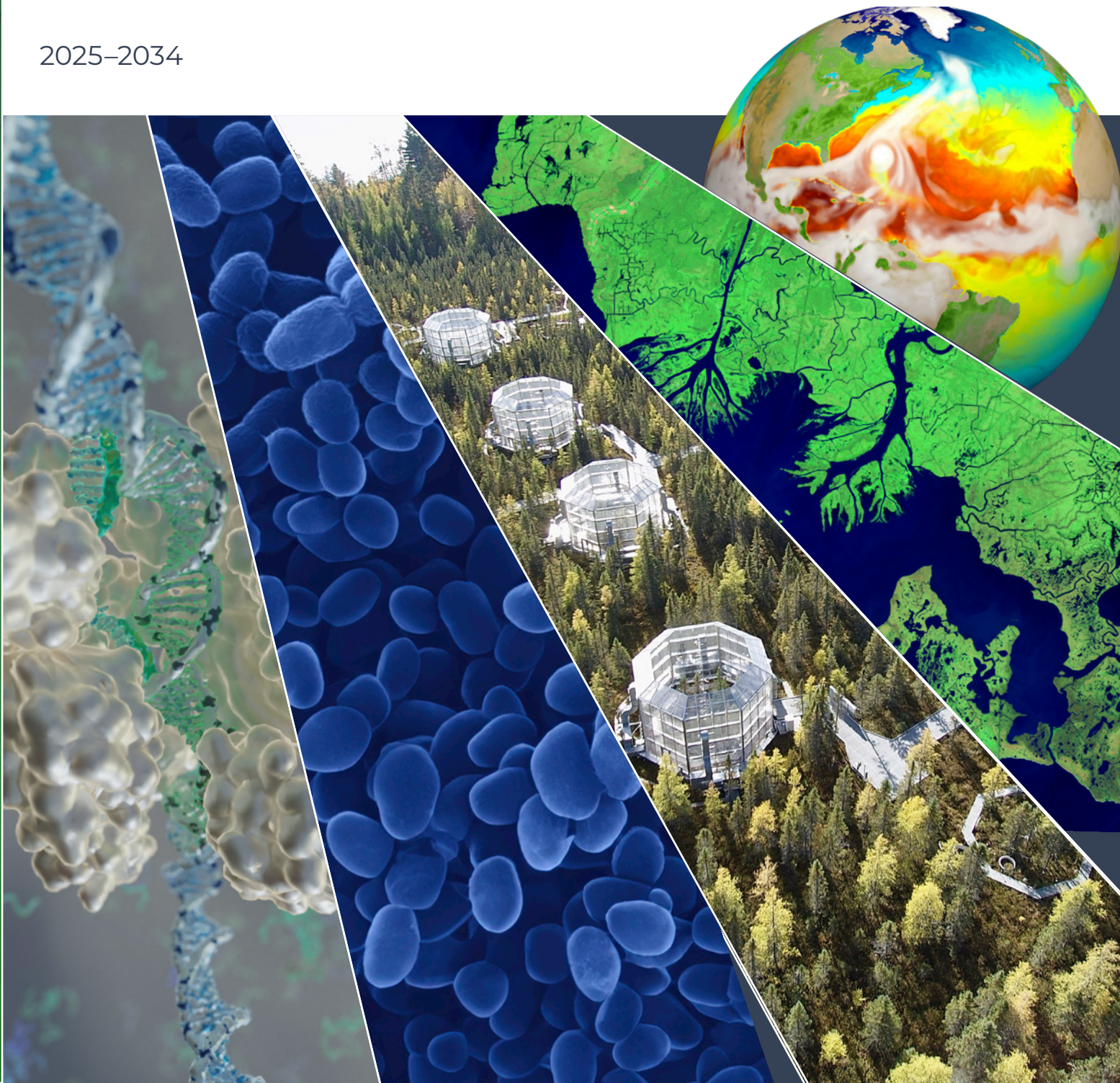


BIOLOGICAL AND ENVIRONMENTAL
SYSTEMS SCIENCE DIRECTORATE

10-Year Strategic Plan

2025–2034

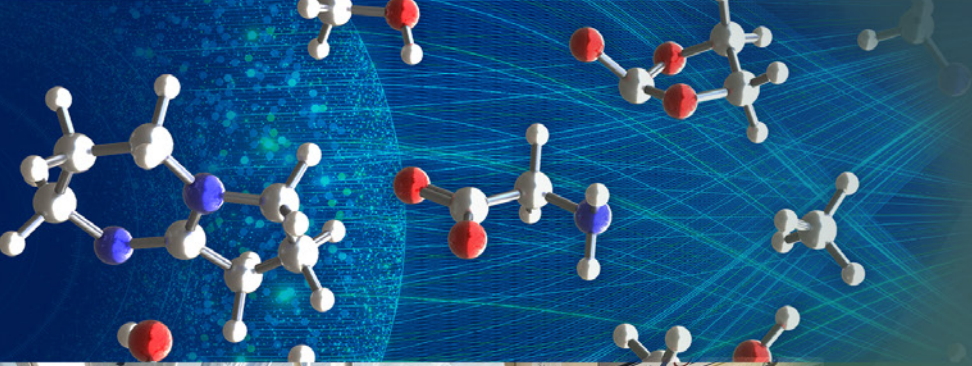


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Figure 1



Biological and Environmental Systems Science

Enhance understanding and harness coupled biological, environmental, and built systems in a changing world

MISSION

To provide innovative solutions to problems of global significance in energy, environment, and health through collaborative research and advanced technologies

VISION

Sustainable life on Earth with clean energy and resilient biological, environmental, and human systems

EXECUTIVE SUMMARY

The convergence of escalating environmental crises with a rapidly changing international landscape, supply chains, and economies ***has brought the Earth toward a critical tipping point***. Changing climate and extreme disturbance events such as droughts, heat waves, floods, and wildfires are already impacting our drinking water, agricultural crops, energy security, and built infrastructures (Ref. 1). Roughly half of the world's population experiences severe water scarcity for at least one month a year. At the same time, we are experiencing more severe flooding with rising economic impact, and sea level rise is affecting groundwater in coastal areas of the U.S. The Earth is incredibly complex, with biological and environmental systems that are tightly coupled across multiple spatial and temporal scales. Today, ***there is a large gap between our predictive understanding of planet Earth and our ability to harness and manipulate biological and environmental systems as a strategy to address the existential challenge we face***.

Simultaneously, emerging breakthrough technologies like artificial intelligence (AI), automation and remote sensing, and synthetic biology and systems biology offer new ways to bridge this knowledge gap. In tandem with exascale computing, AI has already increased the reliability of predicting carbon, biogeochemical, and water cycles in some Earth system models (Ref. 2). New synthetic biology tools, such as CRISPR/Cas9, are revolutionizing our ability to engineer microbes with enhanced properties, including the production of chemicals and fuels from renewable biomass feedstocks rather than petroleum (Ref. 3). These technologies promise to accelerate development of urgently needed innovative solutions to the catastrophic impacts of extreme disturbances and to propel a growing bioeconomy.

Motivated by these challenges and opportunities, the Biological and Environmental Systems Science Directorate (BESSD) at Oak Ridge National Laboratory (ORNL) presents this 10-year Strategic Plan and a bold new vision and research strategy to support ***sustainable life on Earth with clean energy and resilient biological, environmental, and societal systems***. Our vision and strategy align closely with the U.S. Department of Energy's (DOE) mission to ensure the nation's security and prosperity by addressing its challenges through transformative science and technology solutions. We leverage the unique environment, capabilities, and strengths of ORNL and the diverse talents of 300 directorate staff with the objective of addressing four ***Grand Challenge Themes***:

- 1. Predict Earth and environmental systems across scales**—We will produce reliable predictions of climate–carbon feedbacks and changes in the water cycle that pose risks to humanity, supporting informed decision-making.
- 2. Understand ecosystem response to changing climate and disturbance regimes**—We will conduct observations and experiments to understand the causes and consequences of abrupt ecosystem transitions arising from human-caused climate and environmental change.
- 3. Connect genes to ecosystems for sustainability and resilience**—We will apply genomic-level variations and modifications to manipulate ecosystems, enhancing their carbon storage capacity to aid in climate change mitigation and improving their resilience to disturbance events.
- 4. Engineer a circular bioeconomy**—We will develop the technologies and capabilities to predict, manipulate, and design biological systems for efficient production of bioenergy, bioproducts, and biomaterials—optimizing carbon use and transitioning production processes from linear to circular while supporting the bioeconomy and preserving ecosystem diversity and services.

The **Grand Challenge Themes** are a coordinated approach to **understanding and harnessing coupled biological and environmental systems**. To illustrate their interdependence, **Theme 1** improves models that provide accurate probabilities for the occurrence of extreme disturbance events, while **Theme 2** provides understanding of their impact on ecosystems, including recovery, transition, or collapse. Together, **Themes 1 and 2** inform us on ecosystems at risk of tipping into catastrophic collapse. **Theme 3** advances biological systems science to support solutions that reduce the probability of disturbances occurring, and to lessen their impact on vulnerable ecosystems and thus overall risk. It also provides new predictive information on the connection between genes and ecosystem processes that could be fed back to extended models in **Theme 1**, thereby connecting **Themes 1, 2, and 3** in a positive feedback loop. In **Theme 4**, we further minimize risks to ecosystems by providing the technologies needed to propel a circular bioeconomy with renewable fuels, clean energy, and a sustainable, low-carbon society.

Working with experts from multiple disciplines at ORNL, including world-leading DOE neutron and computing user facilities (App. C), emerging breakthrough technologies will be added to current cutting-edge capabilities to build a **foundational science infrastructure** to help address the **Grand Challenge Themes**. Leveraging synergies and partnerships across ORNL, BESSD will focus these technology developments in two **transformational crosscutting areas**:

- **Advanced computing and data science**—We will create a rapid and flexible deployment of foundation AI models and data and computing to accelerate systems-level understanding in biological and environmental research. We will link data, modeling, and experimentation to AI and cutting-edge analytical capabilities for integrated measurement, experimentation, and hypothesis testing, enabling actionable science, and creation of digital twins.
- **Biological and analytical tools**—We will create a science infrastructure at ORNL, building on our foundational assets in plant, microbial, and environmental research, of unique analytic tools and approaches to generate, quantify, and analyze biological and environmental datasets across scales, providing insights critical to each **Grand Challenge Theme**. This infrastructure will complement those at other national laboratories (App. B) and contribute to an unrivaled coordinated network of DOE capabilities for biological and environmental research.

An accelerating trend in our research within each **Grand Challenge Theme** is the convergence of ranges of scales and coupling of systems. For example, in **Theme 1**, we are extending Earth system predictions down from global to regional scales and coupling them to processes at the microbial level. In **Theme 2** we are broadening environmental measurements and experiments from a small number of locations toward global coverage and shorter timescales. In **Themes 3 and 4**, we are extending understanding of biological systems upward from the molecular and genetic to the metabolic, organism and ecosystem scales. Capturing exponential technology change in our transformational crosscutting areas, further development of this convergence and coupling will lead us toward a **holistic multiscale systems understanding of Earth and biological systems**. **This would represent a paradigm shift in our predictive understanding of planet Earth.**

As a DOE laboratory, ORNL brings diverse viewpoints, wide-ranging capabilities, and individual creativity and ingenuity to science and technology in a way few other research institutions can match. **We will aggressively pursue strategic partnerships (App. A), including strong research collaborations across the infrastructure of DOE laboratories in both the environmental and biological domains**, to urgently translate our breakthrough science and growing knowledge base into actionable solutions for the nation.

THE CHALLENGE

Gaining a predictive understanding of complex biological and environmental systems—to provide innovative solutions for sustainable life on Earth—is one of the **biggest scientific challenges of the 21st century** (Ref. 20). It is key to safely navigating current threats of climate change and to fulfilling the potential of a clean, prosperous, and sustainable bioeconomy. Oak Ridge National Laboratory (ORNL) is a U.S. Department of Energy (DOE) laboratory with a legacy of 80 years of delivering scientific discoveries to address the nation's most urgent research and development needs. Today, with a sharp focus on DOE missions, ORNL builds on that legacy of big science to address the ambitious grand challenge themes in this Plan and to realize **sustainable life on Earth with clean energy and resilient biological, environmental, and societal systems**.

ORNL is ready to address this challenge as home to several leading biological and environmental research programs, including Next-Generation Ecosystem Experiments in the Arctic (NGEE Arctic; Fig. 9, App C-2) and the Center for Bioenergy Innovation (CBI; Fig. 17, App. C-2). These programs leverage DOE **user facilities**, such as ORNL's world-leading neutron and computing facilities, to reveal the structure and dynamics of biological and environmental systems, and **shared-use demonstration facilities** to additively manufacture biomaterials from genetically advantaged feedstocks and develop automation and sensor platforms for ecosystem experiments (App. C-1). **Truly unique and innovative ORNL capabilities built to accelerate discovery in plant and microbial sciences** include the Advanced Plant Phenotyping Laboratory (APPL; App. C-1). With one of the world's broadest range of imaging modalities, APPL enables wholly new high-throughput automated experiments to phenotype plants and to identify the genetic basis for their response to changing conditions (Fig. 13).

ORNL is strategically investing in the foundational scientific infrastructure, innovative research, and diverse strategic hiring necessary to propel this Plan forward (App. C and Fig. 4). These investments position ORNL at the leading edge of rapidly advancing frontiers in artificial intelligence (AI), computing, ecosystem manipulation, climate modeling, data science, plant and microbial transformation and phenotyping, and the scientific laboratory of the future concept. They will enable transformative new approaches to conducting research outlined in this Plan including foundation AI models applied to climate modeling on the world's first exascale computer, engineering enzymes into a circular pathway to synthesize and recycle new polymers from renewable feedstocks, and automation and remote sensing systems that couple laboratory and field experiments across a huge range of spatial and temporal scales (Fig. 16 and Fig. 21, App. C).

As a **multipurpose laboratory supported by several sponsors** of basic and applied science, and in partnerships with universities and industry, ORNL leverages its role as **an integrator to accelerate translational science-to-solution pathways** (App. A). Examples include synthetic biology discoveries applied to engineer microbes at ORNL that are now licensed to industry to produce new chemicals and biofuels (Fig. A2, Fig. A4). New pathways under development at ORNL include coupling urban and rural environmental data with high-resolution modeling in digital twins to inform decision-making on development and protection against disturbances (Ref. 5).

DOE laboratories are the legacy of the Manhattan project, the nation's urgent response to the threat of nuclear attack (Ref. 6). Today they serve as a globally unrivaled network of multidisciplinary laboratories for mission-driven scientific discovery and technical innovation. They have the powerful ability to come together to solve grand challenges, such as sequencing the human genome (Ref. 7) and providing the infrastructure of atmospheric measurements needed to inform development of solutions to the nation's energy challenges (Ref. 8). **ORNL will leverage existing partnerships with sister DOE laboratories, and aggressively pursue new ones, to bring to bear the collective power of DOE big science to advance this Plan and secure the future** (App. B–C).

