efforts to communicate study findings to the scientific community, funding agencies, and external interested parties are critical and essential parts of a project's legacy.

7.2 Criteria for Assessing Success

Throughout the workshop, several discussions emerged about how research teams, funding agencies, and the external community could assess the success of a long-term or large-scale study. No single criteria list can adequately represent the unique boundary conditions, drivers, expectations, and objectives set by each study. However, several key criteria did emerge that can be used to assess performance and long-term value at each stage of a study, including its design, implementation, operations, and completion. These criteria include:

Design Phase

- Scientific goals are recognized as meaningful and important by the scientific community.
- Research life cycle planning is conducted carefully with flexibility built into the design at the outset and planned through decommissioning.

Implementation Phase

- Management is flexible, collaborative, communicates effectively, and develops capacity for current and future leadership, enabling nimble responses to changing circumstances and unexpected events.
- Projects address core scientific goals but also embrace thoughtfully planned high-risk, high-reward endeavors.

Operations Phase

- Leadership makes careful and intentional investments in all project participants and across the collaborative team, from students and technicians to senior investigators.
- Projects build a supportive culture where physical and psychological safety are protected for all team members.
- Clear and open communication is established, allowing external partners and communities to effectively engage with the project.
- Research findings are communicated to the entire team, interested parties, the public, and funding sponsors.

Completion Phase

- Papers, data, knowledge, and collaborative teams produced through the project represent significant advances that persist beyond the project.
- Decommissioning minimizes negative long-term impacts to communities and the environment.
- The intellectual impact and legacy of these projects—and the well-trained project teams—extend beyond papers and datasets, fostering new collaborations and leading to follow-on research led by the next generation of scientists.

Ultimately, the findings in this report are not a one-size-fits-all solution, and teams, along with funding agencies, will need to achieve the right balance to meet proposed objectives and goals. However, it is important to remember that scientific curiosity is what motivates people to undertake challenging long-term and large-scale ecological research endeavors. As such, the scientific community needs to make time to reflect and have fun throughout the rewarding scientific process.

Appendix A
Workshop Agenda

All times Eastern

Day 1: Tuesday, January 14

11:00 a.m.		**Welcome:** Daniel Stover, Dorothy Koch, and Gary Geernaert (U.S. Department of Energy)
11:10 a.m.		**Introductions**
12:10 p.m.		**Workshop Charge and Expectations:** Daniel Stover and Beth Drewniak (U.S. Department of Energy)
12:25 p.m.		**Workshop Process and Agenda:** Beth Drewniak
12:30 p.m.		**Break**
12:45–4:00 p.m.		**Breakout Session 1: Science Questions, Design, Methods, and Site Selection**
	12:55 p.m.	**Survey Report-Out:** Elizabeth Borer (University of Minnesota)
	1:05 p.m.	**Panel Discussion:** Peter Groffman (Cary Institute of Ecosystem Studies and City University of New York); Lara Kueppers (University of California–Berkeley); Pat Megonigal (Smithsonian Environmental Research Center)
	1:35 p.m.	**Breakout Session 1**
	3:05 p.m.	**Break**
	3:20 p.m.	**Out-Briefings from Breakout Session 1**
	3:40 p.m.	**Discussion**
4:00 p.m.		**Discuss Plans for Thursday**
4:30 p.m.		**Adjourn**

Day 2: Thursday, January 16

11:00 a.m.	**Welcome and Reconvening Comments**	
11:10 a.m.–1:20 p.m.	**Breakout Session 2: Management and Operations and Collaborations and Data Sharing**	
	11:10 a.m.	**Survey Report-Out:** Tim Scheibe (Pacific Northwest National Laboratory)
	11:20 a.m.	**Panel Discussion:** Nicki Hickmon (Argonne National Laboratory); Bruce Hungate (Northern Arizona University); Andrew Richardson (Northern Arizona University)
	11:40 a.m.	Breakout Session 2
	12:40 p.m.	Break
	12:50 p.m.	Out-Briefings from Breakout Session 2
	1:10 p.m.	Discussion
1:20–3:40 p.m.	**Breakout Session 3: Interested Party Engagement and Pitfalls**	
	1:20 p.m.	**Survey Report-Out:** Aimée Classen (University of Michigan)
	1:40 p.m.	**Panel Discussion:** Amy Goldman (Pacific Northwest National Laboratory); Ted Schuur (Northern Arizona University); Stan Wullschleger (Oak Ridge National Laboratory, retired)
	2:00 p.m.	Breakout Session 3
	3:00 p.m.	Break
	3:10 p.m.	Out-Briefings from Breakout Session 3
	3:30 p.m.	Discussion
3:40–5:20 p.m.	**Breakout Session 4: Decommissioning and Wrap-Up**	
	3:40 p.m.	**Survey Report-Out:** Paul Hanson (Oak Ridge National Laboratory)
	3:50 p.m.	**Panel Discussion:** Colleen Iversen (Oak Ridge National Laboratory); Nate McDowell (Los Alamos National Laboratory); Margaret Torn (Lawrence Berkeley National Laboratory)
	4:20 p.m.	Breakout Session 4
5:20 p.m.	**Adjourn**	

Day 3: Friday, January 17

11:00 a.m.	**Welcome and Reconvening Comments**	
11:10–11:40 a.m.	**Breakout Session 4: Decommissioning and Wrap-Up, Continued**	
	11:10 a.m.	Out-Briefings from Breakout Session 4
	11:30 a.m.	Discussion
11:40 a.m.–1:40 p.m.	**Breakout Session 5: What Hasn’t Been Discussed?**	
	11:40 a.m.	**Survey Report-Out:** Beth Drewniak (U.S. Department of Energy)
	11:50 a.m.	Breakout Session 5
	12:50 p.m.	Break
	1:10 p.m.	Out-Briefings from Breakout Session 5
	1:30 p.m.	Discussion
1:40 p.m.	**Open Discussion and Word Cloud**	
2:10 p.m.	**Report Writing Tasks and Path Forward**	
4:45 p.m.	**Summary and Closing**	

Appendix B

Workshop Participants

Organizers

Elizabeth Borer, *University of Minnesota*

Aimée Classen, *University of Michigan*

Paul Hanson, *Oak Ridge National Laboratory*

Tim Scheibe, *Pacific Northwest National Laboratory*

Daniel Stover, *U.S. Department of Energy*

Beth Drewniak, *U.S. Department of Energy*

Attendees

Vanessa Bailey, *Pacific Northwest National Laboratory*

Gil Bohrer, *Ohio State University*

Ben Bond-Lamberty, *Pacific Northwest National Laboratory*

Eoin Brodie, *Lawrence Berkeley National Laboratory*

Serita Frey, *University of New Hampshire*

Amy Goldman, *Pacific Northwest National Laboratory*

Allison Goodwell, *University of Illinois–Urbana-Champaign*

Chris Gough, *Virginia Commonwealth University*

Peter Groffman, *City University of New York/ Cary Institute of Ecosystem Studies*

Nicki Hickmon, *Argonne National Laboratory*

Kirsten Hofmockel, *Pacific Northwest National Laboratory*

Jennifer Holm, *Lawrence Berkeley National Laboratory*

Bruce Hungate, *Northern Arizona University*

Colleen Iversen, *Oak Ridge National Laboratory*

Julie Jastrow, *Argonne National Laboratory*

Lixin Jin, *University of Texas–El Paso*

Charlie Koven, *Lawrence Berkeley National Laboratory*

Lara Kueppers, *University of California–Berkeley*

Nate McDowell, *Pacific Northwest National Laboratory*

Pat Megonigal, *Smithsonian Environmental Research Center*

Chip Miller, *NASA Jet Propulsion Laboratory*

Jesse Nippert, *Kansas State University*

Rich Norby, Retired, *Oak Ridge National Laboratory*

Peter Reich, *University of Michigan and University of Minnesota*

Andrew Richardson, *Northern Arizona University*

Alistair Rogers, *Lawrence Berkeley National Laboratory*

Dave Schimel, *NASA Jet Propulsion Laboratory*

Ted Schuur, *Northern Arizona University*

Benjamin Sulman, *Oak Ridge National Laboratory*

Pamela Templer, *Boston University*

Peter Thornton, *Oak Ridge National Laboratory*

Margaret Torn, *Lawrence Berkeley National Laboratory*

Diane Wickland, Retired, *NASA*

Stan Wullschleger, Retired, *Oak Ridge National Laboratory*

Observers

Paul Bayer, *U.S. Department of Energy*

Brian Benscoter, *U.S. Department of Energy*

Julia Diaz, AAAS Fellow, *U.S. Department of Energy*

Beth Drewniak, Detailee, *U.S. Department of Energy and Argonne National Laboratory*

Gary Geernaert, *U.S. Department of Energy*

Jay Hnilo, *U.S. Department of Energy*

Dorothy Koch, *U.S. Department of Energy*

J. Michael Kuperberg, *U.S. Department of Energy*

Jeremy Semrau, IPA, *U.S. Department of Energy and University of Michigan*

Daniel Winkler, *U.S. Department of Energy*

Appendix C

Represented Projects

Projects Represented at the Lessons Learned from Ecosystem-Scale Experimental Field Studies Workshop

Asterisk (*) denotes projects that contributed data for the "Studying Ecosystems at Scale" infographic, p. 4.

Alpine Treeline Warming Experiment (ATWE)*

lara-kueppers.com/alpine-treeline-warming-experiment/

Location: Niwot Ridge, CO
Years Active: 2008–2016 (with limited ongoing measurements)

ATWE was a multilocation warming, watering, and common garden experiment to examine tree range shifts. The project combined common gardens with climate manipulations, using infrared heaters to warm soil and plant surfaces by an amount comparable to current average projections of climate warming in the year 2100. ATWE set out to answer three basic questions: (1) Will subalpine trees, currently restricted from cooler, higher elevations, move into alpine habitat and replace alpine plant species as a result of climate warming? (2) Will subalpine trees be stressed by warmer temperatures and be less successful in their existing elevational ranges as a result of climate warming? (3) How will ecosystem properties and species population differences influence the effects of climate warming on subalpine or alpine species within and beyond their current elevational ranges?

Arctic-Boreal Vulnerability Experiment (ABoVE)

above.nasa.gov

Location: Alaska and western Canada
Years Active: 2015–Present

A NASA Terrestrial Ecology Program field campaign, ABoVE is a large-scale study of environmental change and its implications for social–ecological systems that seeks a better understanding of the vulnerability and resilience of ecosystems and society to this changing environment. The project's science objectives are broadly focused on (1) gaining a better understanding of the vulnerability and resilience of Arctic and boreal ecosystems to environmental change in western North America and (2) providing the scientific basis for informed decision-making to guide societal responses at local to international levels. ABoVE research links field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving the analysis and modeling capabilities needed to understand and predict ecosystem responses and societal implications.