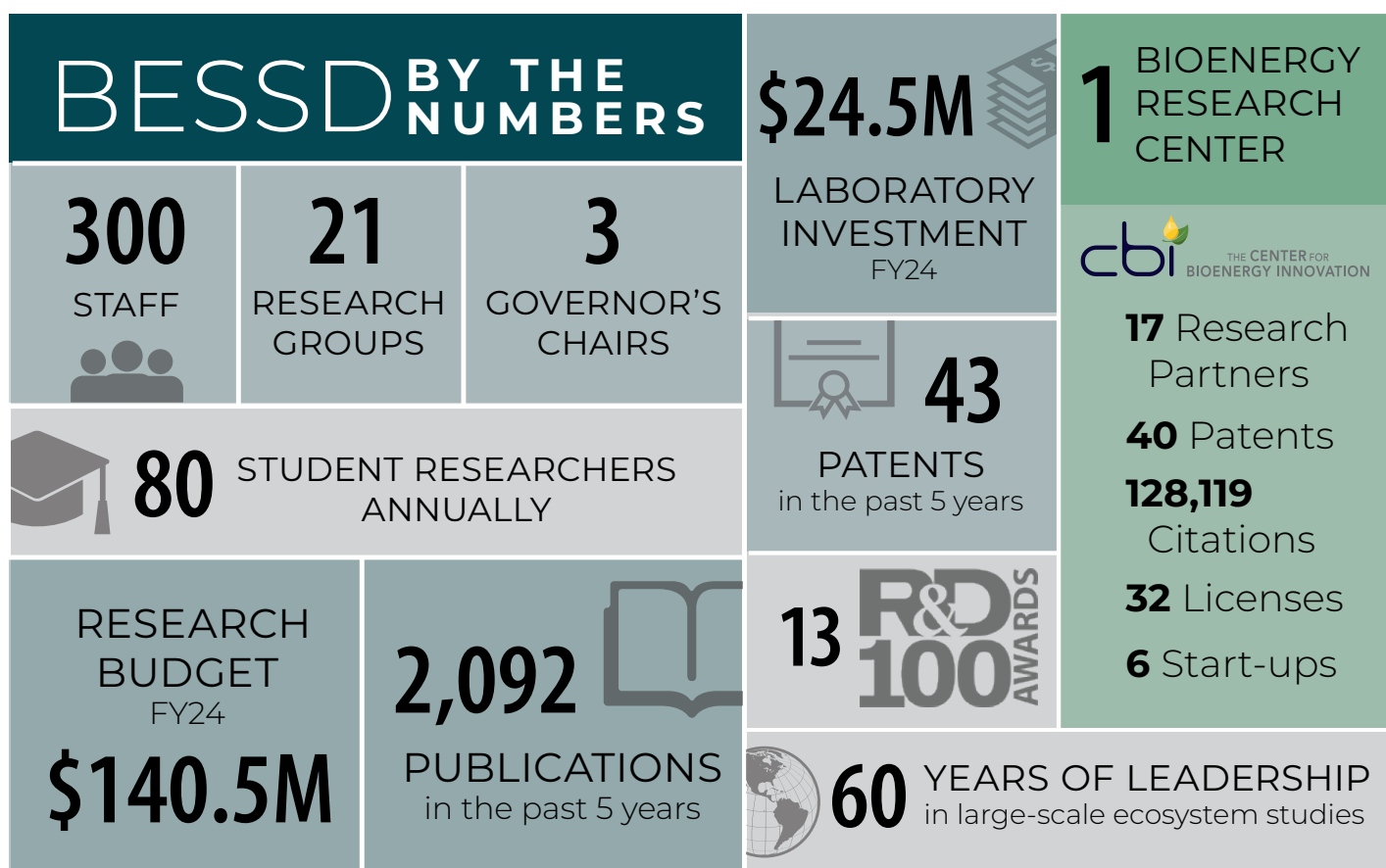


Figure 3. Snapshot of Biological and Environmental Systems Science at ORNL.

DIVERSITY, EQUITY, INCLUSION, AND ACCESSIBILITY

At the core of our organizational ethos lies an unwavering commitment to Diversity, Equity, Inclusion, and Accessibility (DEIA). ORNL has developed and is implementing a comprehensive DEIA Plan that captures our DEIA vision and is built around a series of five goals, given below. DEIA plays a key role in each of our five Core Values: Impact, Integrity, Teamwork, Safety, and Service. These values guide how we treat one another, work together, and measure success—not only as individuals, but as groups and as an institution. Through these concerted efforts, we aim not only to embrace diversity but also to champion equity and cultivate a truly inclusive community where everyone can thrive and excel.

Shared Understanding. Enhance laboratory-wide understanding of DEIA and its value proposition, communicating how diversity in experiences and perspectives advances ORNL's mission and vision.

Balanced Representation. Develop and deploy recruiting, onboarding, and career development strategies to close gaps in representation and retention.

Exceptional Experiences. Create an inclusive environment that inspires everyone to contribute their unique perspectives and talents to the mission.

Enriched Partnerships. Develop and sustain local, regional, and community science and technology partnerships that enhance accessibility of ORNL resources to underrepresented entities and promote broader impacts.

Cohesive Structures. Enhance DEIA structures important for prioritizing, connecting, implementing, and tracking DEIA progress, including a multiyear DEIA framework.

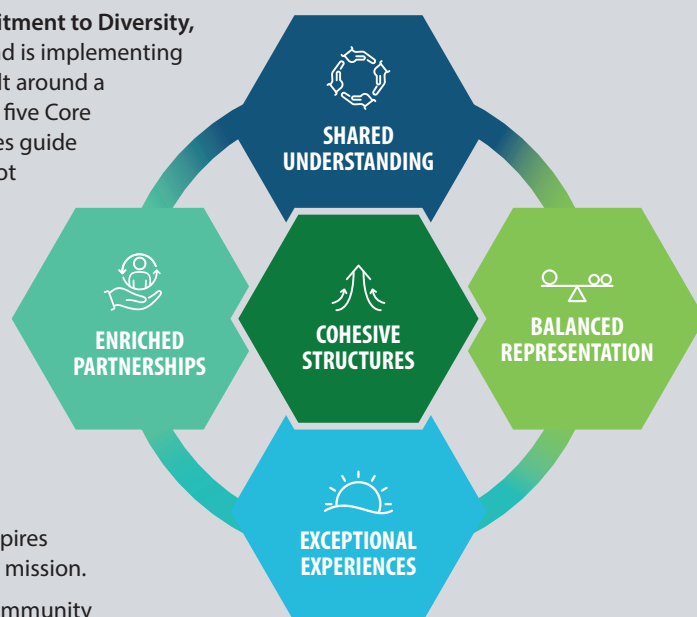


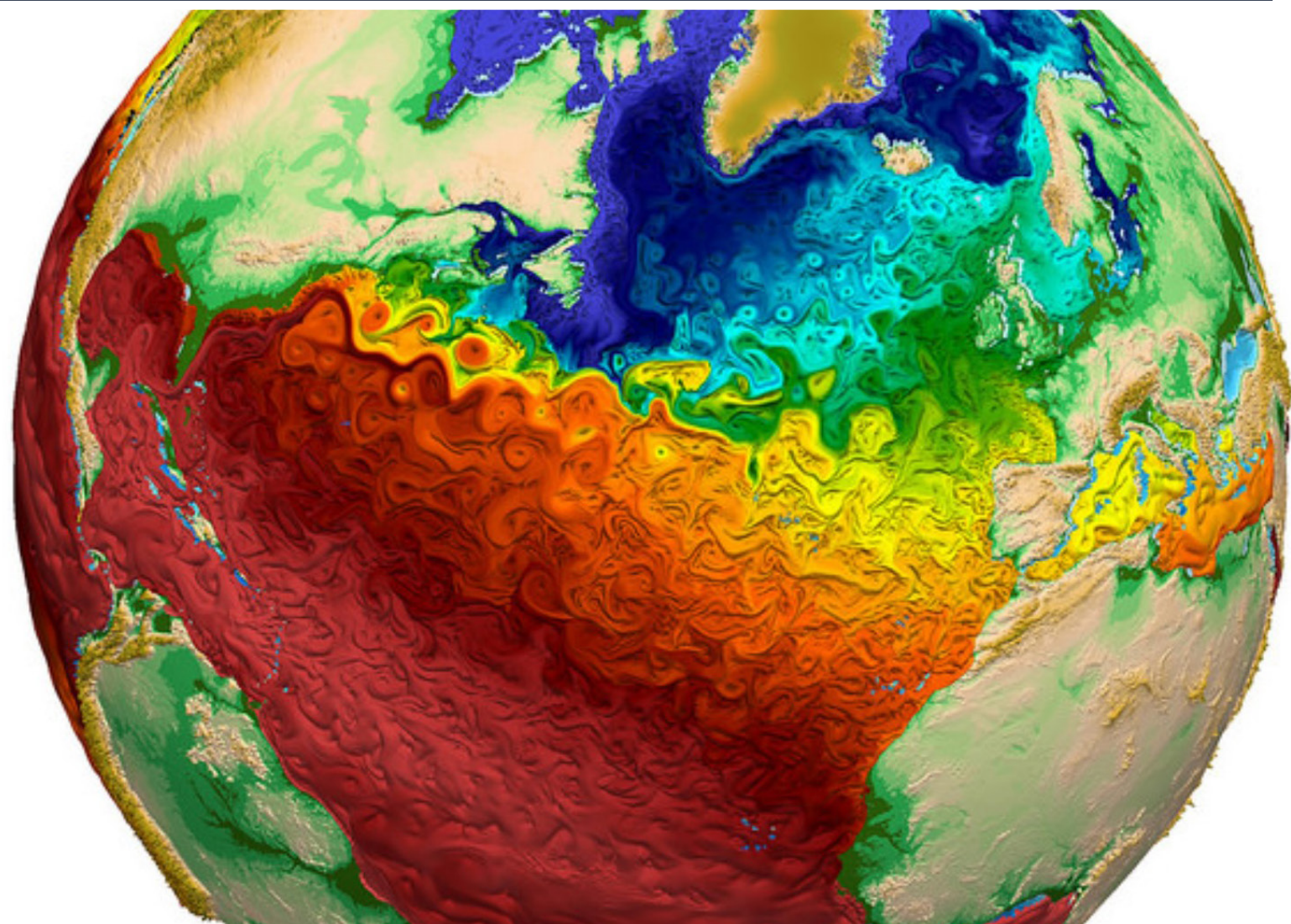
Figure 4. Diversity, equity, inclusion, and accessibility are part of the ORNL culture.



THEME 1

PREDICT EARTH AND ENVIRONMENTAL SYSTEMS ACROSS SCALES

We will produce reliable predictions of carbon feedbacks in the climate system, eliminating major sources of uncertainty through experimentally based discovery of foundational mechanisms for biogeochemical cycling on land. We will develop a comprehensive predictive understanding of risks to humanity resulting from changes in the water cycle, including increased extreme precipitation and flooding, rising intensity of droughts, and impacts to groundwater availability and water quality from climate extremes and increased demand.



THE GRAND CHALLENGE

Uncertainties hinder our ability to make reliable predictions of water, energy, and biogeochemical exchanges in Earth's coupled surface–subsurface systems. Critical gaps in the scale of processes resolved in current models prevent efficient connections between global-scale processes needed for long-term Earth system prediction, and landscape and finer-scale processes needed to understand mechanisms and address management and decision-making. There are also many gaps in the representation of dynamic human systems within existing modeling frameworks. The principal challenge in this area is to develop improved models that represent all critical processes for water, energy, carbon, and biogeochemistry, with effective mechanisms for bridging microscopic to global scales, and with representation of human systems sufficient for management and decision-making applications.

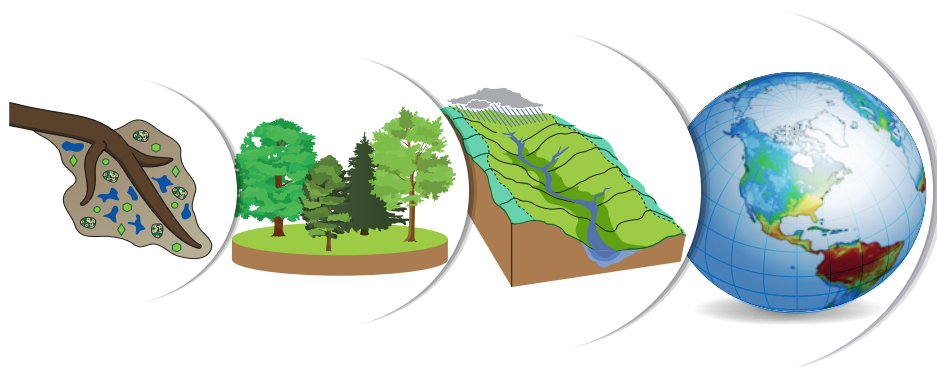
BACKGROUND

We face an existential challenge in accelerating climate mitigation while minimizing harm to humans and the environment in the process. Geological and evolutionary forces have been shaping our planet's history for millennia and epochs, but now the most significant changes in the Earth system are being caused by unprecedented acceleration in human technological advancement.

Notwithstanding the abundant good brought about by rapid development, the harm caused by an accumulation of fossil fuel combustion by-products and other pollutants in our atmosphere, oceans, and land is rapidly emerging from a background of natural variability. This harm manifests as global temperature increase, sea level rise, growth in the intensity of storms, worsening of extremes such as floods and drought, and acceleration of disturbances such as wildfire.

Consumption of slowly renewing resources such as groundwater, fertile soil, and mature forests has supported the growth of the human population and fostered widespread improvements in the global standard of living. We are now seeing the limits of that consumption in the form of groundwater depletion, the increased need for artificial fertilizers to maintain soil fertility, and the loss of forest habitat and biodiversity.

Safely navigating this current danger will require all our ingenuity as a species. To see us through the mounting dangers of climate change, **humanity needs a full and reliable predictive understanding of the Earth system**, including mechanistic knowledge of how our own intentional resource consumption and inadvertent pollution are shaping the trajectory of life on our planet. As new climate change solutions are imagined, tested, and deployed, we need trustworthy and comprehensive assessments of how much good they can do, and at what cost, and with what tradeoffs for ourselves and our environment.



WHY OAK RIDGE?

ORNL is at the forefront of multiscale Earth system model development, especially land system and water cycle model development, evaluation, uncertainty quantification, and application. Our experimentalists, data scientists, and computational scientists collaborate closely to achieve breakthroughs in these science areas. These unique research strengths and collaborations are magnified by ORNL's exceptional technological strengths, including unparalleled capability in ecosystem experimentation, record-setting exascale computing, high-performance data infrastructure, and innovation in the development and application of AI. ORNL leads the development of land modeling for **DOE's Energy Exascale Earth System Model (E3SM)**, which includes predictive understanding of integrated water, energy, carbon, biogeochemistry, and human systems. We are also deeply engaged in basic research focused on Arctic and boreal science, coastal interfaces, climate interactions with infrastructure and urban environments, and ultra-high-resolution land and water modeling. With those foundational strengths and expanding investments in decision science and applied regional climate solutions (e.g., ARMADA, Climate Change Science Institute, Urban Integrated Field Laboratories; Fig. 7, App. C), **we are uniquely positioned to bring an unprecedented level of Earth system, land system, and water cycle understanding to decision-relevant scales.**

Effective collaboration across institutions is a signature strength at ORNL. We coordinate our expertise in land and water system modeling with all the DOE national laboratories working in the climate change space to deliver state-of-the-art Earth system prediction capabilities (see Partners – sidebar). We also connect directly with a broad range of other federal agencies and universities to maximize our impacts through joint science campaigns, shared data and infrastructure, and the development of new fundamental knowledge through the open science community (App. A–B).

Gain new predictive knowledge of coupled controls on biogeochemical cycles, land systems, human systems, and climate systems.

We have identified critical uncertainties in our understanding of biogeochemistry and climate–human system interactions and feedbacks. We will focus on improved understanding of the primary mechanisms regulating carbon storage in land ecosystems under conditions of ongoing climate change and potential future scenarios of climate change mitigation. We will pursue this objective through integration of multiscale models with automated laboratory and field experiments (**Themes 2, 3**) and through synthesis of multiscale Earth system observations leveraging AI and machine learning (ML) tools and methods (**Advanced Computing and Data Science Crosscut**). E3SM will continue to serve as the ultimate large-scale integration platform for our new knowledge and predictive skill.

SCIENCE QUESTIONS

- How do soil biogeochemical processes regulate carbon storage in land ecosystems, and how will those processes interact with climate mitigation strategies?
- How do soil microbial populations metabolize soil organic matter inputs, and how can the complexity of those processes (as elucidated under **Theme 3**, Objective 1) be reduced for large-scale modeling without sacrificing prediction skill?
- How are soil biogeochemical processes in cold climates (elucidated under **Theme 2**, Objective 1) regulated by hydrologic and thermal characteristics of the surface layers of bryophytes (moss and lichen), plant litter, and partially decomposed organic material?
- How do these organic surface layers evolve over time in these highly heterogeneous cold climate landscapes, and how will they be impacted by ongoing climate change?
- What are the historical and current conditions for carbon accumulation in natural and managed land systems?
- What are the limits of predictability for future carbon accumulation in land ecosystems, and can our best models provide robust decision-making support for emerging carbon markets?
- Can foundation AI models, trained on text, remote sensing data, and multi-model output (see **Advanced Computing and Data Science Crosscut**) provide trustworthy guidance to decision-makers and help to structure the representation of human systems in multiscale physics-based models?

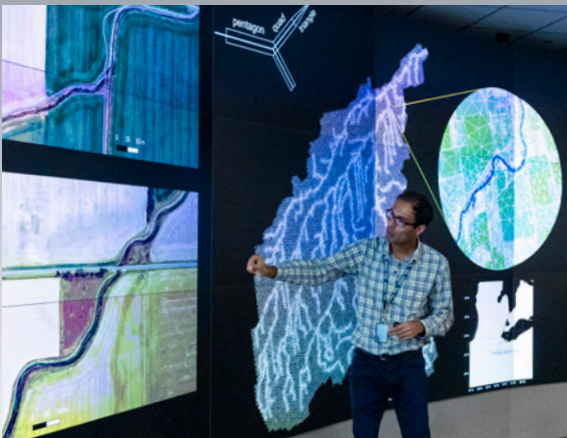


Figure 5. Researchers are using the Advanced Terrestrial Simulator to model and assess flood-prone areas as part of the Southeast Texas Urban Integrated Field Laboratory.

ADVANCED TERRESTRIAL SIMULATOR

Climate change is often a story about water. Will there be enough of it, too much, and how will that change in a hotter world? ORNL leads development of the Advanced Terrestrial Simulator, or ATS, a physics-based software tool that creates highly accurate water flow simulations, taking into account vast above- and belowground topographical complexities. The simulator enables detailed analysis of environmental systems undergoing stresses such as a changing climate or land use. ORNL experts are continually advancing ATS capabilities and applying them to discover critical insights about key environmental processes at decision-relevant scales. ORNL researchers used ATS to address one of the biggest uncertainties about the thawing of carbon-rich Arctic permafrost, finding that related soil subsidence is unlikely to trigger a feedback loop that results in rampant thawing in the future. The simulator was also used to model a Texas watershed that contains a large population, key energy infrastructure for the nation, and is at risk of hurricanes and legacy pollution issues. The resulting in-depth model provides accurate projections of future flooding risk that can guide climate mitigation measures. Collaborators on ATS include Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), and Pacific Northwest National Laboratory (PNNL).

5-YEAR GOALS

- Quantify the microbe-mediated process of plant litter decomposition and soil organic matter formation across a range of soil and litter types through highly replicated and automated laboratory tracer experiments combined with AI-driven model formulation and parameterization studies (connection to **Theme 3**, and see **Biological and Analytical Tools Crosscut**).
- Develop a predictive model of the structure and function of surface organic layers in peat-dominated cold-climate ecosystems, based on high-resolution landscape characterization with remote sensing data, ecosystem-scale observations and manipulations, and laboratory mesocosm studies (connection to **Theme 2**).
- Establish quantitative high-resolution global-scale baselines for the amount of carbon that has been gained or lost over the recent historical period in natural and managed land ecosystems, through process-based models optimized against multi-modal observations using AI and ML methods. Data from multiple CMIP-class models will be integrated in the analysis through **ESGF2-US** data infrastructure and compute capability.
- Starting with an existing AI foundation model trained on multi-modal climate observations, remote sensing data, and Earth system modeling results, fine-tune this model with text inputs from the decision-support literature to generate reliable answers to questions posed by actual decision-makers or stakeholders (see **Advanced Computing and Data Science Crosscut**).

10-YEAR GOALS

- Broaden the multiscale representation of microbial dynamics in soil carbon and nutrient cycling models. The knowledge gained in early stages of this research will allow the complexity of the models to be reduced or expanded depending on the scale of application and evaluated for predictive skill against multi-modal observations at site, regional, and global scales. Integrate this new knowledge into E3SM (connection to **Theme 3**).
- Expand predictive modeling of surface organic layers in peat-dominated systems by simulating the stages of accumulation and decomposition of separate vegetation and mineral components over decadal and longer timescales. Evaluate these new process representations in large-scale simulations that incorporate ecosystem-scale manipulations and observations as well as field- and remote sensing-based measurements of temperature and hydrologic conditions. Integrate new knowledge into E3SM (connection to **Theme 2**, and see **Biological and Analytical Tools Crosscut**).
- Predict land carbon storage and loss under future climate and carbon offset scenarios, including improved understanding of litter and soil organic matter processes, to constrain additionality requirements central to valuation in emerging carbon offset markets.
- Extend the decision-support functionality of a fine-tuned AI climate foundation model to give trustworthy guidance on configuring new physics-based simulations that can improve answers to user questions where existing training and fine-tuning resources show lower reliability from optimized AI models (see **Advanced Computing and Data Science Crosscut**).

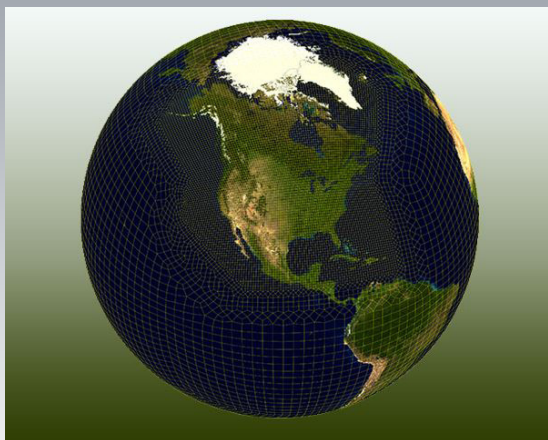


Figure 6. ORNL researchers are leading the development of an ultra-high resolution E3SM Land Model.

ENERGY EXASCALE EARTH SYSTEM MODEL

The Energy Exascale Earth System Model's Land Model investigates land processes and their interactions within the Earth system using DOE supercomputers, with the goal of highly accurate and actionable projections of changes in energy, water, carbon, and biogeochemical cycles over timescales from days to centuries. Focus areas include land-use/land-cover change, hydrology and ice-land interactions, climate-biogeochemistry interactions that affect the carbon cycle, land-atmosphere interactions, topography and elevation impacts, and human-Earth interactions. ORNL has pioneered the development of high-resolution land models in E3SM, running on Oak Ridge Leadership Computing Facility (OLCF) supercomputers. These higher-resolution capabilities are necessary to inform regional, national, and global decision-making. E3SM is a collaborative project with contributions from eight national laboratories.

Provide projections of drought, flood risks, and water quality trends at stakeholder-relevant scales.

Climate change impacts society directly through the water cycle in the form of increased precipitation, more frequent and more intense droughts, and increased demand. We will develop improved projections of flood risks, river flows, groundwater availability, and water quality trends. We will pursue this objective by improving the water cycle representation in E3SM and fine-scale models, extending high-resolution, spatially explicit integrated hydrologic models to river basin scales, and combining multiscale data with AI and ML techniques.

SCIENCE QUESTIONS

- How will climate change and evolving land-use/land-cover, water demand, and water management practices affect water availability in the coming decades?
- Where and when will the capacity of groundwater resources to buffer climate stresses on agricultural systems be exhausted, and what are the consequences?
- What are the risks to municipal water supplies in coastal cities from seawater intrusion resulting from low river flows during future droughts?
- How will non-stationary precipitation extremes across a wide range of frequency levels (10^2 to 10^7 years) affect flood risk, and what are the implications for infrastructure?
- How will climate change, evolving land-use/land-cover, and changing nutrient and contaminant loading affect water quality?
- How will rising water temperatures affect the capacity to cool thermoelectric power plants, and how will those risks vary regionally in the U.S.?

5-YEAR GOALS

- Couple the land component of E3SM to the surface–subsurface simulation capabilities of the ATS and demonstrate improved prediction of hydrologic variables at the regional scale. This capability will include improved water temperature modeling capabilities to better represent effects of warming on energy production and ecosystems.
- Combine high-resolution integrated hydrology simulations and AI/ML-based surrogate models to make ensemble decadal projections of water availability for a sensitive water resources region (see **Advanced Computing and Data Science Crosscut**).
- Implement improved representation of hydrology in the land model component of E3SM by using watershed-based meshes with between-grid and subgrid representations of lateral flows. Demonstrate and evaluate this new modeling capability at the national scale.
- Refine AI, ML, and/or agent-based models for water demand and land-use/land-cover change and integrate them with high-resolution integrated surface–subsurface hydrological models.
- Develop high-resolution inundation modeling and mapping capabilities that leverage leadership-class computing resources in exascale hydrodynamic studies.
- Establish and release a national data platform that can provide the necessary terrain, infrastructure, remote sensing, and *in situ* observations to support community efforts on flood modeling, validation, and impact assessment.
- Evaluate the capacity of the current generation of integrated hydrologic models to predict event-scale exports of nutrients, carbon, and contaminants, including how shifting redox and salinity associated with hydrologic events perturb biogeochemical processing.

10-YEAR GOALS

- Couple the E3SM Land Model (ELM) to a continental-scale model for deep groundwater to represent the effects of groundwater pumping for irrigation, resolving impacts on streamflow and evapotranspiration.
- Implement a watershed-based variant of ELM at the global scale and couple to a global groundwater model.
- Make high-resolution ensemble projections of surface water and groundwater availability accounting for climate change, evolving water demand, and land-use/land-cover change.
- Develop physics-informed methods to estimate probable maximum precipitation and flood in a changing environment.
- Provide ensemble-based, high-resolution inundation projections to support climate-informed risk assessment for energy–water security and resilience.
- Develop AI/ML data analytics to extract actionable information from high-resolution ensemble projections.
- Use high-resolution integrated hydrologic models to make decadal projections of water-quality trends for different climate-change scenarios (see **Advanced Computing and Data Science Crosscut**).



Figure 7. Researchers from ORNL and Georgia Tech discuss strategies with community members and regional experts at the Southeast Decarbonization Workshop.

INFORMING REGIONAL SOLUTIONS

ORNL's Climate Change Science Institute (CCSI) brings together interdisciplinary experts across the laboratory to create science-to-solution pathways. CCSI has worked with the automotive industry to apply the E3SM global model to assess the impact of direct air capture of CO₂ on transported heat and concentration anomalies in the atmosphere. CCSI also launched several ORNL Laboratory Directed Research and Development projects (App. C) in its new Science and Technology for Applied Regional Solutions (STARS) program, providing science to underpin an equitable, sustainable future for stakeholders in communities across the Southeastern United States.

KEY PROJECTS, SPONSORS, AND PARTNERS

PROJECTS

- AI Initiative (ORNL Laboratory Directed Research and Development)
- Atmospheric Radiation Measurement Data Center
- Climate Change Science Institute – Science and Technology for Applied Regional Solutions
- Coastal Observations, Mechanisms, and Predictions Across Systems and Scales – Field, Measurements, and Experiments
- Coastal Observations, Mechanisms, and Predictions Across Systems and Scales – Great Lakes Modeling
- DOE Early Career Projects
- Earth System Grid Federation 2 – United States
- Energy Exascale Earth System Model
- Exasheds
- Interoperable Design of Extreme-Scale Application Software–Watersheds
- Interdisciplinary Research for Arctic Coastal Environments
- NetZero-ARMADA: Scalable Multi-Sector Analysis Platform for the Energy Transition (ORNL Laboratory Directed Research and Development)
- Next-Generation Ecosystem Experiments in the Arctic
- Next-Generation Ecosystem Experiments in the Tropics
- ORNL Distributed Active Archive Center for Biogeochemical Dynamics
- Reducing Uncertainties in Biogeochemical Interactions through Synthesis and Computation
- Spruce and Peatland Responses Under Changing Environments
- Two-Dimensional Runoff Inundation Toolkit for Operational Needs
- Urban Integrated Field Laboratories (Baltimore, Southeast Texas, Southwest)
- Uncertainty-Aware, Machine Learning-Enabled Hydropower Forecast Model
- Watershed Dynamics and Evolution

SPONSORS

- DOE Office of Science, Biological and Environmental Research
- DOE Office of Energy Efficiency and Renewable Energy
- DOE Office of Environmental Management
- DOE Office of Advanced Scientific Computing Research
- NASA Earth Science
- National Oceanographic and Atmospheric Administration
- United States Air Force

PARTNERS

- Oak Ridge Leadership Computing Facility
- ORNL Computing and Computational Sciences Directorate
- ORNL Energy Science and Technology Directorate
- Argonne National Laboratory
- Brookhaven National Laboratory
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories
- Smithsonian Environmental Research Center
- Universities (numerous partnerships)



THEME 2

UNDERSTAND ECOSYSTEM RESPONSE TO CHANGING CLIMATE AND DISTURBANCE REGIMES

We will establish a comprehensive and predictive understanding of Arctic and boreal ecosystems and their response to climate change, building on our world-leading experimental and observational efforts while drawing together the global knowledge base through synthesis and modeling studies. We will develop and test new theories explaining the vulnerability and response of ecosystems to disturbance and climate extremes, and we will apply that new predictive understanding to show the causes and consequences of abrupt ecosystem transitions in response to human-caused climate and environmental change.