AmeriFlux Management Project (AMP)

ameriflux.lbl.gov/about/about-ameriflux/ameriflux-management-project/

Location: North, Central, and South America, and Canada
Years Active: 2012–Present

DOE established AMP in 2012 at Lawrence Berkeley National Laboratory to support the broad AmeriFlux community and the AmeriFlux sites. AMP works with AmeriFlux scientists and sites to ensure the quality and availability of the continuous, long-term ecosystem measurements necessary to understand these ecosystems and to build effective models and multisite synthesis.

Atmospheric Radiation Measurement (ARM) User Facility*

www.arm.gov

Location: Worldwide
Years Active: 1992–Present

DOE's ARM User Facility delivers 30-plus years of atmospheric measurements, including data sets from all seven continents and five oceans, to advance the understanding of the Earth's atmosphere. ARM provides the climate research community with strategically located atmospheric observatories to improve understanding and representation in Earth system models of clouds and aerosols and their interactions with the Earth's surface.

Barre Woods Soil Warming Experiment

harvardforest1.fas.harvard.edu/exist/apps/datasets/showData.html?id=hf018

Location: Harvard Forest (Petersham, MA)
Years Active: 2003–2023

Conducted in the Barre Woods area of the Harvard Forest, this soil warming experiment examined long-term warming on soil biogeochemistry using two 30 by 30 m megaplots (a heated plot and a control plot) that encompassed whole trees. The purpose of the study was to determine whether warming results in the movement of nitrogen from the soil to the trees and to learn how this movement affects the net carbon balance of the ecosystem.

Bartlett Experimental Forest AmeriFlux Site

ameriflux.lbl.gov/sites/siteinfo/US-Bar

Location: Bartlett Experimental Forest (Bartlett, NH)
Years Active: 2004–Present

Initiated in 2004 as a pilot "Tier II" site for the North American Carbon Program, the Bartlett Experimental Forest AmeriFlux site enables long-term observations to study trends and variability on seasonal-to-interannual timescales. The tower is surrounded by an array of forest inventory and analysis plots. Despite limited funding, the project has been maintained for 20-plus years and data show a significant reduction in carbon sink strength over the period of record.

Belowground Biogeochemistry Science Focus Area*

tes.lbl.gov

Location: Various locations across Northern California
Years Active: Terrestrial Ecosystem Sciences SFA 2012–2018; Belowground Biogeochemistry SFA 2018–Present

The Belowground Biogeochemistry Science Focus Area (SFA), previously the Terrestrial Ecosystem Sciences 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. To accomplish these goals, this SFA integrates a team of experts in biogeochemistry and ecosystem ecology, microbial ecology and genomics, geochemistry, and ecosystem modeling. The SFA has run a whole-soil warming experiment since 2014 at Blodgett Forest Research Station, CA.

Biodiversity, Carbon Dioxide, and Nitrogen (BioCON) Experiment and Temperature, Rainfall, Carbon Dioxide, and Nitrogen (TeRaCON) Experiment

cedarcreek.umn.edu/research/experiments/e141

Location: University of Minnesota Cedar Creek Ecosystem Science Reserve (East Bethel, MN)
Years Active: BioCON 1997–Present; TeRaCON 2012–Present

The BioCON and TeRaCON projects involve multiple nested global change experiments to address basic scientific questions about coupled biogeochemical cycles, biodiversity, temperature, and rainfall, and their impacts on plant and soil processes from leaf to community to ecosystem scales. The main BioCON experiment was designed to test interactions among species diversity, elevated carbon dioxide, and nitrogen deposition (Reich et al. 2001). TeRaCON, a subexperiment within BioCON, investigates synergistic effects of four drivers–temperature, rainfall, carbon dioxide, and nitrogen deposition–on terrestrial carbon cycling.

Boreal Forest Warming at an Ecotone in Danger (B4WarmED)

forestecology.cfans.umn.edu/research/climate-change

Location: University of Minnesota Cloquet Forestry Center (Cloquet, MN) and Hubacheck Wilderness Research Center (Ely, MN)
Years Active: 2008–Present

B4WarmED researchers assess the potential for climate warming to alter tree species composition at the southern boreal–temperate forest ecotone by experimentally warming 72 plots at two forested sites in northern Minnesota. This experiment enables researchers to examine multiple processes at different scales and document the effects on establishment, growth, and survival of seedlings of 10 important tree species near their warmer or colder range limits to understand how direct and indirect climate effects influence germination, growth, and survival at the establishment stage.

Boreal Soil and Air Warming (BoSAW)

Location: Northern Manitoba, Canada
Years Active: 2004–2007

BoSAW is a large-scale manipulative experiment warming both soil and air in a black spruce plantation of a Canadian boreal forest. The project was created to understand the interacting effects of growing season warming and shrinking winter snowpack (with greater frequency of soil freeze-thaw cycles) on a northern hardwood forest.

Carbon in Permafrost, Experimental Heating Research (CiPEHR) Project*

www2.nau.edu/schuurlab-p/CiPEHR.html

Location: Eight Mile Lake research site near Healy, AK, just outside Denali National Park
Years Active: 2008–2022; Warming manipulations have ended but plots continue to be monitored for permafrost recovery.

CiPEHR is an ecosystem air and soil warming experiment that was established to test hypotheses about changes in the carbon cycle that are expected as a result of warming temperatures and permafrost thaw. The CiPEHR project used snow fences coupled with spring snow removal to increase soil and permafrost temperatures and open-top chambers to increase growing season air temperatures.

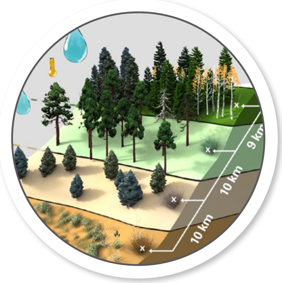
Cedar Creek Long-Term Ecological Research (CDR LTER) Program

cedarcreek.umn.edu/

Location: East Bethel, MN
Years Active: 1982–Present

Research at CDR LTER uses mathematical models, experiments, and long-term data from grasslands, savannas, and forests to forecast how these interacting human-driven environmental changes will alter Earth's ecosystems and the ability of ecosystems to provide the services that support human well-being.

C. Hart Merriam Elevation Gradient Climate Change Experiment



Location: Northern Arizona
Years Active: 2002–2024

The C. Hart Merriam Elevation Gradient Experiment offers a model for conducting impactful, long-term research on a sustainable budget. Initiated in 2002, the experiment utilized a cost-effective passive warming design, transplanting intact soil monoliths along a natural elevation gradient to simulate climate change without the high energy and infrastructure costs of active manipulations. This sustainable approach enabled a 22-year study, which proved critical for uncovering ecosystem responses that short-term experiments would miss. For instance, an initial stimulation in plant productivity was found to diminish over time, a progressive effect that reverses the conclusions a typical three-year study might draw (Wu et al. 2012). Furthermore, the decadal timescale was essential for gaining the statistical power needed to confidently detect a cumulative loss of nearly one-third of all soil carbon (Purcell et al. 2021). Because soil carbon is a large reservoir that turns over slowly, short-term changes are often too small to be distinguished from natural variability and measurement noise. By extending the experiment over two decades, the cumulative effect size became large enough to be clearly detected, demonstrating that sustained investment is necessary to quantify critical changes in slow-moving pools vital to Earth system feedbacks.

Chronic Nitrogen Amendment Study

Location: Harvard Forest (Petersham, MA)
Years Active: 1988–Present

The Chronic Nitrogen Amendment Study is a long-term experiment investigating the effects of increasing atmospheric nitrogen on a temperate forest ecosystem. The study focuses on how forest ecosystems respond to chronic nitrogen additions, particularly in red pine and mixed deciduous stands.

Climate Adaptation and Sustainability in Switchgrass*

Location: Batavia, IL.; Columbia, MO.; Temple, TX
Years Active: 2015–Present

This large genome-by-environment project addresses sustainable switchgrass production by exploring plant systems, the plant microbiome, and ecosystem processes through the integrative lens of multiscale modeling. Researchers began by exploring plant–microbe–soil interactions across continental scale environmental gradients (first 5 years), then shifted to testing predictions of plant–microbe–environment interactions to optimize climate adaptation and improve sustainability in switchgrass feedstocks (second 5 years). The goal of the ecosystem processes (plot-scale) component of this project was to evaluate the impacts of switchgrass traits and phenology, productivity, and associated microbial communities on aboveground and belowground carbon cycling (e.g., soil respiration and net ecosystem exchange) and soil carbon (and nitrogen) pool dynamics across continental-scale environmental gradients. Together with the genome-wide association study component of the project (at seven additional sites from southern Texas to South Dakota), researchers aimed to identify plant–microbe–soil traits that may be manipulated, through breeding or agronomic management, to improve the sustainability of biofuel feedstocks.

Climate Change Across Seasons Experiment (CCASE)

hubbardbrook.org/project/climate-change-across-seasons-experiment-ccase/

Location: Hubbard Brook Experimental Forest (Woodstock, NH)
Years Active: 2012–Present

The CCASE project investigates the interactive effects of climate change on forest ecosystems, specifically focusing on the combined impacts of winter soil freeze-thaw cycles and growing season warming. The experiment aims to understand how these changes impact trees, soil microbes, and biogeochemical processes in northern hardwood forests.

Coastal Observations, Mechanisms, and Predictions Across Systems and Scales–Field, Measurements, and Experiments (COMPASS-FME)*

compass.pnnl.gov/FME/COMPASSFME

Location: Mid-Atlantic, Great Lakes (Lake Erie)
Years Active: 2020–Present

COMPASS-FME aims to build a transferable understanding and capability to predict how carbon, nutrient, and water exchanges vary across coastal terrestrial–aquatic interfaces and in response to ecosystem state changes. COMPASS-FME research captures and represents ecosystem control points with spatially and temporally appropriate resolution based on drivers (e.g., sea level rise, lake-level change, and extreme events) to predict the ensuing impacts to ecosystems. Through a combination of observations, experiments, and modeling, the project creates transferable models applicable across different study regions in support of the Energy Exascale Earth System Model (E3SM).

Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE)*

Location: Multiple U.S. sites representing forest, grassland, and agricultural ecosystems
Years Active: 1999–2011

The CSiTE project involved multiscale, integrated laboratory, field, and modeling research that capitalized on existing field sites with chronosequences, long-term manipulations, or varied management practices. Phase 1 aimed to discover and characterize links between mechanisms for enhancing the creation of larger, longer-lasting carbon pools in terrestrial ecosystems. Specific objectives were to develop (1) fundamental understanding of carbon capture and sequestration mechanisms from the molecular scale to the landscape, (2) conceptual and simulation models for extrapolation of process understanding across spatial and temporal scales, (3) estimates of regional and national carbon sequestration potential, and (4) assessments of environmental impacts and economic implications of different approaches to carbon sequestration.

Phase 2 of CSiTE aimed to deepen and test process understanding of the roles of carbon inputs, soil structural controls, microbial community function and dynamics, humification chemistry, and intrasolum carbon transport on soil carbon sequestration. To achieve these objectives, Phase 2 used coordinated, intensive, hierarchically organized field and modeling studies—in the context of the potential carbon sequestration opportunities afforded by large-scale production of perennial herbaceous bioenergy crops, such as switchgrass.

Critical Interface Network (CINet) in Intensively Managed Landscapes

data.imlczo.org

Location: Multiple sites in Illinois, Nebraska, and Iowa
Years Active: 2021–Present

The CINet project focuses on critical interfaces, which are regions important to material transport and transformation in the Earth's critical zone, and include root-soil, near surface, and river-floodplain environments. CINet researchers study processes at these critical interfaces in midwestern U.S. landscapes that are intensively managed for agriculture to gain predictive understanding of dynamics under controls of climate and weather, glacial landscape legacy, and human energy inputs.

Critical Zone Observatories (CZO) / Critical Zone (CZ) Clusters

https://criticalzone.org/

Location: Across the United States

The Critical Zone Collaborative Network (CZNet) is funded by NSF's Critical Zone research program, comprised of nine Thematic Clusters and one coordination hub. The study areas cover a wide range of geological, climatic, and land-use settings that provide an opportunity to better understand the evolution, service, and function of the critical zone. CZNet builds upon the outcomes of the Critical Zone Observatories to address significant interdisciplinary scientific questions at the regional and national scale and develop predictive models of complex critical zone phenomena with future shifts in climate and land use.

Detrital Input and Removal Treatments (DIRT) Network

dirtnet.wordpress.com

Location: China, Germany, Hungary, and the United States
Years Active: 1956–Present

The international DIRT network was established to assess how rates and sources of plant litter inputs control the long-term stability, accumulation, and chemical nature of soil organic matter in forested ecosystems over decadal time scales. DIRT scientists have established treatment plots in several locations worldwide where long-term litter manipulations are conducted. Sites span climatic and soil gradients.

Drylands Critical Zone Project*

drylandcz.org

Location: Multiple sites in Texas, New Mexico, and Idaho
Years Active: 2020–Present

This project aims to increase capacity to quantify and predict dryland carbon budgets across land-use and climatic gradients by examining the role of water and nutrient availability in regulating the movement of organic and inorganic carbon.

Ecosystem-Scale Rainfall Manipulation at the Sevilleta National Wildlife Refuge*

digitalrepository.unm.edu/lter_sev_data/77/

Location: Sevilleta, NM
Years Active: 2006–2011

This large-scale experimental system allowed testing of the ecosystem impacts of precipitation changes. Researchers replicated drought, drought-control, ambient, and irrigation treatments along with tree mortality, measurements, and modeling.

Elevated Carbon Dioxide x Nitrogen Addition*

serc.si.edu/gcrew/nitrogen

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 2005–Present

In this tidal marsh whole-ecosystem global change manipulation, two levels of atmospheric carbon dioxide (ambient, 750 parts per million) are crossed with two levels of nitrogen addition (+0, +25 g/m^2/yr) in a native C3 plant community. The goal is to test hypotheses about interactions between elevated carbon dioxide and nitrogen limitation on soil carbon sequestration rates through soil elevation gain, including the progressive nitrogen limitation hypothesis.

Elevated Carbon Dioxide x Nitrogen x Phragmites*

serc.si.edu/gcrew/phragmites

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 2011–Present

In this tidal marsh whole-ecosystem global change manipulation, two levels of atmospheric carbon dioxide (ambient, 750 ppm) are crossed with two levels of nitrogen addition (+0, +25 g/m^2/yr) in a native C3 plant community undergoing displacement by invasive *Phragmites australis*. The goal is to test hypotheses about the influence of elevated carbon dioxide and nitrogen limitation on competition between native plant species and a novel species with distinctly different traits, including the role of genetic variation in traits among genotypes.

Elevated Carbon Dioxide x Plant Trait Experiment*

serc.si.edu/gcrew/CO2

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 1987–Present

This tidal marsh whole-ecosystem global change manipulation studies two levels of atmospheric carbon dioxide (ambient, 750 ppm) are in three plant communities (C3, C4, Mixed C3+C4). The initial goal was to test hypotheses about negative feedbacks between rising carbon dioxide and photosynthesis in a field setting. It evolved over decades to test hypotheses about the effects of elevated carbon dioxide interacting with sea level rise on the resilience and greenhouse gas balance of coastal ecosystems.

Enriched Background Isotope Study (EBIS)

Location: Multiple sites across a climate and soil gradient throughout the eastern United States
Years Active: 2000–2013

Made up of a multi-institutional team, EBIS used enriched background (^{14}C) litter deployment in a range of eastern U.S. forest sites to evaluate the carbon transfer rate from litter deposits to the underlying mineral soils. The project allowed for significant improvement in understanding and model representation of ecosystem carbon cycling.

Eucalyptus Free-Air CO_2 Enrichment (EucFACE)

eucface.hieresearch.org

Location: New South Wales, Australia
Years Active: 2013–Present

EucFACE aims to predict decades in advance the effects of exposure to rising carbon dioxide (CO_2) levels on Australian unique native forest ecosystems. The project exposes large areas of Australia's Cumberland Plain Forest, a mature eucalyptus woodland, to elevated CO_2 at around 550 ppm, which is what CO_2 levels in the air are expected to reach by 2050.

Fire Frequency Experiment in Oak Woodland

forestecology.cfans.umn.edu/research/oak-savanna-and-fire

Location: University of Minnesota Cedar Creek Ecosystem Science Reserve (East Bethel, MN)
Years Active: Ongoing

This long-term study investigates the effects of differing prescribed fire frequency on oak woodland communities and ecosystems. The study includes 60 years of spring burning at varying frequencies: no fires, one fire in 10 years, one fire in 3 years, one fire in 2 years, and two fires in 3 years. Goals included assessing direct (fire) and indirect (change in plant communities and thus light, water, and nutrient supply) effects on plant and soil communities and biogeochemical processing.

FLUXNET Canada and CanFlux

www.earthdata.nasa.gov/data/catalog/ornl-cloud-fluxnet-canada-1335-1

https://canflux.github.io/

Location: Canada
Years Active: FLUXNET Canada 1993–2014, CanFlux 2025–Present

FLUXNET Canada was a research network of eddy covariance tower sites in the Fluxnet-Canada Research Network (FCRN) and the Canadian Carbon Program (CCP). It received national funding from 1993–2014 to coordinate observations at 32 forest and peatland flux sites to study the influence of management, nitrogen, climate, and wildfire on land–atmosphere fluxes of carbon, water, and energy. Many sites continued measuring fluxes after 2014, and new sites have been started. Launched in 2025, CanFlux is revitalizing the national network concept for Canada, but with a larger number of measurement stations (there are >100 sites in CanFlux) and expanded goals that include integrating eddy flux data, remote sensing, and modeling to document trends in ecosystem fluxes, improve models, and inform management and adaptation.

Forest Accelerated Succession ExperimenT (FASET)*

https://ameriflux.lbl.gov/sites/siteinfo/US-UMd#overview

Location: University of Michigan Biological Station (Pellston, MI)
Years Active: 2007–Present

FASET is large-scale ecological study that examines how accelerated forest succession impacts carbon storage and other ecosystem processes. The project aims to understand the effects of early-successional aspen and birch removal on fungal and plant communities, nutrient cycling, and carbon storage in a temperate forest.

Forest Global Earth Observatory (ForestGEO)

forestgeo.si.edu/

Location: The Americas, Africa, Asia, Europe, and Oceania
Years Active: 1980–Present

ForestGEO is a global network of scientists and forest research sites dedicated to advancing long-term study of the world's forests. The multi-institutional network comprises 84 forest research sites across the Americas, Africa, Asia, Europe, and Oceania. ForestGEO monitors the growth and survival of approximately 7 million trees and nearly 12,000 species that occur in the forest research sites. ForestGEO also supports initiatives in the forest sites to monitor climate, carbon flux, vertebrates, insects, soil microorganisms, and much more.

Forest Resilience Threshold Experiment (FoRTE)*

fortexperiment.github.io/fortedata/

Location: University of Michigan Biological Station (Pellston, MI)
Years Active: 2018–Present

FoRTE is a forest disturbance severity manipulation using field measurements, model simulations, and a model–data feedback loop to examine how and why forest carbon cycling processes will respond to a range of disturbance severities caused by insect pests and pathogens.

Free-Air CO_2 Enrichment Experiments (FACE)

Location: Chapel Hill, NC; Oak Ridge, TN.; Nevada National Security Site, NV.; Rhinelander, WI.

Years Active: 1995–2007

FACE experiments were a series of long-term, large-scale field studies designed to understand how ecosystems respond to elevated levels of atmospheric carbon dioxide (CO_2). Conducted between 1995 and 2007 across a range of U.S. ecosystems—including forests, grasslands, deserts, and agricultural lands—these experiments used advanced open-air technology to enrich CO_2 levels in natural settings without enclosing the plants. The goal was to generate data that could inform Earth system models and improve predictions of the global carbon cycle. FACE experiments demonstrated a variety of ecosystem responses: some forests showed sustained growth and carbon sequestration under elevated CO_2, while other systems, especially nutrient- or water-limited ones, had more transient or variable responses. The findings underscored the complexity of ecosystem feedbacks and the importance of long-term experimentation. In addition to producing hundreds of influential scientific papers, the program fostered collaboration between experimentalists and modelers, leading to a new standard for integrating empirical data into Earth system models. The FACE program's legacy now guides next-generation ecosystem studies such as DOE's NGEE Arctic and NGEE Tropics projects.

Greenhouse Gas Emissions NeXus (GENX)*

serc.si.edu/labs/biogeochemistry-projects/genx

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 2021–Present

The newest experiment at the Global Change Research Wetland, GENX has 12 automated chambers arranged across an active soil warming gradient that continuously measure fluxes of methane, carbon dioxide, and nitrous oxide with the goal of better understanding the anaerobic decomposition pathways that regulate greenhouse gas emissions across model-relevant time scales.

Hanford 300 Area Integrated Field Research Challenge (IFRC)

www.pnnl.gov/main/publications/external/technical_reports/PNNL-20257.pdf

Location: Department of Energy Hanford Site, southeastern Washington
Years Active: 2007–2011

The Hanford 300 Area IFRC project studied multiscale mass transfer processes, focusing on a legacy uranium contaminant plume, in a complex subsurface hydrogeologic setting where groundwater and river water interact. The site had 35 instrumented wells and an extensive monitoring system and included a deep borehole sampled throughout the full thickness of the surficial aquifer. Comprehensive site and laboratory characterization, combined with results from multiple field experiments, led to new conceptual and numerical models of uranium flow and transport at the site and provided new insights on the microbiological community and associated biogeochemical processes.