THE GRAND CHALLENGE

There is a critical need to transform our understanding of disturbance and climate change impacts on ecosystem function, biodiversity, and biogeochemical cycles across a range of spatial and temporal scales through modular and transferable ecosystem-scale manipulations, multiscale observations, and predictive modeling.

BACKGROUND

Both natural and anthropogenic factors will affect ecosystem response to, resilience to, and recovery from disturbance. Long-term ecosystem trajectories may also be altered by reaching tipping points and crossing thresholds, resulting in irreparable damage to ecosystem functions and, potentially, the emergence of novel biomes. Our challenge in this area is to understand the cumulative impacts of climate change, extreme events, disturbances, and land-use/land-cover changes on biogeochemical cycling and to connect that knowledge to improve predictive understanding of ecosystem function and the potential implications for climate futures.

Flexible and quickly deployable capabilities are needed for multiscale observations, manipulations, and modeling across diverse ecosystems. A modular, economical, and publicly accessible design for coordinated measurements will promote transferability across institutions. Rapid data access and uptake in mechanistic and AI/ML-driven modeling efforts will enable robust ecological forecasting of response to extreme events and disturbances. Our approach will achieve a much broader understanding of how different organisms, populations, ecosystems, and biogeochemical cycles respond to climate change and disturbance regimes predicted in **Theme 1**, informing the focus for target ecosystems in **Theme 3**. Such scalable platforms will have great utility not only for DOE research, but across national programs and agencies with diverse mission scopes.

WHY OAK RIDGE?

ORNL is a leader in large-scale ecosystem studies, manipulation experiments, and in using knowledge from experiments to improve models. Our efforts have included multidecadal studies of disturbances, such as acid rain, mercury contamination, hydrological processes, ecosystem climate change, and cooling water discharges. ORNL leads two of DOE's flagship projects—NGEE Arctic and the Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment—examining the carbon balance in higher latitudes, where temperature is increasing three to four times faster than the rest of the globe. Insights from these flagship projects and deep expertise in terrestrial and aquatic ecosystem science are complemented by newer projects focused on coastal, aquatic, and urban areas.

ORNL is a partner on three Urban Integrated Field Laboratories, working with other institutions to predict and mitigate flood risks in Baltimore and along the Texas Gulf Coast, as well as investigating extreme heat and drought in Arizona. ORNL hosts the Aquatic Ecology Laboratory, which is an experimental facility dedicated to understanding impacts of anthropogenic contamination on aquatic ecosystems. In collaboration with the U.S. Department of Agriculture (USDA) Forest Service, the remote sensing platform ForWarn can track disturbances such as wildfire, insect outbreaks, wind, and hail in U.S. forests. ORNL has a growing network of collaborators on climate change, disturbance, ecosystem, and decarbonization projects in the Southeastern United States.



Develop new predictive understanding of high-carbon Arctic and boreal landscapes and how they respond to climate change.

Over approximately the past decade, ORNL scientists have stewarded multiple DOE investments and projects focused on understanding trajectories of change and functional responses within boreal and Arctic ecosystems to multiple climate forcings. As these efforts move towards completion, the synthesis of observations and experimental results enable scaling of the process understanding gained to better inform predictive models across these globally important ecosystems. Additionally, the remaining sources of uncertainty regarding changes in these ecosystems, and technical lessons learned from these studies, will be brought forward to inform the directions of future research in these and other ecosystems.

SCIENCE QUESTIONS

- How do increasing temperatures affect plant productivity, microbial function, greenhouse gas emissions, and water and biogeochemical cycling in these systems?
- Does elevated CO₂ increase vegetation productivity and nutrient cycling in Arctic and boreal ecosystems, and to what extent can plants and microbes compensate for the effects of increasing temperature on carbon and water cycles?
- What do long-term and multiscale observations of these systems tell us about the effects of ongoing climate change, and what trajectories are expected in the future?

5-YEAR GOALS

- Successfully complete the 10-year active treatment phase of the SPRUCE whole ecosystem warming experiment in northern Minnesota in the next two years and conclude measurements to quantify the systems-level impacts of temperature and elevated CO₂ on the hydrobiogeochemistry of this southern boreal peat bog.
- Synthesize results on the plant and microbial communities and the carbon, nitrogen, and water cycles, and apply model-based approaches to understand how findings from this single location translate and scale across regional and global peatland biomes.
- Implement these synthesis and scaling efforts through both customized individual simulations and community-driven model intercomparison approaches. Scaling targets for projecting these results will include initially very similar boreal ombrotrophic peatland ecosystems and will ultimately more broadly include non-permafrost peatlands in North America and internationally.
- Compile a decade of observations and modeling in permafrost Alaska over the next three years under NGEE Arctic.
- Predict changes in ecosystem function, hydrology, and carbon storage capacity based on data collected at ORNL field sites, and from a range of international collaborator sites across the global permafrost Arctic.
- Use long-term observations and model-data integration to predict climate-ecosystem feedbacks across these pan-Arctic permafrost ecosystems, and predict responses to future climate change (connection to **Theme 1**).
- Deliver an Arctic-informed version of DOE's E3SM capable of representing evolution of pan-Arctic ecosystems in a changing climate at the scale of a high-resolution grid cell (connection to **Theme 1**).
- Identify key remaining questions about climate change and response across the pan-Arctic and boreal ecosystems.





Figure 8. The SPRUCE experiment in Minnesota provides a unique opportunity to measure the effects of potential future climates now.

SPRUCE

The Spruce and Peatland Responses Under Changing Environments is the largest global change biology experiment in the world, providing a unique large-scale infrastructure to analyze the response of carbon-rich peatlands to elevated temperature and carbon dioxide. A part of the ORNL Terrestrial Ecosystem Science Scientific Focus Area, SPRUCE encompasses 10 large, open-top chambers (each 40' wide by 32' tall) built over 7 acres in the USDA Marcell Experimental Forest in Minnesota. The chambers enclose large sections of peat bog that are heated to five different temperatures, giving us a glimpse of the future. SPRUCE data are used to improve Earth-scale models of the changing climate, resulting in more accurate long-term predictions. The experiment has been in continual operation since 2015. Collaborators include Lawrence Livermore National Laboratory, USDA Forest Service, and multiple universities.

NEXT-GENERATION ECOSYSTEM EXPERIMENTS IN THE ARCTIC

NGEE Arctic collects and analyzes observational data on key processes like permafrost thaw and their effects on carbon, nutrient, and water fluxes in the Alaska tundra. These crucial measurements and insights are incorporated into Earth system models to advance predictive understanding of this important ecosystem on the frontlines of climate change. Led by ORNL, the multi-institutional research team has captured tundra observations since 2012 and fosters an integrated model-experiment (ModEx) approach. The project has improved DOE's E3SM Land Model by studying processes from the soil core to plot, landscape, and watershed levels. NGEE Arctic scientists are now evaluating their model using observational data collected in other Pan-Arctic nations. Partner institutions include LBNL, LANL, and the University of Alaska Fairbanks.



Figure 9. Researcher takes measurements on the tundra.



Figure 10. Tennessee is home to diverse freshwater fish species like this blueside darter.

BIOLOGICAL MONITORING AND ABATEMENT

The Biological Monitoring and Abatement Program (BMAP) has monitored aquatic ecology on the Oak Ridge Reservation for almost 40 years to understand interactions between ecosystem contamination and organismal distribution and fecundity. BMAP provides data for human and ecological risk assessments and actionable information for the design and application of remediation technologies, pollution abatement actions, and watershed best management practices.

Develop new theory explaining ecosystem response to disturbance and new predictive understanding of abrupt ecosystem transition.

The vulnerability of ecosystems to changing climates and other disturbance factors is variable across the landscape, but it is particularly acute at ecotones: the zones where two distinct ecosystems or biomes meet. Marginal environmental conditions may already exist at these transitional areas. Changes in intensity and frequency of climatic events, and the role of cumulative and compounding events, should strongly affect the biogeochemical cycles of carbon, nutrients, and water. The factors governing the resilience of ecosystem functions will be important determinants of changes in biodiversity, trajectories of recovery, and severe ecosystem decline. However, the biological basis of such factors, their limits, and their variation across landscapes are poorly understood. Predicting the trajectories of response, resilience, and recovery, understanding the underlying causes of different trajectories, and developing a theoretical basis for the role of biodiversity will enable predictive understanding of impacts to biogeochemical cycling in ecosystems and concomitant effects on climate (**Theme 3**).

As climate change, extreme events, repeated disturbances, and compound events build up over time, the integrity of ecosystems can become compromised. Environmental thresholds or tipping points may be reached, after which the functional capacity of a biome or ecosystem is severely damaged and recovery to the former state may become impossible. Permafrost thaw and wildfire across the globe can both cause lasting or permanent damage to ecosystems, altering biodiversity, hydrology, greenhouse gas emissions, and carbon stocks. Examples of compound events are loss of one or more keystone species, such as *Sphagnum* mosses in a peat bog due to warming and drying, or decline of trembling aspen (*Populus tremuloides*) and *Pinus* species that are weakened due to fire damage and become more susceptible to insect infestations. Invasion can also cause broad ecosystem change; for example, the invasion of beavers is dramatically changing the hydrology of the pan-Arctic landscape. Likewise, invasion of exotic plants displaces native species and alters ecosystem functions and sustainability. The continental U.S. is currently experiencing an invasion of numerous insect and fungal pathogens from abroad, resulting in severe damage to ecosystems across the country. New system-level investigation of the interactions of disturbance, extremes, and ecosystem resilience is needed to form a predictive theoretical foundation for understanding how ecosystems will be transformed under the compound stressors of climate and environmental change. This predictive understanding can then be integrated with multiscale Earth system models (**Theme 1**) to inform decision-making to ensure ecosystem and human sustainability (**Theme 4**).

SCIENCE QUESTIONS

- Which ecosystems and components are vulnerable to which types of environmental stressors, and at what scales (further investigated in **Theme 3**)?
- What governs trajectories of response, resilience, and recovery?
- How do different trajectories impact microclimate, biodiversity, ecosystem functions, society, and vulnerable human populations?
- What are the cumulative effects of compound events and stressors?
- What are the effects of disturbance on biodiversity and biogeochemical cycles of carbon and water, and are these effects adequately represented in Earth system models?
- What is the role of tipping points and environmental thresholds on ecosystem function and biodiversity?
- What governs the emergence of novel biomes in response to disturbance?
- How do the frequency, type, and mode of disturbance interplay with ecosystem vulnerability?

5-YEAR GOALS

- Understand which disturbances and cumulative events are most impactful for ecosystem functions by using data analysis to connect specific biomes with the most frequent and consequential disturbances.
- Understand how disturbances affect biogeochemistry, ecosystem function, system hydrology, and biodiversity using multiscale models.
- Identify the types of disturbances, the specific impacted ecosystems, and the spatial and temporal scale of observations needed to capture disturbance, response, and recovery trajectories.
- Include stakeholders in framing research questions to better understand implications for affected human communities, including under-resourced populations, and for sustaining society as a whole.
- Identify examples of tipping points and emergence of novel biomes: for example, permafrost thaw can cause either new bogs or drying peatland landscapes; invasive species can alter ecosystem functions; and pests or climate change can eliminate keystone species.
- Develop criteria to define tipping points, thresholds, and novel biomes in both aquatic and terrestrial ecosystems.
- Conduct sensitivity analysis of how tipping points, thresholds, and emergence of novel ecosystems affect key ecosystem structure (e.g., biodiversity) and functions (e.g., plant productivity, carbon and water cycles, and habitat).
- Develop a coupled model and experimental strategy to investigate how tipping points, thresholds, and emergence of novel biomes will affect key ecosystem functions (connection to **Themes 1 and 3**).

10-YEAR GOALS

- Develop the science questions and approaches to support the next generation of field studies to investigate how disturbance, response, and recovery affect biodiversity, biogeochemical cycling, and major ecosystem functions.
- Employ observations and novel experiments to enable predictions of how key changes in ecosystem processes and functions affect biogeochemical carbon and water cycles across ecosystems, regions, and landscapes.
- Develop multiscale model–experimental (ModEx) strategies to represent ecosystem observations, improve representation of processes in models, and scale findings across space and time.
- Implement field-scale studies that are designed to resolve model deficiencies, and loop in experimental results to continually improve model efficacy and inform experimental directions.
- Conduct field investigations at the ecosystem scale to understand and predict the effects of tipping points and thresholds on vulnerable ecosystem processes and properties, and on biogeochemical cycles at regional and global scales.
- Carry out observations along a chronosequence, ecotone, or gradient that is experiencing ecosystem shifts.
- Determine what is needed in models to represent common biome and ecotone shifts, such as probabilistic approaches, dynamic shifts in vegetation, changes in water cycle, timing and magnitude of changes above- and belowground, and the extent of aboveground–belowground interactions (connection to **Theme 1**).
- Use models to predict how threshold ecosystem changes can ripple across a landscape and enlarge their effects, and to represent the spatial and temporal extent of the effects on biodiversity, and water and carbon cycles.