Harvard Forest Long-Term Ecological Research (LTER)*

harvardforest.fas.harvard.edu/research/lter/

Location: Petersham, MA
Years Active: 1988–Present
The Harvard Forest LTER program is part of a national network of long-term ecological research sites. Within this framework, program researchers examine ecological dynamics in the New England region resulting from natural disturbances, environmental change, and human impacts.

Hopland Soil Warming Experiment

ucanr.edu/rec/hopland-research-and-extension-center

Location: Hopland Research and Extension Center (Hopland, CA)
Years Active: 2013–2016

The Hopland Soil Warming Experiment used the field lysimeter facility of the University of California Hopland Research and Extension Center to study the effects of whole-profile soil warming (+4°C), rhizosphere activity (tested with plant removal), and depth of root-litter inputs on decomposition rates and soil organic matter production in a Mediterranean grassland. ^{13}C-labeled root litter *Avena fatua* (wild oat grass) was added to two soil depths of each treatment. The experimental design was able to elucidate the interaction of multiple factors on microbial decomposition and distinguish the lost pathways of carbon from soil as heterotrophic carbon dioxide respiration or leaching of dissolved organic carbon.

Hubbard Brook Long-Term Ecological Research (LTER) Site*

hubbardbrook.org/hubbard-brook-lter/

Location: New Hampshire
Years Active: 1965–Present

The Hubbard Brook LTER is driven by a conceptual model that focuses on three drivers of ecosystem change: changing atmospheric chemistry, changing climate, and changing biota. These drivers interact with a hydrobiogeochemical template and produce responses in hydrology, vegetation, biogeochemistry, and food webs. The project uses watershed monitoring and manipulations; plot-scale manipulations; and long-term monitoring of soil, water, birds, insects, etc.

International Diversity Experiment Network with Trees (IDENT)

treedivnet.ugent.be/experiments/IDENT.html

Location: University of Minnesota Cloquet Forestry Center (Cloquet, MN)
Years Active: 2010–Present

IDENT is a network of Biodiversity-Ecosystem Functioning (BEF) experiments in North America, Europe, and Africa that focus on the early years of tree development, the role of functional diversity, and BEF relationships over stress gradients. The experiment consists of eight sites: six in temperate ecoregions, one in a Mediterranean region, and one in a tropical region. In total, 2,241 plots have been planted with native as well as exotic tree species. At four of the sites, the impacts of water availability and nutrient addition are also studied.

Konza Prairie Long-Term Ecological Research (LTER)

https://lternet.edu/site/konza-prairie-lter/

Location: Konza Prairie Biological Station (Flint Hills, northeastern Kansas)
Years Active: 1981–Present

The Konza Prairie LTER program is a comprehensive, interdisciplinary research program designed to provide an understanding of ecological processes in mesic grasslands, particularly tallgrass prairie, and contribute to conceptual and theoretical advances in the field of ecology. The program also offers educational and training opportunities for students at all levels, contributes knowledge to address land-use and management issues in grasslands, and provides infrastructure and data in support of scientific pursuits across a broad range of disciplines.

Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA-ECO)

www.earthdata.nasa.gov/data/projects/lba-eco

Location: Amazonia Region of South America
Years Active: 1998–2013

LBA-ECO investigates how the terrestrial ecosystem and water resources of the Amazon basin are impacted by changing environmental conditions and human activity. The project focuses on the question: How do tropical forest conversion, regrowth, and selective logging influence carbon storage, nutrient dynamics, trace gas fluxes, and the prospect for sustainable land use in Amazonia? To answer this question, project researchers have been developing new comprehensive regional models and datasets to describe the behavior of terrestrial ecosystems and hydrological resources of the Amazon River Basin.

Los Alamos Survival-Mortality (SUMO) Experiment*

data.ess-dive.lbl.gov/view/doi:10.15485/1454272

Location: Los Alamos, NM
Years Active: 2009–2015

The SUMO experiment was a tree manipulation study that investigated the relative impacts of drought and warming on plant function and reveals how trees adapt to drought and heat in semi-arid regions. The study replicated drought, elevated temperature, and compounded drought and temperature treatments. It factored the role of tree hydraulic acclimation to both precipitation and temperature and separated their effects.

Molecular Observation Network (MONet)

https://www.emsl.pnnl.gov/monet

Location: Pacific Northwest National Laboratory (Richland, WA)
Years Active:

MONet is an open science network developed by the Environmental Molecular Sciences Laboratory (EMSL), which is housed on the Pacific Northwest National Laboratory campus. MONet's mission is to develop a continental-scale database of standardized molecular and microstructural data to advance the understanding and prediction of microbially and root-driven inputs in soil ecosystems and terrestrial aerosol processes. The information provided by MONet is essential for advancing the accuracy of multiscale Earth system models, growing American scientific leadership, and enabling the next generation of soil and aerosol research both at EMSL and within the broader user community.

National Ecological Observatory Network (NEON)

https://www.neonscience.org/

Location: Across the United States
Years Active: 2019–Present
NEON is a continental-scale observation facility designed to collect and freely share critical long-term ecological data, samples, and infrastructure with researchers and the public to advance understanding of ecological processes and inform the sustainable management of U.S. ecosystems. NEON's 81 field sites (47 terrestrial and 34 freshwater aquatic) support studies that characterize ecological change and link individual local measurements to site-level and continental-scale questions about ecological change. NEON data inform disaster prediction and resilience; provide insights into water, soil and other natural resources for land management; and more.

National Streamgaging Network (NSN)

www.usgs.gov/mission-areas/water-resources/science/usgs-national-streamgaging-network

Location: Across the United States
Years Active: 1889–Present

NSN consists of all streamgages that continuously monitor streamflow year-round and from which daily mean streamflows are computed and made available online by the U.S. Geological Survey (USGS). NSN is part of the USGS National Water Monitoring Network, which also includes the National Water Quality Network. The data collected at NSN-Streamflow locations serve several functions (including flood warning, water allocation, and recreation), and many streamgages are funded in partnership with one or more federal, state, local, and tribal agencies. All data is publicly available online. The use of consistent methods enables data from the many gages to be combined, expanding the use and value of the data from every gage. The USGS has monitored streams since 1889, with the number of gages and their locations varying over time (https://labs.waterdata.usgs.gov/visualizations/gages-through-the-ages/index.html). As of October 2024, there are 8,705 gages with continuous flow records and an additional 3,460 gages with partial streamflow records in the NSN-Streamflow.

Next-Generation Ecosystem Experiments in the Arctic (NGEE Arctic)*

ngee-arctic.ornl.gov

Location: Arctic Alaska, terrestrial Arctic tundra, the bioclimatic region north of the boreal tree line with an Arctic climate and tundra vegetation
Years Active: 2012–Present

NGEE Arctic is a model-driven, multiscale research project that has built a foundation of model–data integration by leveraging a long history of tundra observations from generations of Arctic scientists and contributing new observations from more than a decade of field research in Arctic Alaska. Our goal is to support the mission of DOE BER to advance a robust, predictive understanding of Earth's environmental systems by delivering a process-rich ecosystem model, extending from bedrock to the interface between the vegetative canopy and the atmosphere, capable of representing the evolution of Arctic ecosystems at the scale of a high-resolution grid cell in DOE's Energy Exascale Earth System Model.

Phases 1–3 of NGEE Arctic conducted a series of collaborative field investigations across a gradient of permafrost landscapes in coordination with landowners from multiple Native Corporations. These landscapes included polygonal tundra underlain by continuous, cold permafrost on the coastal plain at the Barrow Environmental Observatory (BEO) outside of Utqiaġvik, Alaska, as well as tundra hillslopes underlain by discontinuous, warmer permafrost on the Seward Peninsula, Alaska, that spanned a range of coastal and interior climates and glaciation histories. In Phase 4, models trained on observations from Actic Alaska are being evaluated against current observations and projected changes from across the Arctic in partnership with long-term research sites.

Next-Generation Ecosystem Experiments in the Tropics (NGEE Tropics)*

ngee-tropics.lbl.gov

Location: Pantropical via collaboration with pantropical networks (ForestGEO, Global Ecosystem Monitoring, and others) and modeling, with field sites in Panama, Brazil, Puerto Rico and Malaysia
Years Active: 2014–Present

NGEE Tropics uses distributed observations, data synthesis, remote sensing, model development and application to fill the critical gaps in knowledge of tropical forest-climate system interactions. The project's overarching goal is to develop a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers over the 21st Century. NGEE Tropics' grand deliverable is a representative, process-rich tropical forest ecosystem model, extending from bedrock to the top of the vegetative canopy–atmosphere interface, in which evolution and feedbacks of tropical ecosystems in a changing climate can be modeled at the scale and resolution of a next-generation Earth System Model grid cell (approximately 10 x 10 km^2 grid size).

Nutrient Network (NutNet)* and Disturbance and Recovery Across Global Grasslands (DRAGNet)*

nutnet.org/; https://dragnetglobal.org/

Location: Multiple sites across both projects (222 grassland sites in 37 countries in total)
Years Active: NutNet 2007–Present; DRAGNet 2019–Present

NutNet and DRAGNet are distributed, collaborative experiments that study nutrients and grazing (NutNet) and soil disturbance, nutrients, and recovery (DRAGNet). NutNet's treatments—herbivore exclusion and nitrogen, phosphorus, and potassium and micronutrient addition—build from long-term theoretical and empirical work to advance understanding of local, regional, and global controls on grassland biodiversity and function. DRAGNet is interoperable with NutNet (same plot size and sampling protocols) and is designed to reveal interactive impacts of physical disturbance and nutrients on grasslands and responses to cessation of these impacts.

Oak Ridge National Laboratory Free-Air CO_2 Enrichment Experiments (ORNL FACE)

richnorby.org/home/face-home/

Location: Oak Ridge, TN

Years Active: 1996–2010

ORNL FACE experiments studied integrated response to elevated CO_2 in a temperate forest. Net primary production was increased by elevated CO_2, but the response was not maintained because of the development of progressive nitrogen limitation. Stimulation of fine-root production resulted in increased soil carbon.

Old-Field Community, Climate, and Atmosphere Manipulation (OCCAM)

Location: Oak Ridge, TN

Years Active: 2002–2008

The OCCAM study investigated interactive effects of elevated CO_2, warming, and altered water availability in a constructed ecosystem with plants typical of an old-field system (including C3 and C4 grasses, forbs, and legumes). The project explored direct and interactive effects of multiple climate change drivers through multiple years of plant, soil, and ecosystem data; seedling establishment and emergence; and community and ecosystem responses.

Old Woman Creek*

ameriflux.lbl.gov/sites/siteinfo/US-OWC

Location: Old Woman Creek National Estuarine Research Reserve (Huron, OH)

Years Active: 2015–Present

The AmeriFlux Tower at Old Woman Creek provides data that advances understanding of carbon flux budgets and extremely high methane emissions from a riverine, lake coastal wetland. Flux measurements, combined with daily and weekly water quality and hydrology monitoring, allow for a focus on improving methane prediction with the Energy Exascale Earth System Model (E3SM) Land Model (ELM).

PhenoCam Network

phenocam.nau.edu/webcam/

Location: Across the U.S., but specifically 20 cameras located at Spruce and Peatland Responses Under Changing Environments (SPRUCE; Bovey, MN)

Years Active: 2008–Present

The PhenoCam Network is a cooperative continental-scale phenological observatory that uses repeat digital photography to track the seasonal variation in vegetation activity, or phenology, from tundra to tropics across North America and around the world at high spatial and temporal resolution. PhenoCam imagery can also be used to track the progression of long-term manipulative experiments and are particularly useful when “surprises” occur (e.g., stress from extreme events).

Prospect Hill Soil Warming Experiment

harvardforest1.fas.harvard.edu/exist/apps/datasets/showData.html?id=hf005

Location: Harvard Forest (Petersham, MA)
Years Active: 1991–Present

The soil warming experiment at Prospect Hill allows researchers to investigate the effects of a 5°C temperature increase on soil processes fundamental to the global cycling of carbon and nitrogen. Located in an even-aged mixed hardwood forest, the experiment involves six replicates of three treatments (control, disturbance control, and warming) in 5 x 5 m plots to examine long-term warming on soil biogeochemistry.

River Corridor Science Focus Area*

pnnl.gov/projects/river-corridor

Location: Yakima River Basin, WA
Years Active: 2017–Present

The River Corridor Science Focus Area (SFA) aims to mechanistically understand how perturbations affect hydrobiogeochemistry across the hillslope-to-stream continuum. The SFA progressively delivers new understanding, model advances, and benchmark data to Earth system modeling efforts to improve predictive confidence for future states of the Earth system. Its near-term objective is to reveal how wildfires and hydrologic perturbations influence ecohydrology and hydrologic connectivity from hillslopes to streams, variable inundation dynamics in stream networks, and subsequent biogeochemical impacts.

Salt Marsh Accretion Response to Temperature Experiment (SMARTX)*

serc.si.edu/gcrew/warming

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 2016–Present

SMARTX is a whole-ecosystem active warming experiment in the Global Change Research Wetland dedicated to understanding the ecosystem-scale consequences of warming and elevated CO_2 on carbon cycling in tidal wetlands. In particular, the study looks at how the plant- and microbial-driven processes that regulate coastal wetland carbon sequestration are affected by multiple simultaneous ecosystem stressors (four levels of whole-system warming and two levels of elevated CO_2) and what that means for coastal wetlands and other ecosystems in the future. Research from this project is also being used to develop extensions that will enhance capabilities of PFLOTRAN and E3SM to represent these processes in models.

Smithsonian Environmental Research Center (SERC)

https://serc.si.edu/

Location: Edgewater, MD
Years Active: 1965–Present

SERC provides science-based knowledge to meet the environmental challenges of the 21st century. The SERC research site in Chesapeake Bay serves as a natural laboratory for long-term and cutting-edge ecological research where scientists explore issues affecting the environment, including water quality, fisheries, invasive species, conservation, land use, toxic chemicals, and global change. SERC research on coastal ecosystems informs real-world decisions for wise policies, best business practices, and a sustainable planet.

Soil Carbon Response to Environmental Change Science Focus Area*

tessfa.evs.anl.gov/

Location: Many locations across Alaska, with most sites in arctic tundra and some in subarctic tundra and boreal forest

Years Active: 2013–Present

The Soil Carbon Response to Environmental Change Science Focus Area (SFA) uses field campaigns employing consistent sampling designs across multiple sites to assess multiscale variations related to cryopedogenic processes, geomorphology, and soil parent materials. The overall goal is to quantify the carbon currently preserved in soils of the permafrost region, determine its spatial and vertical distributions, and assess how susceptible this carbon is to decomposition and release to the atmosphere. New measurements of soil carbon and nitrogen stocks aim to improve knowledge of the factors and processes affecting their amount and distributions, and they are coupled with existing observations and environmental covariates to obtain regional estimates using digital soil mapping techniques. Soil organic matter composition and decomposability are assessed with physicochemical fractionations, infrared spectroscopy, and incubation bioassays. SFA data and process knowledge are contributing to synergistic interactions with NGEE Arctic model development.

Soil Carbon Responses to Elevated Atmospheric Carbon Dioxide (FACE Soil Carbon)*

Location: Oak Ridge, TN; Rhinelander, WI; Urbana, IL; Manhattan, KS

Years Active: 1995–2012

The project leveraged several long-term atmospheric CO_2 enrichment experiments to better understand and quantify the mechanisms and processes involved in soil carbon storage and turnover, with the ultimate goal of obtaining data and process knowledge to inform the development of soil organic matter simulation models. Researchers used repeated measurements of soil organic matter fractions and stable isotopes to (1) quantify the dynamics, sources, and persistence of measurable soil carbon pools and (2) evaluate whether these pools and their dynamics are altered in response to atmospheric CO_2 enrichment.

Soil Warming and Nitrogen Addition (SWaN) Study

harvardforest1.fas.harvard.edu/exist/apps/datasets/showData.html?id=HF045

Location: Harvard Forest (Petersham, MA)

Years Active: 2006–Present

The SWaN study investigates whether warming and nitrogen (N) additions restructure microbial communities and alter the response of soil carbon (C) pools to these two stressors. To examine interactions between warming and soil nitrogen availability, the study includes six replicates of four treatments: control, warming (+5°C), warming +N, +N only (5 $g/m^2/yr$).

South Oyster Site Bacterial Transport*

Publication: Lessons Learned from Bacterial Transport Research at the South Oyster Site

Location: Oyster, VA
Years Active: 1995–2001

The South Oyster Site included four major experimental campaigns aimed at understanding and quantifying bacterial transport in the subsurface environment. Research involved bacterial injection into groundwater and observation of transport through a multiwell sampling system. The research effort was focused on the concept of "bioaugmentation"—the introduction of microorganisms into an aquifer system to enhance bioremediation—and was part of a larger DOE research program called Natural and Accelerated BIoremediation Research (NABIR).

Spruce and Peatland Responses Under Changing Environments (SPRUCE)*

mnspruce.ornl.gov/

Location: Bovey, MN
Years Active: 2010–Present

SPRUCE is a whole-ecosystem experiment in an ombrotrophic bog (i.e., a raised bog that receives all water and nutrients from direct precipitation) located in the Marcell Experimental Forest of northern Minnesota. The project enables the assessment of ecological responses across multiple spatial scales—including microbial communities, moss populations, various higher plant types, and some insect groups. SPRUCE research evaluates a wide range of increased temperatures and levels of elevated atmospheric CO_2 concentrations. The project also tracks and analyzes direct and indirect effects of the experimental perturbations over a decade. This comprehensive suite of spruce-peatland process studies and observations is being linked to model development and application requirements for improving process representation, calibrating models, and evaluating model predictions for boreal ecosystems.

Temperature and Carbon Dioxide Interactions in Trees (TACIT)

Location: Oak Ridge, TN
Years Active: 1994–1997

Publication: Evaluating Ecosystem Responses to Rising Atmospheric CO_2 and Global Warming in a Multi-Factor World

TACIT was a 4-year carbon dioxide (CO_2) and temperature experiment with maple trees grown from seedlings in open-top chambers that had been modified to control air temperature (ambient or ambient +4°C) and CO_2 (ambient or ambient +300 ppm). Temperature elevation increased aboveground growth rates because of its effect on phenology, but the generally positive effect of elevated temperature on growth did not compensate for the negative effect that occurred during a particularly hot, dry period in the second summer. The negative effects of temperature increases on growth were completely offset by CO_2 enrichment.

Terrestrial Ecosystem Manipulation to Probe the Effects of Storm Treatments (TEMPEST)

compass.pnnl.gov/FME/COMPASSFME

Location: Chesapeake Bay (Edgewater, MD)
Years Active: 2021–Present

TEMPEST is a whole-ecosystem global change manipulation experiment in a coastal hardwood forest, which undergoes pulse additions of freshwater and estuarine water that increase in frequency over time. The project's goal is to understand the earliest impacts of storm surge on coastal forested ecosystems undergoing state change to coastal wetlands. TEMPEST, a subset of COMPASS-FME, is designed to evaluate and model the vegetation, soil, microbial, and environmental processes to advance Earth system models.

Throughfall Displacement Experiment (TDE)

www.ornl.gov/content/throughfall-displacement-experiment-tde

Location: Walker Branch Watershed, East Tennessee
Years Active: 1993–2005

The TDE was established to provide data on the responses of upland forests to altered precipitation regimes projected for future environmental changes. The TDE was a large-scale field experiment that involved manipulating precipitation levels in a mature hardwood forest. The TDE simulated various precipitation scenarios by intercepting one-third of natural rainfall on an 80 x 80 meter dry plot and redistributing across an ambient reference area it to a nearby wet plot. Scientists used 2,000 suspended subcanopy troughs, designed to reduce soil moisture to levels comparable to historic drought conditions observed in the 1980s. The treatments resulted in a 33% decrease in precipitation reaching the forest floor on the dry plot and a corresponding increase in precipitation on the wet plot. The TDE showed that for regions of ample winter rains and deep soils, upland hardwood-dominated forests were largely resilient to current and anticipated future droughts.

Tropical Responses to Altered Climate Experiment (TRACE)

forestwarming.org

Location: Luquillo Experimental Forest, eastern Puerto Rico
Years Active: 2016–Present

An *in situ* field warming experiment, TRACE is currently the only experiment in the world studying the interactive processes between environmental change and hurricane disturbance on tropical forests, particularly effects on carbon and nutrient cycling. TRACE researchers use infrared heat to warm the soil and plants of the understory, as well as individual leaves and branches in the forest canopy, and measure the potential impacts of temperature increase on soil structure, carbon cycling, and plant physiology. This experiment will help improve conservation strategies for these irreplaceable ecosystems and all the biodiversity and natural resources they sustain.

University of Michigan Biological Station

lsa.umich.edu/umbs

Location: Pellston, MI
Years Active: 1915–Present

The University of Michigan Biological Station (UMBS) is one of the nation's largest and longest continuously operating field research stations. It has hosted a variety of short- and long-term projects and has data from a range of observational and manipulative experiments.

University of Michigan Biological Station Burn Plots

storymaps.arcgis.com/stories/7fa8394e09c649608909576e9ca6e978

Location: Pellston, MI
Years Active: 1932–Present

The burn plots at UMBS are a long-term experimental forest chronosequence and serve as valuable snapshots of forests across the ages. The burn plots provide wide-ranging ecological insights that enhance understanding of forest succession after logging and fire, forest disturbance and its effects on fungal communities, and effects of long-term carbon storage in forests and their soils.