KEY PROJECTS, SPONSORS, AND PARTNERS

PROJECTS

- A Roadmap to Intelligent Watersheds
- Artificial Intelligence (ORNL Laboratory Directed Research and Development)
- Biological Monitoring and Abatement Program
- Center for Bioenergy Innovation
- Coastal Observations, Mechanisms, and Predictions Across Systems and Scales—Field, Measurements, and Experiments
- eDNA of Hydropower
- Effects of Climate Change on Hydropower
- Forest Threat Early Warning System (ForWarn)
- INTERSECT (ORNL Laboratory Directed Research and Development)
- Missouri Ozarks AmeriFlux
- Mobilizing Billion-Ton Resources Under Uncertainty
- Next-Generation Ecosystem Experiments in the Arctic
- Next-Generation Ecosystem Experiments in the Tropics
- Plant-Microbe Interfaces
- Quantifying Greenhouse Gas Emissions from Hydropower Reservoirs
- Spruce and Peatland Responses Under Changing Environments
- Terrestrial Ecosystem Science
- Urban Integrated Field Laboratories (Baltimore, Southeast Texas, Southwest)
- Watershed Dynamics and Evolution

SPONSORS

- DOE Office of Science, Biological and Environmental Research
- DOE Office of Energy Efficiency and Renewable Energy
- DOE Office of Environmental Management
- DOE Bioenergy Technologies Office
- DOE Water Power Technologies Office
- DOE Office of Clean Energy Demonstrations
- Tennessee Valley Authority
- U.S. Department of Agriculture Forest Service

PARTNERS

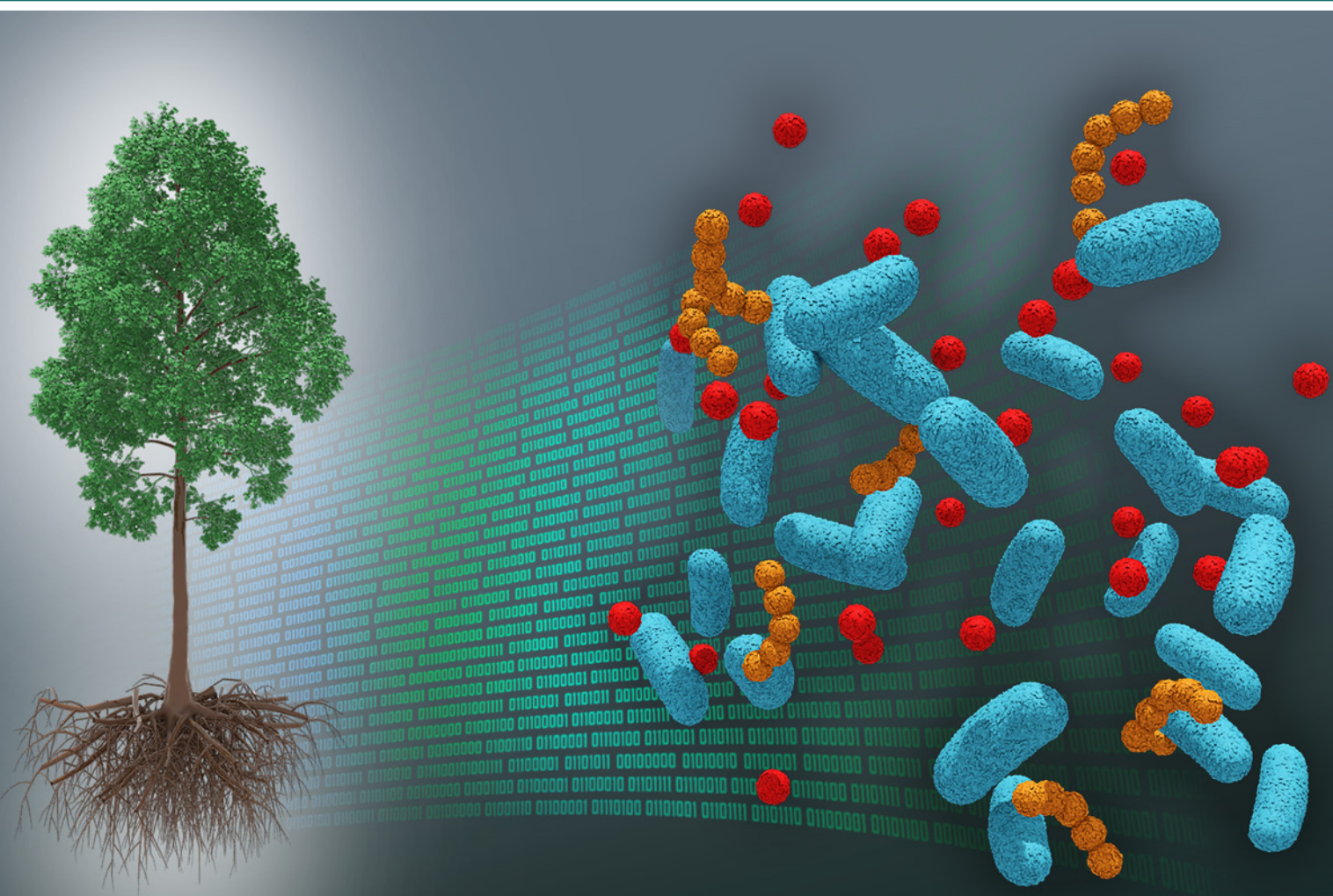
- Oak Ridge Leadership Computing Facility
- Argonne National Laboratory
- Brookhaven National Laboratory
- Environmental Molecular Sciences Laboratory
- Joint Genome Institute
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- National Microbiome Data Collaborative
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- Smithsonian Environmental Research Center
- Universities (numerous partners)



THEME 3

CONNECT GENES TO ECOSYSTEMS FOR SUSTAINABILITY AND RESILIENCE

We will apply genomic-level variation and modifications to manipulate the carbon storage capacity of ecosystems to aid in climate change mitigation and enhance resilience to extreme disturbance events. We will achieve this by increasing our fundamental understanding of microbes and plants, how they interact within communities and their environment, and how the system works collectively to enhance plant resilience. We seek to connect genes to key traits and phenotypes driving ecosystem processes.



THE GRAND CHALLENGE

Changing climate and extreme disturbance events such as droughts, heat waves, floods, and wildfires have the potential to catastrophically impact terrestrial ecosystems, including bioenergy and agricultural crops (Ref. 9). Some ecosystems at risk are essential for global energy and food security and are being pushed toward irreversible tipping points, and even collapse (Ref. 11). In research described earlier in this Plan (See **Grand Challenge Themes 1 and 2**) ORNL will provide reliable predictions of the occurrence of disturbance events and measures of their impact on ecosystems, revealing which critical ecosystems are at greatest risk and require urgent intervention. Here, we address the pressing need to advance the fundamental plant, microbial, and systems biology discoveries enabling innovative research solutions to minimize the occurrence of these disturbances and to lessen their impact on vulnerable ecosystems.

BACKGROUND

Today's unprecedented pace of advances in biological sciences creates new opportunities to address the grand challenge of this theme (Ref. 10). At ORNL, discoveries are revealing how plants and microbes interact within communities and their natural environment, and how they have evolved in the context of complex microbiomes and environmental change and disturbance (Fig. 11). Progress is accelerated by development of a forward-looking infrastructure of laboratory-to-field integrated research approaches, emerging systems biology and synthetic biology technologies, and advances in data sciences (see **Foundational Science Infrastructure** and App. C-4 LDRD). Our strategy is to reach a level of understanding that reveals connections from genes to key traits and phenotypes influencing ecosystem processes across spatial and temporal scales (Ref. 12).

With this predictive knowledge, we will safely apply genomic-level variations and modifications to manipulate ecosystems so that they have enhanced carbon storage capacity to aid in climate change mitigation, and so that they are more resilient to the impact of disturbance and extreme environmental events (Ref. 12). An outcome of achieving this challenge will be creation of opportunities to engineer ecosystems for a variety of other purposes, including environmental sustainability of bioenergy feedstocks, manipulation of nutrient and water cycles, and preservation of key ecological services. The ability to engineer or manipulate plant-microbe-soil systems can thus be tuned to address several DOE missions and inform our **Grand Challenge Theme 4. A visionary long-term goal is to couple the genes-to-ecosystem modeling framework developed here to DOE's flagship Earth systems model, E3SM, in Grand Challenge Theme 1, to provide the first genes-to-Earth-system predictive model.**

Our initial focus is to develop a testable and predictive understanding of how genomic-level variation and modification can influence ecosystem services in response to environmental changes such that carbon storage and resilience to extreme disturbance events can be realized. We will develop a scale-aware modeling framework that integrates with ML workflows to predict phenotypes from genomic information, and that provides feedback to our automated laboratory-to-field experimental platforms for data generation and model refinement. As fundamental knowledge of complex biological and ecological systems deepens, we target engineering plants and microbiomes to enhance ecosystem resilience to extreme disturbance events (as explored in **Theme 2**) and supporting development of a sustainable circular bioeconomy (**Theme 4**).

WHY OAK RIDGE?

ORNL is a recognized leader in many areas of plant and microbial sciences, and large terrestrial ecosystem measurement and manipulation experiments (App. C-2). ORNL's long-standing science focus area efforts in Plant-Microbe Interfaces (PMI) have helped define the complex interactions between plants, microbes, and the environment. This understanding is further deepened by the extensive resources developed by ORNL's CBI (Fig. 17). Sister DOE laboratories have strengths in complementary areas. For example, there is complementarity between the approaches being taken to develop automated plant and microbial transformation and phenotyping platforms, and between controlled ecosystems experiments that range in scale from benchtop, to laboratory, to ecosystem module, to field, and beyond (App. B). A collaborative effort across DOE laboratories would accelerate development of the coordinated infrastructure and expertise needed to realize our genes-to-ecosystem vision. Bringing to bear the full power of the DOE laboratories to create a multi-organizational infrastructure would generate, quantify, and analyze massive, heterogeneous datasets ranging in complexity from individual proteins up to and including natural and managed ecosystems across spatial and temporal scales associated with plant and microbial systems and would require tight coupling data between management and modeling (Ref. 13).

Enhance soil carbon storage to aid in climate change mitigation.

Soil carbon storage and release occur at the molecular level and are governed by abiotic and biotic factors and interactions that operate across spatial and temporal scales, making it difficult to predict which parameters are most important for the design of long-term carbon sequestration strategies. We will enhance data collection and modeling of the above–belowground system to predictably optimize and manage plant–microbe–soil systems toward improving carbon storage. Data will be collected across diverse ecosystems to assess how various plants and microbial traits influence carbon cycling, **including connections to multiscale models (Theme 1)**. ML and AI will then be used to determine the genetic basis of these traits and their contribution to ecosystem services (**Advanced Computing and Data Science Crosscut**).

SCIENCE QUESTIONS

- Can a fundamental understanding of plant–microbial assemblages, functions, and soil interactions across scales be used to predict the fate of carbon in soils?
- Can lab and field data be synthesized with systems biology and process-based models to holistically evaluate the effects of different plant and microbial traits on productivity and soil carbon storage?
- Can use of varied plant and microbes be co-optimized for enhanced aboveground carbon fixation and belowground carbon storage?
- Can we improve traits in plants and microbes that lead to enhanced ecosystem carbon storage, greenhouse gas reduction, and resilience?

5-YEAR GOALS

- Develop the components for a laboratory-to-field automated and integrated experimental research infrastructure for resilience and soil carbon storage traits across organism and population scales. Demonstrated high-throughput, high-precision, above- and belowground measurements and phenotyping. Components include instrumented reconfigurable mesocosms, APPL with a rhizotron imaging system, complementary neutron imaging (App. C), SMART Plant Field series technologies, automated plate-based screening of plant and microbial metabolism, and high-throughput microbial isolation and phenotyping capabilities that cover the phylogenetic breadth representative of the rhizosphere (**Biological and Analytical Tools Crosscut**).
- Integrate experimental measurements with a predictive framework for plant–microbe–soil interactions being developed in Strategic Research Objective 2 to improve predictions of microbial characteristics and plant genotypes that improve carbon storage and tolerance to multiple abiotic stresses.
- Establish a monitoring/sensing system to track carbon fixation and belowground carbon storage and link it to plant–microbe–soil interactions.

10-YEAR GOALS

- Demonstrate improvements in aboveground carbon fixation and belowground carbon storage through the operations of laboratory-to-field automated and integrated experimental research infrastructure.
- Fully couple laboratory-to-field infrastructure with a scale-aware modeling framework that integrates with ML workflows to predict phenotypes from genomic information, and which provides feedback for data generation and model refinement (Strategic Research Objective 2).
- Demonstrate capability to engineer or manipulate biological systems for improved carbon storage.

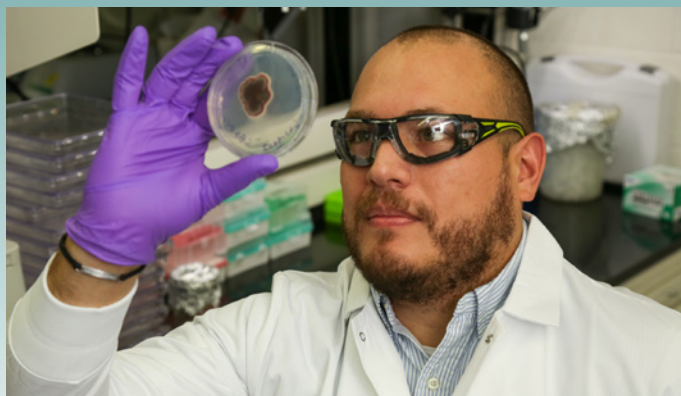


Figure 11. Tomás Rush examines a culture as part of his research into a plant-fungus relationship that can help or hinder ecosystem health.

PLANT-MICROBE INTERFACES SCIENCE FOCUS AREA

Insights into the exchange of energy, information, and materials across the plant-microbe interface are essential to a deeper understanding of mutually beneficial interactions between plants and microbes in the soil environment, and they are the key focus of the ORNL-led PMI SFA. Research under PMI has accelerated understanding of how plants detect, interact with, and alter their associated environments with microbes, including beneficial mycorrhizal associations. Knowledge about the molecular signaling and genetic responses underpinning these symbioses can be used to improve bioenergy crops, environmental remediation, and natural carbon sequestration. Collaborators include the University of Washington, INRAE/National Research Institute for Agriculture, Food, and Environment, and Duke University.

Integrate conceptual, genome-scale metabolic and process-based models with experimental data to better predict community interactions and ecosystem processes.

We lack an integration of hierarchical theory with modeling. We also currently lack a modeling architecture that integrates commonly used genome-scale models (e.g., Flux Balance Analysis) with ecosystem- and global-scale process-based models (e.g., Earth system models). Creating a predictive framework that can establish a connection between the changes in metabolism and their ecosystem impacts is challenging. Accurate parameter estimation is crucial to ensure that the framework is reliable and produces meaningful predictions. Thus, there is a need for a comprehensive approach that can combine different models and experimental data to develop a robust predictive framework.

SCIENCE QUESTIONS

- How do we bridge genome-based molecular-scale modeling with larger-scale models through a ModEx approach that increases data collection, selection, and integration into models?
- How do we link diverse information such as that related to plant and microbial genetics, rhizosphere soil interactions, and nutrient cycling?

5-YEAR GOALS

- Bridge the divide between molecular, ecosystem, and global-scale process-based models through workshops with modelers and experimentalists and define experimental needs and workflows that enable ModEx integration.
- Determine how AI and ML can be used to link and integrate the modeling scales listed above.
- Identify proof-of-concept processes that can be modeled across multiple scales, from protein structure to metabolic process to parameterize values in process-based, physiological models used in **Theme 1**.

10-YEAR GOALS

- Establish an integrated modeling framework that can effectively combine mathematical models of varying scales, ranging from the biochemical to the ecosystem level. The model will be designed to integrate with an ML workflow, which can leverage genotype and phenotype information to predict microbial interactions, phenotypes, and environmental properties.
- Enhance the predictive capability of the modeling framework using extensive experimental datasets.
- Use the integrated modeling framework as a virtual replica of the experimental system, allowing it to simulate the outcomes of experiments, much like a digital twin. This simulation will enable researchers to test hypotheses, guide experimental design and selection, and provide a deeper understanding of the underlying mechanisms that govern microbial interactions and ecosystem behavior.

SOILCOSMS AND ARCTIC MESOCOSMS

To better understand belowground biogeochemical processes, scientists created instrumented microcosms and mesocosms in the laboratory. These soil incubation systems allow scientists to perform laboratory experiments in tightly controlled conditions using engineered samples or samples collected from field sites to answer questions about carbon and nutrient cycling, microbiome composition, and other key biogeochemical dynamics.