University of Michigan Biological Station Long-Term Research in Environmental Biology (LTREB)*

um-biological-station-umich.hub.arcgis.com/documents/a27488b4514345b79f1b1e26c6b90719/explore

Location: Pellston, MI
Years Active: 2014–2025

This project draws on long-term experimental plots at UMBS, a 110-year-old field station in northern Michigan. Forests and their soils lose substantial amounts of carbon and nutrients following disturbances such as clear-cutting and fire. The long timescale of forest recovery hinders efforts to (1) measure how long forests require to regain carbon and nutrient stocks and (2) determine how re-growing vegetation, soil development, and climate variation jointly regulate carbon and nutrient recovery as forests mature. The long-term experimental plots at UMBS allow researchers to examine how changes in forest structure, nutrient cycling, and climate interact over time to shape tree growth, nutrient retention, and overall carbon capture and storage.

Warming and (species) Removal in Mountains (WaRM)

arcticcirc.net/our-projects/climate-change-carbon-sequestration-mountains

Location: Sites in Argentina, Canada, China, France, Greenland, New Zealand, Sweden, Switzerland, Tasmania, and the United States
Years Active: 2014–Present

The WaRM network employs experimental warming and plant species removals at high- and low-elevation sites in a factorial design to examine the combined and relative effects of climatic warming and the loss of dominant species on community structure and ecosystem function, both above- and belowground.

Warming Meadow Experiment

digitalrmbl.org/case-studies/the-warming-meadow-experiment/

Location: Gothic, CO
Years Active: 1990–2019

The Warming Meadow Experiment led by John Harte was a long-term ecosystem warming experiment that simulated climate warming effects on a subalpine meadow by artificially warming the land surface of select plots using suspended heaters. The experiment's major findings showed that ecosystem responses to climate change are likely to trigger large feedback effects that will likely enhance, not reduce, climate warming. More recent findings showed interesting trends in soil microbial community responses and plant composition, and unexpected trends in carbon storage tied to the encroachment of woody plants such as sagebrush.

Watershed Function Science Focus Area

watershed.lbl.gov

Location: Headwaters of Colorado River (East River, Taylor River), CO
Years Active: Ongoing

The Watershed Function SFA is an integrated, multi-laboratory project focused on interacting impacts of warming and drought on the hydro-biogeochemical functioning of mountainous watersheds and their retention or release of water, carbon, nitrogen, and other elements. The SFA aims to understand mechanisms underlying the resistance and resilience of watersheds to disturbance to predict pathways of watershed adaptation to future climate conditions.

Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (WHONDRS)*

pnnl.gov/projects/WHONDRS

Location: Global river corridors with an emphasis on contiguous United States
Years Active: 2017–Present

WHONDRS uses a collaborative and participatory science framework to understand coupled hydrologic, biogeochemical, and microbial function across subsurface and surface components of river corridors, from local to global scales, with an emphasis on increasing accessibility of resources and knowledge throughout the research life cycle.

Represented Projects Image Credits

Alpine Treeline Warming Experiment (ATWE). Structures supporting infrared lamps around heated plot rings in the alpine tundra site of ATWE in mid-summer. Tall posts allowed the lamps to be raised above the snowpack in winter. [Courtesy Ken Etzel]

Arctic-Boreal Vulnerability Experiment (ABoVE). [Courtesy ABoVE]

AmeriFlux Management Project (AMP). A flux tower sited in a montane riparian corridor. The tower estimates fluxes from within the riparian ecosystem. [Courtesy David Gochis]

Atmospheric Radiation Measurement (ARM) user facility. An Aerosol Observing System facility located at the Southern Great Plains atmospheric observatory in Oklahoma. [Courtesy ARM]

Barre Woods Soil Warming Experiment. Soil warming megaplot at Harvard Forest. [Courtesy Serita Frey, University of New Hampshire]

Bartlett Experimental Forest AmeriFlux Site. View to the west from the AmeriFlux tower at Bartlett Experimental Forest in the White Mountains of New Hampshire. The instrument shown is the sonic anemometer that is the basis for all eddy covariance measurements. [Courtesy Andrew Richardson]

Belowground Biogeochemistry Science Focus Area. A researcher takes soil and root samples at Point Reyes National Seashore in California where scientists are studying how roots and minerals influence redox processes in the soil. [Courtesy Jeremy Snyder, Lawrence Berkeley National Laboratory]

Biodiversity, CO_2, and Nitrogen (BioCON) Experiment. Ring 4 of the BioCON experiment at the Cedar Creek Ecosystem Science Reserve in Minnesota. [Reprinted under a Creative Commons License (CC-BY-SA 4.0). Courtesy Jacob Miller]

Boreal Forest Warming at an Ecotone in Danger (B4WarmED). One of 72 plots in the B4WarmED free-air climate change experiment at two sites in northern Minnesota. [Courtesy Peter Reich, University of Minnesota]

Boreal Soil and Air Warming (BoSAW). A university of Wisconsin team assembles one of the project's warming chambers south of Thomson, Manitoba, in October 2022. [Courtesy Ben Bond-Lamberty, Pacific Northwest National Laboratory]

Carbon in Permafrost, Experimental Heating Research (CiPEHR) Project. Soil warming treatment increased summer thaw depth by over 500% after 14 years of manipulation. [Courtesy Ted Shuur, Northern Arizona University]

Cedar Creek Long-Term Ecological Research (CDR LTER) Program. Biodiversity experiment at Cedar Creek Ecosystem Science Reserve. Scientists from the Cedar Creek Long Term Ecological Research program have investigated biodiversity and ecosystem function since the 1990s. [Courtesy Maowei Liang, University of Minnesota–Twin Cities]

C. Hart Merriam Elevation Gradient Climate Change Experiment. Schematic of the ecosystems sampled along the C. Hart Merriam elevation gradient near Flagstaff, AZ. [Reprinted with permission of Springer Nature from Morrissey, E.M., et al. 2019. "Evolutionary History Constrains Microbial Traits Across Environmental Variation," *Nature Ecology and Evolution* **3**, 1064–69. DOI:10.1038/s41559-019-0918-y

Chronic Nitrogen Amendment Study. Initiated in 1988 at the Harvard Forest in central Massachusetts to understand long-term nitrogen enrichment on forest dynamics. [Courtesy Serita Frey, University of New Hampshire]

Climate Adaptation and Sustainability in Switchgrass. Chamber-based measurements of the net ecosystem exchange of CO_2 are used to evaluate ecosystem carbon cycling and compare the carbon sink/source capacity of switchgrass ecotypes under differing environmental conditions of project sites in Illinois, Missouri, and Texas. [Courtesy Argonne National Laboratory]

Climate Change Across the Seasons Experiment (CCASE). A study plot shoveled in winter to simulate a reduced snowpack in New Hampshire. [Courtesy Pamela Templer, Boston University]

Coastal Observations, Mechanisms, and Predictions Across Systems and Scales–Field, Measurements, and Experiments (COMPASS-FME). A researcher takes soil and root samples at Point Reyes National Seashore to study how roots and minerals influence redox processes in the soil. [Courtesy Pacific Northwest National Laboratory]

Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems (CSiTE). [Courtesy Oak Ridge, Pacific Northwest, and Argonne National Laboratories]

Critical Interface Network (CINet) in Intensively Managed Landscapes. A Management Induced Reactive Zone research infrastructure installed in a restored prairie in Nebraska. [Courtesy Ashley Dere, University of Nebraska–Omaha]

Critical Zone Observatories (CZO)/ Critical Zone (CZ) Clusters. [Courtesy Consortium of Universities for the Advancement of Hydrologic Science]

Detrital Input and Removal Treatments (DIRT) Network. Double litter plot at the DIRT experiment located at Harvard Forest in central Massachusetts. [Courtesy Serita Frey, University of New Hampshire]

Drylands Critical Zone Project. Environmental Science and Geology students from University of Texas–El Paso conduct field measurements of river discharge and channel profile at Oak Creek in Arizona. [Courtesy Marianne Karplus, University of Texas–El Paso]

Ecosystem-Scale Rainfall Manipulation at the Sevilleta National Wildlife Refuge. An ecosystem-scale drought manipulation at the Sevilleta National Wildlife Refuge, New Mexico. [Credit Andrew Peltier]

Elevated Carbon Dioxide x Nitrogen Addition. A 2 m-wide open-top chamber for elevating carbon dioxide and soil nitrogen concentrations in brackish tidal marsh at the Smithsonian Environmental Research Center established to test the hypothesis that CO_2-enhanced belowground productivity stimulates soil elevation gain and soil carbon sequestration. [Courtesy Adam Langley]

Elevated Carbon Dioxide x Nitrogen x Phragmites. Open-top chambers for elevating carbon dioxide and soil nitrogen concentrations in brackish tidal marsh at the Smithsonian Environmental Research Center established to test the hypothesis that elevated CO_2 and soil nitrogen accelerate invasion of native marsh ecosystems by non-native *Phragmites australis*. [Courtesy Tom Mozdzer]

Elevated Carbon Dioxide x Plant Trait Experiment. Open-top chambers located in tidal marsh plant communities that were dominated by species with C3 photosynthesis, C4 photosynthesis, or a mixture of the two nearly 40 years ago, marking the establishment of the Smithsonian Environmental Research Center's Global Change Research Wetland and one of the world's longest-operating climate change experiments. [Courtesy Pat Megonigal]

Enriched Background Isotope Study (EBIS). Enriched litter application to a 2 x 2 m EBIS experimental plot. [Courtesy Oak Ridge National Laboratory]

Eucalyptus Free-Air CO_2 Enrichment (EucFACE). Aerial view of the EucFACE experiment in mature eucalyptus woodland Sydney, Australia, showing three elevated carbon dioxide plots and three control plots. [Courtesy Western Sydney University]

Fire Frequency Experiment in Oak Woodland. Spring prescribed burn in progress on sand savanna with northern pine and bur oak, Cedar Creek Ecosystem Science Reserve, Minnesota. [Courtesy Kalev Jõgiste]

FLUXNET Canada and CanFlux. The Mer Bleue bog flux tower, Ontario, Canada (flux site ID CA-Mer), a FLUXNET Canada site that is still operating in CanFlux and AmeriFlux networks. [Courtesy Elyn Humphreys]

Forest Accelerated Succession ExperimenT (FASET). The Forest Accelerated Succession Experiment stem girdled nearly 7,000 aspen and birch trees within a 39-hectare area to hasten the transition from early to middle succession. [Courtesy Chris Gough]

Forest Global Earth Observatory (ForestGEO). [Courtesy ForestGEO]

Forest Resilience Threshold Experiment (FoRTE). FoRTE simulated varying degrees of wood-boring insect disturbance by stem girdling 45%, 65%, or 85% of all trees within a 16-hectare area. [Courtesy Chris Gough]

Free-Air CO_2 Enrichment Experiments (FACE). Spring prescribed burn in progress. Experimental plots emerging from the loblolly pine canopy at the FACE site near Duke University in North Carolina. [Courtesy Jeffrey S. Pippen, Duke University]

Greenhouse Gas Emissions NeXus (GENX). Sunrise over the GENX project at the Global Change Research Wetland. Different chamber colors represent soil warming treatments of +0°C, +1.7°C, +3.4°C, +5.1°C above ambient soil temperature. The chambers are automated to close in a sequence to quantify methane, carbon dioxide, and nitrous oxide fluxes in support of refining DOE-supported models. [Courtesy Geneveive Noyce]

Hanford 300 Area Integrated Field Research Challenge (IFRC). Hydrologist Fred Day-Lewis (USGS Office of Groundwater, Branch of Geophysics) monitors a tracer experiment at the site in July 2012. [Courtesy U.S. Geological Survey]

Harvard Forest Long-Term Ecological Research (LTER). View from the Prospect Hill Hardwood Tower at Harvard Forest. [Courtesy Julie Hall]

Hopland Soil Warming Experiment. Lysimeter facility of the University of California Hopland Research and Extension Center. [Courtesy R. J. Keiffer]

Hubbard Brook Long-Term Ecological Research (LTER) Site. Flux tower instrumentation at Hubbard Brook. [Reprinted under a Creative Commons License (CC-BY-SA 4.0). Courtesy U.S. LTER]

International Diversity Experiment Network with Trees (IDENT). A 40 x 40 m plot planted with 12 tree species in the BiodiversiTREE experiment located at the Smithsonian Environmental Research Center, one of nine sites globally that coordinate research on the ecosystem-scale consequences of tree species diversity as members of IDENT. [Courtesy Susan Cook-Patton]

Konza Prairie Long-Term Ecological Research (LTER) Site. The experimental fire and grazing landscape at Konza Prairie results in a mosaic of plant and animal species and varying landscape heterogeneity. [Courtesy Barb Van Slyke]

Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA-ECO). Root sorting. [Courtesy NASA LBA-ECO Project Office]

Los Alamos Survival-Mortality (SUMO) Experiment. SUMO was a long-term field study tracking tree survival and mortality under controlled drought and heat stress in a semi-arid woodland in Los Alamos, N.M. [Courtesy Charlotte Grossiord]

Molecular Observation Network (MONet). A MONet researcher extracts a core of soil to analyze in the lab. [Courtesy Andrea Starr, Pacific Northwest National Laboratory]

National Ecological Observatory Network (NEON). The NEON site and flux tower at Lenoir Landing, Alabama (AmeriFlux ID US-xLE). [Courtesy of the NEON Program and Battelle]

National Streamgaging Network (NSN). U.S. Geological Survey gauging station at Taylor River above Trail Creek in Colorado. [Courtesy Curtis Beutler, Lawrence Berkeley National Laboratory]

Next-Generation Ecosystem Experiments in the Arctic (NGEE Arctic). A researcher conducts snow measurements at the Kougarok-64 study site located on the Seward Peninsula, Alaska. [Courtesy Bob Bolton, Oak Ridge National Laboratory]

Next-Generation Ecosystem Experiments in the Tropics (NGEE Tropics). Researchers gather samples in the Neotropics to better determine how droughts affect rainforest ecosystems. [Courtesy Oak Ridge National Laboratory]

Nutrient Network (NutNet) and Disturbance and Recovery Across global Grasslands (DRAGNet). Researchers sample plants in a grassland experiment at Buck Island Ranch, which is operated by Archbold Biological Station. [Courtesy Dustin Angell, Archbold Biological Station]

Oak Ridge National Laboratory Free-Air CO_2 Enrichment Experiments (ORNL FACE). Aerial view of the ORNL FACE experiment in a sweetgum plantation. [Courtesy Oak Ridge National Laboratory]

Old-Field Community, Climate, and Atmosphere Manipulation (OCCAM). Measuring photosynthesis of old-field plants within an open-top chamber. [Courtesy Richard Norby, Oak Ridge National Laboratory]

Old Woman Creek. AmeriFlux tower in Old Woman Creek, a natural freshwater estuary connected to Lake Erie in northern Ohio. [Courtesy Gil Bohrer, The Ohio State University]

PhenoCam Network. Aspen reaching peak fall colors, as seen by the Hart Prairie phenocam. [Courtesy PhenoCam Network/Andrew Richardson]

Prospect Hill Soil Warming Experiment. Harvard Forest soil warming plots in Massachusetts. [Courtesy Audrey Barker Plotkin, Harvard Forest]

River Corridor Science Focus Area. Burned vegetation within the Yakima River Basin, WA as a result of wildfire. [Courtesy Pacific Northwest National Laboratory]

Salt Marsh Accretion Response to Temperature Experiment (SMARTX). Aboveground heating apparatus among the flowering C4 plant, *Solidago sempervirens*, at SMARTX within the Smithsonian's Global Change Research Wetland (GCREW). [Courtesy Smithsonian Environmental Research Center]

Smithsonian Environmental Research Center (SERC). Aerial view of SERC and surrounding environs. The 1,074-hectare site supports state-of-the-art laboratory buildings, field facilities, and long-term observations and experiments to achieve a holistic, predictive understanding of terrestrial (e.g., forest, agriculture), wetland (e.g., tidal brackish, tidal freshwater, nontidal), and aquatic (e.g., stream, pond, estuary) coastal ecosystems. [Courtesy Chuck Gallegos]

Soil Carbon Response to Environmental Change Science Focus Area. Together with excavated trenches, a series of deep soil cores are used to investigate how landscape features, such as ice-wedge polygons, affect the composition and variability of arctic permafrost-affected soils. [Courtesy Argonne National Laboratory]

Soil Carbon Responses to Elevated Atmospheric Carbon Dioxide (FACE Soil Carbon). A researcher uses a coring tool to take a soil sample at the Free-Air CO_2 Enrichment (FACE) experiment in Rhinelander, Wisconsin. [Courtesy Argonne National Laboratory]

Soil Warming and Nitrogen Addition (SWaN) Study. The SWaN study location at the Harvard Forest in Massachusetts. [Courtesy Serita Frey, University of New Hampshire]

South Oyster Site Bacterial Transport. Groundwater well manifolds being sampled during a bacterial injection experiment. The researcher is comparing real-time observations with model predictions as the experiment unfolds and using results to modify the sampling plan as needed. [Courtesy Tim Scheibe, Pacific Northwest National Laboratory].

Spruce and Peatland Responses Under Changing Environments (SPRUCE). SPRUCE research is conducted on an 8.1-hectare peatland of the Marcell Experimental Forest in northern Minnesota. [Courtesy Oak Ridge National Laboratory]

Temperature and Carbon Dioxide Interactions in Trees (TACIT). Open-top chambers wrapped in shade cloth and with evaporative coolers to provide a realistic light and temperature regime for maple seedlings. [Courtesy Richard Norby, Oak Ridge National Laboratory]

Terrestrial Ecosystem Manipulation to Probe the Effects of Storm Treatments (TEMPEST). Chambers in use to monitor trace gas fluxes at the TEMPEST experiment (Maryland, USA). [Courtesy Ben Bond-Lamberty, Pacific Northwest National Laboratory]

Throughfall Displacement Experiment (TDE). Aerial view of the Throughfall Displacement Experiment's three dry, ambient, and wet 80 x 80 m plots. [Courtesy Oak Ridge National Laboratory]

Tropical Responses to Altered Climate Experiment (TRACE). At the TRACE site in Puerto Rico, infrared heaters are used to warm patches of a wet tropical forest, and the instrument pictured here can measure whether or not more carbon dioxide is released from these warmed soils. [Courtesy Tatiana Barreto-Vélez]

University of Michigan Biological Station. A researcher checks equipment at a UMBS field site. [Courtesy Marc-Grégor Campredon, University of Michigan]

University of Michigan Biological Station Burn Plots. A fire crew uses drip torches containing a mix of diesel fuel and gasoline to ignite dead branches and ground cover at a UMBS burn plot. [Courtesy Roger Hart, Michigan Photography, University of Michigan]

University of Michigan Biological Station Long-Term Research in Environmental Biology (LTREB). A graduate student measures tree included in long term study. [Courtesy Jason Tallant, University of Michigan Biological Station]

Warming and (species) Removal in Mountains (WaRM). A WaRM research site in China. [Courtesy Jin-Sheng He, Peking University]

Warming Meadow Experiment. Suspended infrared heaters over the subalpine terrain of the Warming Meadow Experiment in Gothic, CO. [Courtesy Dr. Heidi Stelzer, Ft. Lewis College]

Watershed Function Science Focus Area. A researcher inserts a probe into a stream in the Surface Atmosphere Integrated Field Laboratory (SAIL) study area. [Courtesy Jeremy Snyder, Lawrence Berkeley National Laboratory]

Worldwide Hydrobiogeochemistry Observation Network for Dynamic River Systems (WHONDRS). A doctoral student takes WHONDRS sediment and water samples in Colorado. [Courtesy Colorado State University]

Appendix D

Pre-Workshop Questionnaire

The following topics will be represented in a report on lessons learned from large ecosystem experiments. We are seeking wisdom from those who have played key roles in designing and leading a range of project types.

Please answer all questions in the Project Description section to characterize your project. We estimate that this section will take 5-10 minutes.

Following this initial section, there are 8 sections. Please choose the section(s) you think are most important to providing key insights, reflections, and lessons learned from your project. It would be particularly helpful if you could answer questions in two or more sections. We estimate that each section will take 5 to 10 minutes.

- **Topic 1:** Study Design and Methodology
- **Topic 2:** Site Selection
- **Topic 3:** Study Management and Operations
- **Topic 4:** Collaborations and Data Sharing
- **Topic 5:** Stakeholder Engagement
- **Topic 6:** Pitfalls, Constraints, and Opportunities
- **Topic 7:** Decommissioning and Wrap-up
- **Topic 8:** What have we missed?

Within these sections, answer the questions that you feel provide the most important insights (successes, failures) that may help future projects. (Fully completed surveys would certainly be welcomed and appreciated).

Please focus on a single project for all answers and provide specific examples, whenever possible. If you have *leadership experience in more than one project*, we'd be happy for you to answer survey questions in a separate form for each project. **For example, answer questions on the form one time for a NGEE study and fill in a second form for an LTER.**

* Indicates required question.

Project Description

These initial questions will help us understand the project design and funding as well as your role on the project. This will provide context for the thoughts and insights you provide in the subsequent sections.