Figure 12. SoilCosms (left photo) allow reproducible, high-throughput experiments with self-guided automation. Arctic mesocosms containing tundra plants and soils (right photos) allow simultaneous porewater sampling and monitoring of root growth and greenhouse gas fluxes.

Gain the necessary fundamental scientific knowledge to understand, predict, manipulate, and design biological systems with enhanced properties.

From a methodology perspective, we lack the ability to measure and predict metabolic interactions or physical organization within complex communities. From a scaling context, we lack the integrative platforms that allow us to measure molecular details at the level of microbes to plants that can inform mesocosms and ecosystems level processes. Importantly, our measurements (e.g., metatranscriptomes) are not always directly correlated with what we try to predict (e.g., nutrient cycling). We will address these challenges and the below science questions by integrating the improved predictions and modeling frameworks described in this Plan with the use of mesocosms, constructed at multiple scales, that are representative of more natural and complex systems that integrate diverse ecosystems (as explored in Theme 2).

SCIENCE QUESTIONS

- How do climate change and human impacts influence complex ecosystem interactions (e.g., plant–microbe–soil interactions), biodiversity, and ecosystem processes (e.g., plant productivity, greenhouse gas emissions) across scales?
- What are the key molecular mechanisms underlying ecosystem resilience to climate change that will allow engineering and manipulation of biological systems?
- How can we scale molecular-level information through increasing levels of biological complexity to predict ecosystem-level function?

5-YEAR GOALS

- Informed by **Theme 2** and **Theme 4** results, define a natural or mixed-species bioenergy cropping ecosystem as a test case for experimental systems needed to investigate episodic extreme events such as rain and heat. Establish and construct a pilot-scale mesocosm system and test approaches.

10-YEAR GOALS

- Develop a methodology and modeling framework to investigate interkingdom interactions across spatial scales from cells and soil pores to hectometer-scale systems. This approach would account for physical organization and diverse temporal increments that will facilitate the use of mesocosm systems to examine diverse ecosystem changes, **informing multiscale models in Theme 1**.
- Create highly instrumented, modular, and replicated synthetic ecosystems (i.e., mesocosms) that are built on-site and amenable to sophisticated environmental manipulation. Such systems could operate as digital twins, either mimicking biotic and abiotic components from natural systems or mimicking novel environments that are predicted from climate simulations but yet to be observed in nature.



Figure 13. Poplar trees move through the Advanced Plant Phenotyping Laboratory during an experiment.

ADVANCED PLANT PHENOTYPING LABORATORY

Science never sleeps, and neither does the automated, high-throughput facility known as APPL. This unique facility at ORNL can accommodate thousands of plants rotating day and night through one of the most diverse suites of imaging capabilities in the world, continuously gathering measurements on plant growth, structure, and health and replacing time-consuming, manual phenotyping. APPL data enable a digital representation of plants, including details that the eye cannot see, ranging from plant size and shape, photosynthetic activity, physiological status, biomass accumulation, water content and use, stress response, and biochemical composition. That information is parsed using AI and high-performance computing (HPC), quickly extracting biologically meaningful traits for genomic analysis. The system lets scientists quickly and accurately ascertain the success of plant transformation efforts and yields critical information on the genotype-to-phenotype relationship that supports the development of robust plants for bioenergy and natural carbon storage. This shared-use facility is supported by ORNL LDRD investment and DOE-supported research programs.



KEY PROJECTS, SPONSORS, AND PARTNERS

PROJECTS

- Advanced Plant Phenotyping Laboratory
- Artificial Intelligence (ORNL Laboratory Directed Research and Development)
- Biofuels Science Focus Area (Solvent Disruption of Biomass and Biomembranes)
- Center for Bioenergy Innovation
- Circular Bioeconomy Systems
- DOE Early Career Projects
- DOE Systems Biology Knowledgebase (KBase)
- ENIGMA: Ecosystems and Networks Integrated with Genes
- INTERSECT (ORNL Laboratory Directed Research and Development)
- Next-Generation Ecosystem Experiments in the Arctic
- Plant Biodesign Hub
- Plant-Microbe Interfaces
- SMART Plant Field Systems
- Secure Biosystem Design
- Secure Ecosystem Engineering and Design
- SoilCosm (ORNL Laboratory Directed Research and Development)
- Spruce and Peatland Responses Under Changing Environments
- Watershed Dynamics and Evolution

SPONSORS

- DOE Office of Science, Biological and Environmental Research
- DOE Office of Energy Efficiency and Renewable Energy
- DOE Bioenergy Technologies Office
- Defense Advanced Research Projects Agency
- Department of Homeland Security
- National Institutes of Health

PARTNERS

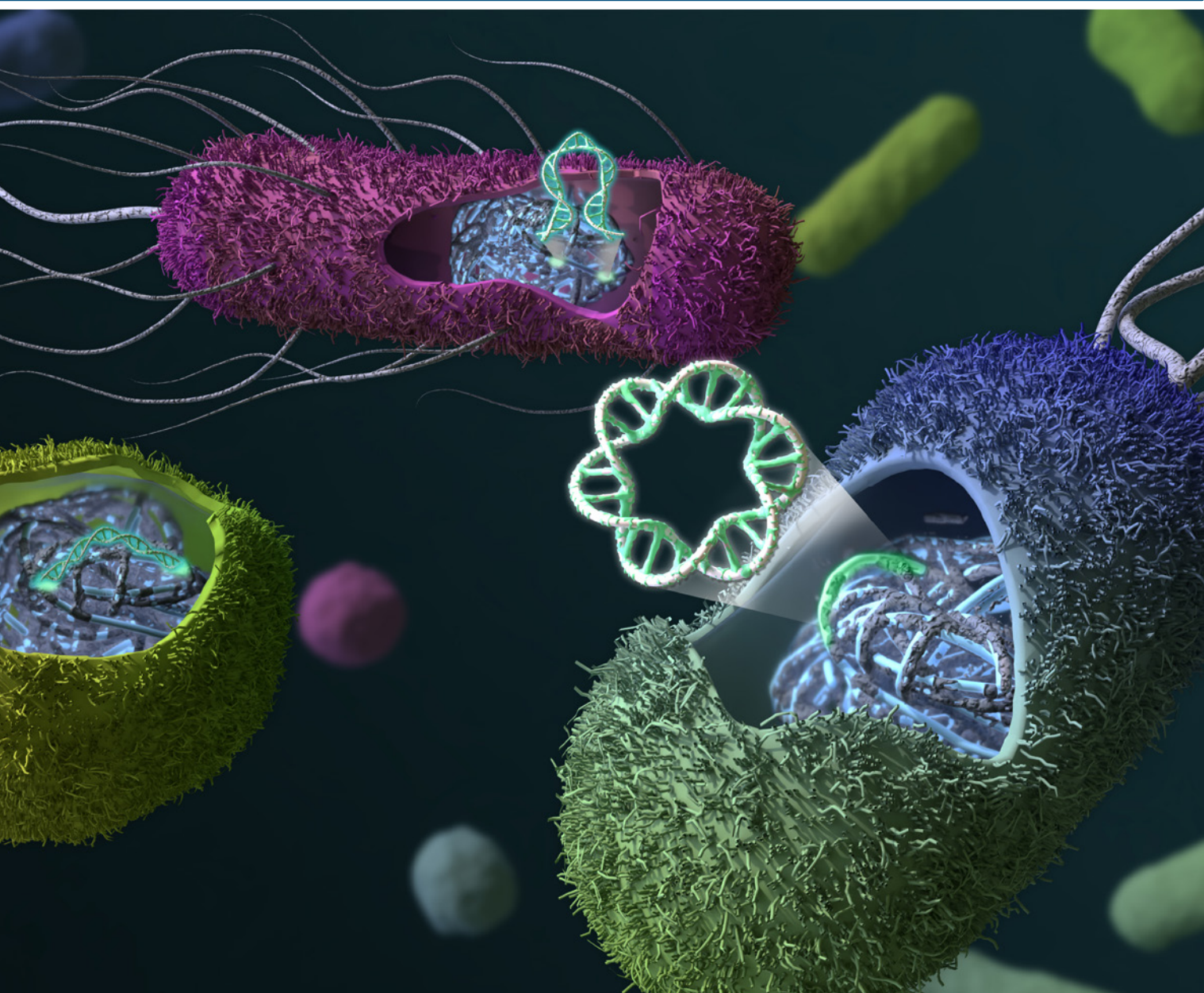
- Oak Ridge Leadership Computing Facility
- ORNL Computing and Computational Sciences Directorate
- ORNL Center for Nanophase Materials Sciences
- ORNL Neutron Sciences Directorate
- Brookhaven National Laboratory
- Environmental Molecular Sciences Laboratory
- INRAE/French National Research Institute for Agriculture, Food and the Environment
- Joint Genome Institute
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- National Microbiome Data Collaborative
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- Universities (numerous partners)
- U.S. Department of Agriculture Forest Service



THEME 4

ENGINEER A CIRCULAR BIOECONOMY

We will develop the technologies and capabilities to predict, manipulate, and design biological systems for efficient production of bioenergy, bioproducts, and biomaterials while also deepening our fundamental knowledge of the related biological and environmental processes. We will leverage those developments to transition from a linear economy to a sustainable, carbon-neutral, circular bioeconomy, preserving ecosystem diversity and services.



THE GRAND CHALLENGE

To meet national goals for reducing greenhouse gas emissions to mitigate climate change, there is an urgent need for sustainable fuels, chemicals, and materials that can replace petroleum-derived products (Ref. 16). With the accelerating pace of breakthroughs in biotechnology, and with over a billion tons of domestic biomass available each year as potential hydrocarbon feedstock (Ref. 17), the U.S. is poised to provide these products using plants and microbes (Ref. 18). The challenge is that there remain gaps in our fundamental knowledge of biological systems that limit progress. In research described earlier in this Plan (see **Theme 3**), ORNL will enhance our fundamental understanding of biological and environmental systems so that they can be manipulated and improved through genomic-level variations and modifications. Here, we extend that approach and couple it with technological advances in engineering and process analysis to propel a circular bioeconomy that benefits rural economic development and provides solutions for climate change, energy independence, food security, sustainable agriculture, supply chain resilience, and national and economic security.

BACKGROUND

Deepening knowledge of plants and microbes, and their interactions with communities and ecosystems promises development of genomic-level approaches to manipulate ecosystems with enhanced properties such as carbon storage capacity and resilience to extreme disturbance (see **Theme 3**). It also creates new science-to-solution commercial opportunities in fields spanning from agriculture, pharmaceuticals, and energy, producing major economic, environmental, and societal benefits. **As a multi-program national laboratory, ORNL plays a key role as integrator, working with partners to take basic scientific discoveries through to commercial application, in areas including bioenergy and bioproducts.**

At CBI, ORNL is developing new biomass feedstocks, engineering microbes and catalysts to produce drop-in fuels from biomass and modifying microorganisms to convert lignin into highly valued products (Fig. 17). In a partnership with the University of Tennessee, ORNL is also developing innovations shaped by a different way of thinking: prioritizing circularity (Fig. 15). Circular bioeconomy systems research focuses on expanding the use of renewable biomass and preventing or reducing waste, with materials used for as long as possible and emissions-reducing practices put into place. The goal is to shift to a carbon-neutral economy in which the use and reusability of every carbon atom are optimized. Here, we further leverage this approach to build more efficient, circular processes by focusing on the intersection of biological systems, carbon cycling, and carbon intensity. Our vision is a sustainable circular bioeconomy advanced through our ability to understand and tailor biological systems for production of renewable fuels and process-advantaged chemicals to create a sustainable, low-carbon society.

WHY OAK RIDGE?

ORNL has deep expertise in key areas directly contributing to fundamental scientific insights and solutions that support the bioeconomy, including synthetic biology, microbial genetics, plant genetics, genomics, and lab-to-field phenotyping. Leveraging the lab's leadership capabilities in HPC, AI, and ML, scientists are accelerating genome-to-phenome understanding. Research teams apply analytical capabilities and expertise in decision sciences to execute cradle-to-grave life-cycle assessments of productivity, cost, sustainability indicators, and carbon accounting. **Building on strengths in the environmental sciences, materials science, chemistry, and data science along with end-use expertise in advanced manufacturing, transportation, and other applied programs, ORNL researchers can drive innovations for every facet of circular, renewable supply chains—across scales from molecular to global. These capabilities can revolutionize how we define circularity and generate strategies to achieve a truly vibrant bioeconomy for the future.**



Figure 14. Structure and impact of a circular bioeconomy.

Accelerate development of high-performance, sustainable bioenergy and biomaterial crops for the bioeconomy.

We will focus on capabilities to understand, design, evaluate, and predict plant performance, from the molecular to the ecosystem scale. With these capabilities, we will develop integrated bioenergy crop systems that generate sustainable, direct, or functional replacements of current petroleum-derived fuels, such as sustainable aviation fuels; chemicals such as solvents; and materials such as fiber composites and polymers (informed by the results of Theme 3 and supported by the Biological and Analytical Tools Crosscut).

SCIENCE QUESTIONS:

- What mechanisms underlie complex plant traits related to sustainability, and can they be engineered to increase stress tolerance, optimize feedstock production, and enable efficient feedstock use?
- What are the biological and genetic bases of plant biocomponent properties that are critical in enabling tailored biomanufacturing of bio-derived materials (biochemicals, biopolymers, and biocomposites) and fuels, including sustainable aviation fuel?
- How do genetic and environmental factors influence phenotypes relevant to enhanced productivity and resilience (as informed by Theme 3)?
- How can automation, sensors, edge computing and AI/ML be leveraged to accelerate plant transformation and integrate with lab and field plant phenotyping to accelerate knowledge generation and informed design of plants (Advanced Computing and Data Science Crosscut, Biological and Analytical Tools Crosscut)?
- How can a higher density of empirical data about genotypic–phenotypic correlations enable autonomous ModEx, or iterative modeling–experiment loops, as well as design–build–test–learn cycles?
- How can we better predict the tradeoffs between maximizing productivity and climate resiliency and inform how bioenergy systems can be managed for economic and environmental co-benefits?

5-YEAR GOALS

- Develop and implement accelerated, high-throughput, automated genome engineering and phenotyping tools and methods in model and emerging non-model plants to identify and engineer properties that are highly relevant to bio-derived materials and fuels production.
- Develop genetically encoded biosensors in plants for molecular phenotyping (e.g., in vivo visualization of gene expression in plants) and real-time monitoring of plant responses to abiotic (e.g., drought, nutrient-deficiency) and biotic (e.g., pathogen, beneficial microbes) factors.
- Develop new plant synthetic biology capabilities, including a plant biodesign knowledge base (linking DNA parts to gene constructs to plant traits relevant to the bioeconomy and environmental sustainability) and a platform plant system for cost-effective production of biobased products.

10-YEAR GOALS

- Establish routine accelerated development and application of advanced genetic tools in novel non-model organisms with outward-facing high-throughput plant transformation capabilities to accelerate the closing of knowledge and capability gaps across genome-to-phenome by the research community—in particular the establishment of a plant synthetic genomics capability for enabling large-scale redesign of plant genomes to optimize the traits of bioenergy/biomaterial crops.
- Develop integrated design–build–test–learn strategies for rapid prediction of genetic designs across a variety of plants to engineer scale and regulation toward economical and efficient bioconversion and feedstock growth and propagation strategies.