1. What is/was the name of your project? *
2. What is/was the acronym/nickname of your project?

3. Were you in a leadership role at the outset of the project?

4. What is/was your original role on the project?

5. Did your role on the project change through time?

6. What is/was your most senior role on the project?

7. How long were you in a leadership role on this project? *

8. What is/was the type of project (e.g., AmeriFlux, CZO LTER, SFA, Distributed Network, Warming Study, etc.)? *

9. Where does your project fall along the following key characteristics. Check all that apply: Single location, Multiple replicated locations, Observational, Single-factor experiment, Multi-factor experiment. *

10. Are there key characteristics not included in the above list that are necessary to describe your project's location or approach?

11. Approximate project Start Date.

12. Approximate project End Date. Leave blank, if data collection is ongoing.

13. Formal data management and sharing processes were established for this project: Prior to data collection/during project development; At the start of data collection; After project data collection began; OR Other. *

14. Is data synthesis from this project ongoing?

15. What is/was the core funding source for your project's empirical work: DOE, NASA, NIH, NOAA, NSF, USDA, USGS, or other? *

16. What were the ORIGINAL scientific goals of your project spelled out in the original proposal? *

17. Did you ultimately answer the questions you set out to answer in this project? *

Topic 1: Study Design and Methodology

These questions are focused on the study design and effectiveness of the project's data–model integration.

Feel free to answer all, some, or none of these questions.

18. Please provide a brief description of your project's experimental design and treatments. Examples: Experimental manipulation (e.g., X treatments, replicated ANOVA or regression design); Multisite observations (e.g., AmeriFlux across ecosystems, NGEEs within a region); Combination (e.g., distributed manipulations [NutNet]); or distributed process studies (e.g., DIRT).

19. What were the successes and challenges of your research approach for achieving your scientific goals?

20. Did the project design allow flexibility to pivot to better understand any unexpected results?

21. The research design facilitated data–model integration in these 1–3 key ways.

22. The research design hindered data–model integration in these 1–3 key ways.

23 We could have improved data–model integration with a change in these 1–3 key design or management choices.

24. Given your project's goals, how could the design or methodology be improved based on your experience? Check all that apply: Better or clearer definition of field protocols; Improved sample handling; Improved data and metadata management; More flexible design; Other
25. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 2: Site Selection

26. Site selection for your research was: Optimized to the science questions; Based on local availability of space and resources; OR Other.
27. Did you have to compromise on your approach to accommodate cost and logistical limits?
28. Did you experience any challenges with site permitting?
29. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 3: Study Management and Operations

These questions are focused on the management and operation of the project (structure of decision-making team, integration of operations managers with project leads).

Feel free to answer all, some, or none of these questions.

30. What 1–3 management approaches were most successful for the operation and productivity of your project?
31. What 1–3 management approaches were ineffective or could be improved on?
32. What 1–3 operations approaches were most successful for the operation and productivity of your project?
33. What 1–3 operations approaches were ineffective or could be improved on?
34. The leadership team was able to effectively modify the project vision, management, and questions in response to new results. Select Yes, No, OR Other.
35. The leadership team was able to effectively modify/use adaptive management to refine hypotheses and tasks. Select Yes, No, OR Other.
36. The leadership team was able to modify/use adaptive management to refine budgets. Select Yes, No, OR Other.
37. The leadership team was able to effectively modify/use adaptive management to refine capabilities. Select Yes, No, OR Other.
38. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 4: Collaborations and Data Sharing

39. How were new research participants added to the initial core group of collaborators?
40. Who made the decisions to add or not add/allow new participants?
41. What are key successes in your project for working across teams or team members (e.g., to integrate data with models) that can be used to inform future project design or management?

42. What are key challenges in your project for working across teams or team members (e.g., to integrate data with models) that can be used to inform future project design or management?
43. What approaches were successful for leveraging existing research infrastructure or data (e.g., ARM Archive, USGS Stream Gage Network, AmeriFlux, or LTERs)?
44. What approaches were successful for disseminating your project's data and model code (e.g., authorship on products, metadata)
45. What approaches were unsuccessful for leveraging existing research infrastructure or data (e.g., ARM Archive, USGS Stream Gage Network, AmeriFlux, or LTERs)?
46. What approaches were unsuccessful for disseminating your project's data and model code (e.g., authorship on products, metadata)?
47. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 5: Interested Party Engagement

48. What is the single most important lesson you learned during your project's implementation about best practices for engaging stakeholders within and outside the research community, including indigenous, underrepresented, and local communities?
49. What is the single most important lesson you learned about developing/implementing effective PIER plans, such as DEI strategies, career development, and safety protocols?
50. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 6: Risks, Constraints, and Opportunities

51. On a scale of 1 to 5, with 5 being highly effective, how well did your project anticipate and address barriers and constraints to achieving project goals (e.g., long-term planning/scheduling, system failures [e.g., CO_2 supply], and adapting operational plans)?
52. What was your project's greatest success in anticipating and addressing barriers or constraints?
53. What was your project's greatest failure in anticipating and addressing barriers or constraints?
54. What was your project's greatest success in leveraging unanticipated opportunities?
55. What is an example of one major success that was not part of the original project objectives?
56. How was this encouraged/incorporated? Select one: Single project leader approved the opportunity; Project leadership collectively decided to pursue opportunity; OR other.
57. What was your project's greatest failure in leveraging unanticipated opportunities?
58. What were the most effective (or ineffective) ways to manage challenges related to funding continuity?
59. What were the most effective (or ineffective) ways to manage challenges related to collaboration in a large team?
60. What were the most effective (or ineffective) ways to manage challenges related to leadership transitions?

61. What were the most effective (or ineffective) ways to manage challenges related to major project decisions (e.g., when to retire a project)?
62. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 7: Decommissioning and Wrap-up

63. What was the process by which decommissioning was decided for your project. Select one: Answered question; Funding ended; OR other.
64. When were decommissioning plans developed? Select one: During the planning phase of the project; When funding ran out; We didn't plan decommissioning; OR other.
65. Who developed the decommissioning plans? Select one: The originators of the project; Leadership in the period just prior to decommissioning; We didn't plan decommissioning; OR other.
66. Were there any contingencies on the site, post-experiment (e.g., returning the research site to its prior condition)?
67. If yes, briefly how did you meet the site contingencies (e.g., returning the research site to its prior condition)?
68. Any other brief reflections or key lessons learned that you would like to add on this topic?

Topic 8: What Have We Missed?

69. If you feel we have not asked a critical question that would allow you to share an important lesson learned from your project, please ask and answer it for us.

Thank you for sharing your insights and brilliance.

Your experience and reflections will help the next generation of scientists avoid pitfalls and build from this generation of successes.

Appendix E

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Appendix F

Acronyms and Abbreviations

ABoVE	NASA Arctic-Boreal Vulnerability Experiment
AI	Artificial Intelligence
AMF	ARM Mobile Facility
AMP	AmeriFlux Management Project
Arctic-COLORS	NASA Arctic-COastal Land Ocean InteRactionS program
ARM	DOE Atmospheric Radiation Measurement user facility
ATWE	Alpine Treeline Warming Experiment
B4WarmED	Boreal Forest Warming at an Ecotone in Danger
BEF	Biodiversity-Ecosystem Functioning
BER	DOE Biological and Environmental Research program
BEO	Barrow Environmental Observatory
BioCON	Biodiversity, Carbon Dioxide, and Nitrogen experiment
BoSAW	Boreal Soil and Air Warming
CARE	Collective Benefit, Authority to Control, Responsibility, and Ethics
CCASE	Climate Change Across Seasons Experiment
CDR LTER	Cedar Creek Long-Term Ecological Research
CINet	Critical Interface Network
CiPEHR	Carbon in Permafrost, Experimental Heating Research
C	carbon
CO_2	carbon dioxide
COMPASS-FME	Coastal Observations, Mechanisms, and Predictions Across Systems and Scales–Field, Measurements, and Experiments
CSiTE	Consortium for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems
CZOs	Critical Zone Observatories
DRAGNet	Disturbance and Recovery Across Grasslands Network
DIRT	Detrital Input and Removal Treatments
DOE	U.S. Department of Energy
DOI	digital object identifier
E3SM	Energy Exascale Earth System Model
EBIS	Enriched Background Isotope Study
ELM	E3SM Land Model
ELM-FATES	E3SM Land Model–Functionally Assembled Terrestrial Ecosystem Simulator
ESS	Environmental System Science
ESS-DIVE	Environmental System Science Data Infrastructure for a Virtual Ecosystem
EucFACE	Eucalyptus Free-Air CO_2 Enrichment
FACE	Free-Air CO_2 Enrichment
FACE Soil Carbon	Soil Carbon Responses to Elevated Atmospheric Carbon Dioxide
FAIR	Findable, Accessible, Interoperable, and Reusable
FASET	Forest Accelerated Succession Experiment
FATES	Functionally Assembled Terrestrial Ecosystem Simulator

Forest-GEO	Forest Global Earth Observatory
FoRTE	Forest Resilience Threshold Experiment
GCREW	Global Change Research Wetland
GLEON	Global Lake Ecological Observatory Network
IDENT	International Diversity Experiment Network with Trees
IFRC	Integrated Field Research Challenge
ITEX	International Tundra Experiment
LBA	Large-Scale Biosphere-Atmosphere Experiment
LBA-ECO	Large-Scale Biosphere–Atmosphere Experiment in Amazonia
LTAR	Long-Term Agricultural Research
LTREB	Long-Term Research in Environmental Biology
LTER	Long-Term Ecological Research
MONet	Molecular Observation Network
ModEx	Model-Observation-Experiment
N	nitrogen
NABIR	Natural and Accelerated Bloremediation Research
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NGEE	Next-Generation Ecosystem Experiments
NGEE Arctic	Next-Generation Ecosystem Experiments in the Arctic
NGEE Tropics	Next-Generation Ecosystem Experiments in the Tropics
NSF	National Science Foundation
NSN	National Streamgaging Network
NutNet	Nutrient Network
OBFS	Organization for Biological Field Stations
OCCAM	Old-Field Community, Climate, and Atmosphere Manipulation
ORNL	Oak Ridge National Laboratory
SAIL	Surface Atmosphere Integrated Field Laboratory
SERC	Smithsonian Environmental Research Center
SFA	Science Focus Area
SPRUCE	Spruce and Peatland Responses Under Changing Environments
SMARTX	Salt Marsh Accretion Response to Temperature Experiment
SUMO	Survival-Mortality
SWaN	Soil Warming and Nitrogen Addition
TACIT	Temperature and Carbon Dioxide Interactions in Trees
TEMPEST	Terrestrial Eco-system Manipulation to Probe the Effects of Storm Treatments
TeRaCON	Temperature, Rainfall, Carbon Dioxide, and Nitrogen
TDEs	Throughfall Displacement Experiments
TNC	The Nature Conservancy
TRACE	Tropical Responses to Altered Climate Experiment
UMBS	University of Michigan Biological Station
WaRM	Warming and (species) Removal in Mountains
WHONDRS	Worldwide Hydrobiogeochemisty Observation Network for Dynamic River Systems