Engineer microbes to produce the fuels and chemicals that we need.

We will design and optimize genes to functional phenotypes for integrated microbial systems to produce sustainable, direct, or functional replacements for current petroleum-derived fuels, chemicals, and materials, such as sustainable aviation fuel, solvents, fiber composites, and polymers (as informed by Theme 3 and supported by Biological and Analytical Tools Crosscut).

SCIENCE QUESTIONS

- What mechanisms underlie complex microbial traits, and how can they be engineered to increase stress tolerance, optimize feedstock generation, increase efficiency of feedstock utilization and conversion to target products, and make scale-up rational?
- How can we leverage advanced genetic tools to accelerate industrialization of bioadvantaged products from non-model microorganisms that naturally possess many of these desirable traits?
- What are the tradeoffs between robust heterologous enzyme and pathway expression and metabolic burden, and what design rules can optimize multi-pathway modularity?
- What combination of engineered microorganisms, proteins, and energy sources (e.g., light, hydrogen, electricity) can enable non-model microbes to convert fermentation-derived pure carbon dioxide streams and other single-carbon compounds into carbon-neutral and/or negative processes?

5-YEAR GOALS

- Demonstrate automated transformation and protein engineering for microbial chassis strains that are needed for bioconversion of industrially relevant feedstocks to bioadvantaged products.
- Develop predictive networks for existing model and emerging non-model microbial chassis strains and protein designs by integrating new and existing genotypic and phenotypic data into AI/ML models to enable accelerated prediction and validation of optimized bioproduction platforms.
- Deploy accelerated, high-throughput, automated genome editing, protein engineering, and phenotyping tools and methods in model and non-model microbial chassis strains to produce at least two replacements for industrial fuels and/or chemicals that are currently petroleum-derived.
- Expand and validate predictive networks using AI/ML approaches for model and emerging microbial chassis strains and protein designs to enable accelerated engineering of process-advantaged bioproduction platforms.

10-YEAR GOALS

- Establish routine accelerated development and application of advanced genetic and protein engineering tools for process-advantaged microbial chassis strains for ORNL and external partners, leveraging outward-facing high-throughput microbial transformation and genome and protein engineering capabilities towards engineering more robust, productive, and scalable organisms to produce bioadvantaged products (**enabled by the Biological and Analytical Tools Crosscut and by ORNL's neutron capabilities at the Spallation Neutron Source [SNS] and High Flux Isotope Reactor [HFIR], and computing capability at the OLCF.**)
- Leverage integrated design-build-test-learn strategies to rapidly predict genetic and protein designs across a variety of process-advantaged microbial chassis strains, advancing economical and efficient bioconversion strategies to produce bioadvantaged products at scale.

CIRCULAR BIOECONOMY SYSTEMS

Less than 10% of total resources entering the global economy today are recycled. In order to reduce waste, decarbonize the economy, and benefit agriculture and industry, ORNL has engaged in a **Circular Bioeconomy Systems Convergent Research Initiative** with the University of Tennessee (UT). The multiyear project's goal is to develop sustainable materials from renewable carbon sources to advance low-energy, low-carbon agriculture and manufacturing. Scientists will focus on strategies to manage, valorize, and extend the lifetime of each carbon atom for a robust circular bioeconomy. They will collaborate with Tennessee industries in the agricultural, forestry, and automotive sectors to develop testbeds for a circular bioeconomy, focused on new recyclable-by-design biomaterials with benefits for farmers, rural economies, and industry. With an initial focus on Tennessee, the project's findings can serve as a blueprint for the region, the nation, and the world. This research is supported by ORNL LDRD, UT, the State of Tennessee, and the DOE Office of Energy Efficiency and Renewable Energy.



Figure 15. Researchers at ORNL and the University of Tennessee collaborate with local industry partners to advance a circular bioeconomy.

Employ data science to quantify impact and identify bottlenecks in transitioning from linear to circular bioeconomy pathways.

We will develop comprehensive strategies to de-risk biomass feedstock system deployment by integrated modeling, monitoring, and analyses for the valuation of carbon, ecosystem services, and biodiversity amidst uncertainty in climate and policy.

SCIENCE QUESTIONS

- Can we develop more sustainable landscape designs to adapt to changing industry needs and market forces by utilizing land-use and condition data available via remote sensing and other advanced technologies?
- Can we design optimal biomass production and collection scenarios—identifying ideal regional feedstocks and the best use of that biomass to achieve sustainability goals—by utilizing dynamic modeling and advanced data science?
- Can we de-risk deployment scenarios via the expansion of modeling and data capabilities; the convergence of environmental science, economics, engineering, and social science; and integration with fundamental biological and Earth systems science?
- Can we develop integrated modeling and monitoring frameworks that facilitate the tracking of carbon derived from biomass through its inception in photosynthesis, across multiple product lifecycles and end-of-life strategies?
- Can parameter optimization, data assimilation, and model inter-comparison techniques improve the performance of process-based agroecosystem models used to inform ecosystem function and for carbon project measurement, reporting, and verification?

5-YEAR GOALS

- Establish a comprehensive definition of circularity for the bioeconomy and identify its associated metrics to quantify the benefits of alternative pathways.
- Collaborate with ORNL Earth system modelers to apply their data assimilation techniques to more local-scale process modeling toward better representation of plant drought response and soil organic matter dynamics.
- Develop analytical tools to assess the economic implications of biodiversity and ecosystem service changes for spatially explicit, regional deployment scenarios of biomass production and collection systems.
- Develop advanced atom-to-systems data science strategies for tracking carbon through its entire lifecycle in circular pathways.
- Develop an integrated multi-objective modeling framework to scrutinize near-infinite diverse scenarios for circular bioproduct pathways, dynamically adapting strategies to pursue optimal solutions amid changing conditions due to climate, policy, and stakeholder decisions.

10-YEAR GOALS

- Deliver datasets and tools to support stakeholders in quantifying regional feedstock production and collection strategies' risk, economic potential, and sustainability impacts.
- Provide robust, dynamic decision-making tools for stakeholders around circular bioeconomy pathways that adjust strategies to pursue optimal solutions, resiliently adapting to changing conditions.



SMART PLANT FIELD SYSTEMS

Speeding up the work of developing better plants for sustainable fuels, products, and materials is essential to attaining a decarbonized economy. ORNL researchers are designing robotic systems and automated sensor arrays to monitor and measure the development of plants in trial gardens, eliminating the slow, painstaking process of manually recording observations to guide plant transformation research. The system, called **Sensors, Machine vision, Automation and Robotics for Transforming Plants (SMART Plant Field Systems)**, gathers data that can be fed directly into ML models to generate automatic, highly accurate assessments of plant phenotypes grown in the field. This research is supported by ORNL LDRD (App. C).

Figure 16. Researchers at the DOE Manufacturing Demonstration Facility at ORNL created this soil sampling robot for the SMART Plant project.



Figure 17. Center for Bioenergy Innovation research focuses on advancing production of cost-effective, environmentally positive, and industrially relevant bioproducts and biofuels, including sustainable aviation fuels.

CENTER FOR BIOENERGY INNOVATION

CBI is dedicated to the development of new low-carbon sustainable aviation fuels to help meet the goal of zero carbon emissions from the nation's commercial jets by 2050. Led by ORNL, CBI brings together 250 scientists from 17 partner institutions and industry to develop better biomass feedstock plants, custom-engineered microbes, and bioprocessing and conversion methods and tools to break down and convert the natural polymer lignin to fuels and other valuable bioproducts. Building on 15 years of scientific breakthroughs in plant-based fuels, CBI is now characterizing the biofuel blendstocks that its breakthroughs have enabled, a key step in certification for end-use. CBI's research has resulted in 256 invention disclosures, 101 patent applications, 37 patents, and 6 startup firms as it moves science to the streets. The center worked with technology licensee Vertimass to scale up ORNL-invented technology for a renewable gasoline blendstock that has been approved for use by the U.S. Environmental Protection Agency (EPA). Displacing fossil fuels with bio-based alternatives has multiple benefits in addition to being cleaner-burning. Bioenergy crops draw down carbon dioxide from the atmosphere and store it away in soils, helping mitigate climate change. The business of supplying billions of gallons of biofuel for transportation creates new green jobs and supports rural economies.



KEY PROJECTS, SPONSORS, AND PARTNERS

PROJECTS

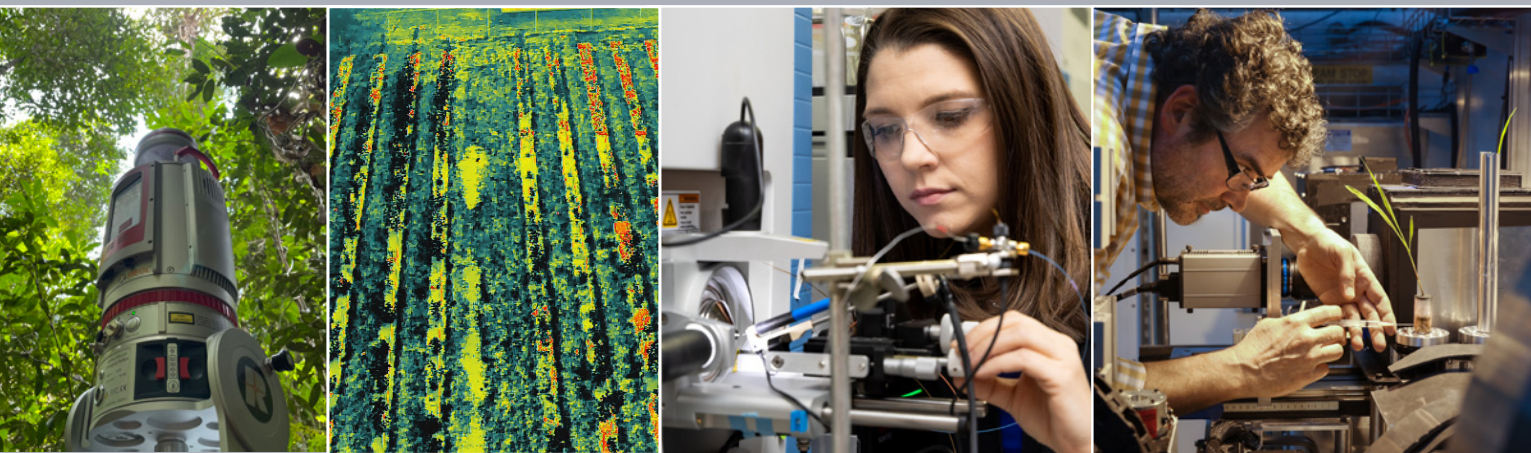
- Advanced Plant Phenotyping Laboratory
- Artificial Intelligence (ORNL Laboratory Directed Research and Development)
- Agile BioFoundry
- Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment
- Biofuels Science Focus Area (Solvent Disruption of Biomass and Biomembranes)
- Center for Bioenergy Innovation
- Center for Molecular Biophysics
- Center for Plastics Innovation
- Center for Structural Molecular Biology
- Circular Bioeconomy Systems
- Enzyme Engineering (ORNL Laboratory Directed Research and Development)
- INTERSECT (ORNL Laboratory Directed Research and Development)
- Plant-Microbe Interfaces
- Secure Biosystems Design
- Secure Ecosystem Engineering and Design
- SMART Plant Field Systems (ORNL Laboratory Directed Research and Development)

SPONSORS

- DOE Office of Science, Biological and Environmental Research
- DOE Office of Energy Efficiency and Renewable Energy
- DOE Bioenergy Technologies Office
- DOE Advanced Materials and Manufacturing Technologies Office
- DOE Basic Energy Sciences
- DOE Advanced Research Projects Agency-Energy
- Defense Advanced Research Projects Agency
- State of Tennessee
- University of Tennessee-Oak Ridge Innovation Institute

PARTNERS

- ORNL Computing and Computational Sciences Directorate
- ORNL Manufacturing Science Division
- ORNL Neutron Science Directorate
- ORNL Physical Sciences Directorate
- Argonne National Laboratory
- Brookhaven National Laboratory
- Environmental Molecular Sciences Laboratory
- Idaho National Laboratory
- INRAE/French National Research Institute for Agriculture, Food and the Environment
- Joint Genome Institute
- Lawrence Berkeley National Laboratory
- Los Alamos National Laboratory
- National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- Sandia National Laboratories
- Regional landowners, farmers, industry
- Universities (numerous partners)



Building a Foundational Science Infrastructure through a Network of Emergent Technologies and Tools

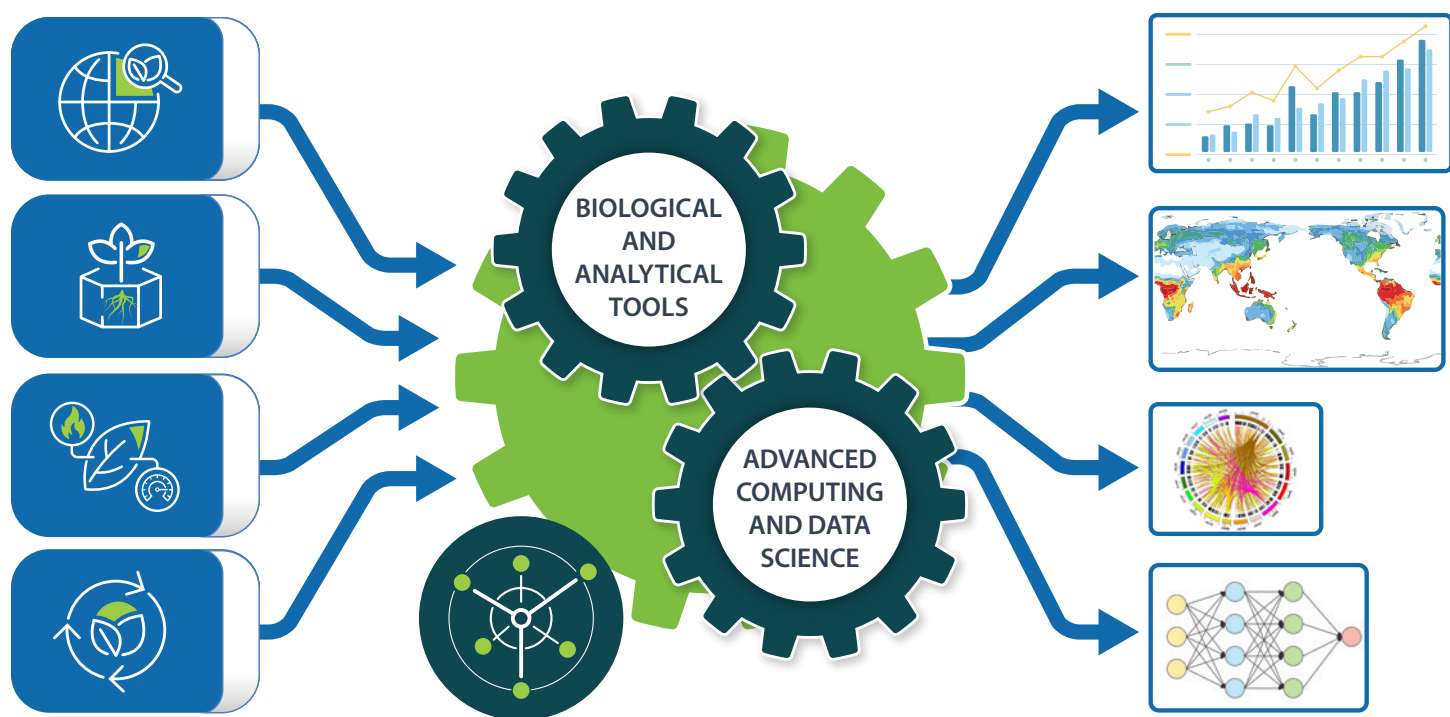


Figure 18. All themes are advanced through a foundational science infrastructure incorporating an array of technologies and tools.

CROSSCUT: Advanced Computing and Data Science

THE CHALLENGE

AI and exascale data and computing capabilities are rapidly transforming the scientific enterprise. Solutions to long-standing and intractable problems in the biological and environmental sciences are coming into view as a direct result of these new technologies. It is now feasible to construct digital twins of complex biological and environmental systems that span scales of mechanistic understanding from genes to ecosystems, even extending up in scale to a twinned representation of the full Earth system. **ORNL is positioned at the forefront of these emerging technologies and is prepared to act quickly and decisively to deploy revolutionary approaches in computation and data science to accelerate solutions in each of the four grand challenge areas described in this strategic plan.**

The new frontiers in biology and environmental science involve a holistic understanding of integrated systems. Revolutions in analytical methods (see **Biological and Analytical Tools Crosscut**) now make it possible to quantify entire biological and environmental systems from the scale of genes and molecules, to precise identification of individual organisms and their associations within soil and vegetation systems, to dynamic distributions of ecosystems at landscape and watershed scales. AI methods combined with exascale computing and data infrastructures are providing avenues for ingesting this wealth of multi-modal information and using it to crack the toughest problems that have hindered our system-level understanding. Specifically, teams at ORNL have recently created AI foundation models that take in vast quantities of multi-dimensional,

multi-modal, and unlabeled data to provide orders-of-magnitude acceleration in solving complex coupled system problems in biology and environment.

The stage is set for us to apply these new analytical, computational, and data science capabilities—together with our expanding mechanistic understanding of integrated biological and environmental systems—to create new digital twins of these complex systems. These twins will serve as the integration and communication centers for our laboratories of the future, connecting real-world and real-time measurements and experimental results with new hypothesis development and testing, and connecting trustworthy and actionable knowledge and insight to decision-makers through natural language interfaces.

A further challenge is to anticipate new phases of technological revolution and maintain flexibility and resilience in our research enterprise to take advantage of those advances as they arrive. One example is a focus on quantum computing (QC) and its implications for advancing biological understanding and prediction of coupled environmental and Earth systems. In particular, the use of QC for AI could drive science toward the goal of an artificial general intelligence (AGI), able to learn and reason in ways analogous to human thought. **By collaborating with today's leaders in AI technology and exascale computation to solve our current grand challenges, biological and environmental systems scientists can be ready to adapt to a new QC-driven AGI paradigm when it arrives.**

OUR VISION

A rapid and flexible deployment of AI models and exascale data and computing to accelerate systems-level understanding in biological and environmental research. Data, modeling, and experimentation linked to AI and cutting-edge analytical capabilities to create digital twins for hypothesis testing and actionable science.

OUR STRATEGY

With ORNL's world-class AI models, such as ORBIT, as a foundation, and enabled by ORNL's exascale computing and data capabilities (such as Frontier and the ARM Data Center Computing Cluster), we will develop configurable solutions to address each of the four grand challenge areas outlined in this strategic plan. We are already working toward accelerated spinup of coupled Earth system biogeochemistry codes using ORBIT with fine-tuning from massive archives of observational data and climate model output (**Theme 1**). We are automating data collection and analysis in laboratory and field settings through collaborations with ORNL's INTERSECT initiative (**Theme 2**). We are connecting

biological systems science to AI and ML capabilities and exascale computation to accelerate discovery of synthetic biology, improve mechanistic understanding of plant and microbial phenotypes and resilience, and design of novel enzymes and materials for circular bioeconomy solutions (**Themes 3 and 4**). We will increase our impact through AI and ML approaches that connect people to data and understanding, applying natural language models to translate complex mechanistic representations of biological and environmental systems into practical answers to questions posed by decision-makers. A detailed list of Strategic Infrastructure Objectives with 5-year and 10-year goals is given in Appendix D.



Figure 19. The Frontier supercomputer at the Oak Ridge Leadership Computing Facility.

EXASCALE COMPUTING

From Earth-scale climate modeling to drug discovery to materials for a decarbonized economy, the Frontier supercomputer—the world’s fastest for open science—is accelerating solutions for some of the most complex challenges of our time. Frontier, the HPE Cray EX supercomputing system at DOE’s OLCF, is also the planet’s first exascale system, capable of more than 1 quintillion calculations per second. Frontier achieved record speeds in modeling worldwide cloud formations in 3D, compressing the work of years into days to bring detailed estimates of extreme weather and long-term climate change effects within reach. The system also modeled half a trillion atoms to simulate room-temperature water molecules and is improving simulations of extreme weather and global ocean circulation models.

ARM DATA CENTER COMPUTING CLUSTER

To accommodate access to a world’s worth of data on key atmospheric properties at the heart of key climate models, the ORNL-managed Atmospheric Radiation Measurement Data Center makes use of the Cumulus computing cluster at the OLCF. The Cluster consists of 16,384 processing cores with a 4 PB General Parallel File System, allowing users to access information and perform simulations without downloading the data. That computing power enables advanced model simulations, big-data storage and analytics, and machine learning approaches. The ARM Data Center gathers some 50 terabytes or more of data per month from more than 450 instruments cited in climate-critical locations around the world, offering more than 11,000 data products. The center is part of the ARM User Facility, which is managed and operated through the collaboration of nine national laboratories, including ORNL.



Figure 20. Giri Prakash and Gary Geernaert discuss ARM capabilities at the Oak Ridge Leadership Computing Facility.



Figure 21. ORBIT is the largest Earth system foundation model.

ORBIT FOUNDATION AI MODEL

ORNL researchers are developing ORBIT, an AI foundation model for Earth system predictability. ORBIT leverages vast amounts of heterogeneous Earth system data to advance a wide range of Earth system modeling applications. With 113 billion parameters, ORBIT is the largest Earth system foundation model, offering significant potential to enhance predictability in terms of accuracy, efficiency, and versatility. Pretrained on climate model simulation data, ORBIT can be fine-tuned for various applications, from climate prediction to accelerating Earth system model simulations across local to global scales. ORBIT has achieved exascale computing performance, demonstrating strong scaling efficiency on the Frontier supercomputer. In weather prediction applications, ORBIT has shown superior accuracy in forecasting critical atmospheric variables compared to state-of-the-art models. Its high efficiency enables rapid generation of large ensembles, crucial for quantifying prediction uncertainty and capturing extreme events. This capability provides actionable science to support climate-resilient decision-making. ORBIT development is supported by ORNL LDRD and the DOE Advanced Scientific Computing Research program.

CROSSCUT: Biological and Analytical Tools

THE CHALLENGE

The 21st century is often referred to as the “Century of Biology” by leading scientists, politicians, and global leaders. Advances in long-read, high-throughput DNA and RNA sequencing, sophisticated analytical tools, innovative imaging platforms, and AI and ML approaches have all fostered this enthusiastic perspective. This perspective is further supported by the imminent challenges we face in the 21st century, including feeding a growing population, meeting increasing energy demands in a sustainable manner, and addressing the social, environmental, and political impacts of climate change. **Systems biology and synthetic biology offer new ways to tackle these issues via cutting-edge instrumentation and technologies.**

Systems biology can be defined as an approach to understanding living systems at the holistic level, rather than defining the component features of individual parts in a reductionist manner. Systems biology utilizes a broad range of interdisciplinary methodologies, from computational and mathematical approaches to molecular and cellular tools to broad and detailed imaging techniques. From a Systems Biology approach, nascent properties, such as adaptation, resilience, and robustness, emerge. Synthetic biology can be defined as a multidisciplinary field of biology that applies engineering principles to the development of new biological parts, strategies, and/or systems designed to realize a desired product or outcome in order to create resilient biological systems. Like systems biology, synthetic biology employs a broad range of disciplines and expertise, including biochemistry, biotechnology, bio-derived material sciences, genetic engineering, molecular biology, molecular engineering, transgenesis, and evolutionary biology.

ORNL currently applies cutting-edge infrastructures that are continually developed, upgraded, and applied to DOE Biological and Environmental Research (BER) missions related to ecosystem resilience, biofuels development and deployment, and fundamental understanding of living systems. For example, neutron scattering resources, including the Biological Small-Angle Neutron Scattering (SANS) instrument at HFIR and a deuteration and protein expression laboratory at SNS, are being used to address biological questions within the current Biofuels SFA (App. C). A DOE effort is ongoing to develop a new multimodal (BER)SANS instrument prototype for the SNS Second Target Station directed toward biological applications.

In addition, ORNL possesses capabilities in cryo-electron microscopy, solid and solution nuclear magnetic resonance spectroscopy, mass spectrometry, laser spectroscopy, and multiple modalities of imaging. Notably, ORNL has recently acquired a novel high-throughput laser spectroscopy instrument that can be used to determine the ionome and pinpoint the presence of elements via 2D scanning of leaves. As one of a very few institutions with this capability, we have used this approach to characterize plant biomass as it relates to bioenergy and climate change. Our mass spectrometry-based capabilities were recently expanded with three new cutting-edge high-performance systems to interface with a broad range of both liquid and gas chromatography platforms to better address applications that include biomass characterization, proteomics

and metabolomics, and chemical imaging. ORNL is also leading the Quantum Science Center, which aims to develop quantum materials, sensors, and algorithms. We have recently added new capabilities in automated aerobic and anaerobic microbial transformation.

Despite these leading-edge capabilities, there is a critical need for further development and deployment of enhanced biological and analytical tools in order to address the above challenges in a timely manner and to realize the potential of a new bioeconomy. There is an urgent need to improve transformation efficiencies across a broad range of non-model plants and microbial taxa. In addition, agile methods for rapid and effective multigene construct design and production are needed to meet the demands of synthetic biology. Further improvements in measuring and quantifying gene expression at all levels—from transcriptional regulation and gene editing to RNA stability and protein turnover, including tissue- and cell-specific expression—are needed. Moreover, there is a need for expanded inducible and tissue-specific promoters, selectable marker libraries, and *in vivo* reporter genes.

On the analytical side, mass spectrometry, optical spectroscopy, and nuclear magnetic resonance capacities must be further developed with a focus on improved resolution and throughput. Comprehensive spectral imaging of entire plants growing in close association with their bacterial and fungal associates must be widely adopted in conjunction with remote satellite and unmanned aerial vehicle surveillance of managed and natural ecosystems. Critically, the data generated from these infrastructure platforms must be ingested into a FAIR (Findable, Accessible, Interoperable, and Reusable) data management system linked to exascale computing infrastructure (**Advanced Computing and Data Science Crosscut**).

To fully realize the potential of the emerging bioeconomy, we must ensure that these tools are made accessible at ORNL and to the broader scientific community. **A coordinated effort across the entire DOE research complex is essential to avoid redundancies, increase resource utilization and efficiencies, and increase scientific and technological output.** A functional, genes-to-phenotype initiative, similar to the SLAC Integrated Research Infrastructure initiative in structural biology, is needed. **The new biology for the 21st Century, guided by ORNL’s vision and fostered by DOE BER support, will leverage current local and distributed capabilities along with emerging biological infrastructure to meet the challenges of ensuring ecosystem health, generating energy to meet increasing world and national demand, and mitigating the social and biological impacts of global climate change.**

OUR VISION

To establish multi-organizational, integrated research infrastructure capable of generating, quantifying, and analyzing biological datasets. These datasets will range in complexity from individual proteins up to and including natural ecosystems across spatial and temporal scales associated with plant and microbial systems.

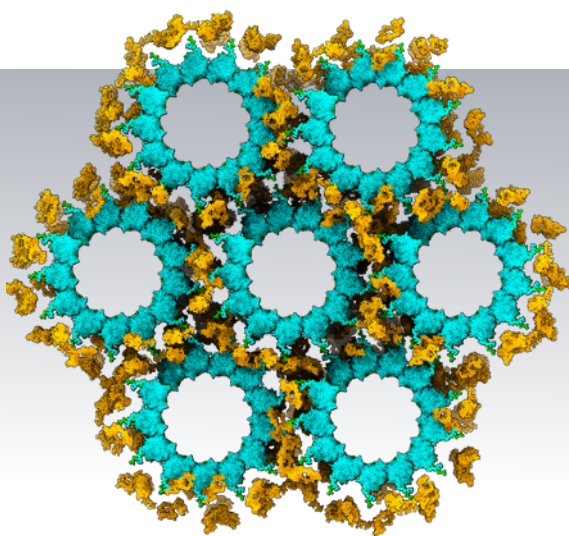
OUR STRATEGY

The promise of systems and synthetic biology will only be realized with various advances in experimental platforms and instrumentation, development of cutting-edge software and computational hardware, and innovations in analytical and phenotyping methods (in coordination with the **Advanced Computing and Data Science Crosscut**). To continue to tackle issues related to ecosystem function, the emerging bioeconomy, and the advancement of our fundamental understanding of biological systems in **Themes 2, 3, and 4**, we will continue to build upon the lab's current capabilities and embrace emerging capabilities that can propel ORNL science to new levels. For example, we will pursue applications of synthetic biology to customize transformation and manipulations of microbial and plant genomes to better understand genotype-phenotype connections—both in isolated systems as well as complex multi-organism communities.

Similarly, there is a need (and opportunity) to create a systematic pipeline designed to enable the accelerated development of any organism of interest. In addition, we have not yet addressed targeted engineering of microbial synthetic communities and community reconstruction in native environments. To bridge the gap between natural and synthetic microbial communities, we need to employ new automated high-throughput microbial transformation systems towards methods development to augment ongoing engineering efforts.

We will develop automated capabilities for field-deployed systems, lab-based characterizations (APPL, lab mesocosm characterizations) to help achieve the objectives of **Theme 1** (Predict Earth and Environmental Systems across Scales). We will develop autonomous approaches to measure ecosystem change/recovery, and explore new remote sensing technologies to support **Theme 2** (Understand Ecosystem Response to Changing Climate and Disturbance Regimes). We will develop integrated analytical approaches (omics, imaging) to understand complex systems in support of **Theme 3**. Finally, we will advance gene/genome editing techniques, integrated omics, bio-derived materials characterization, and automated phenotyping in support of **Theme 4**.

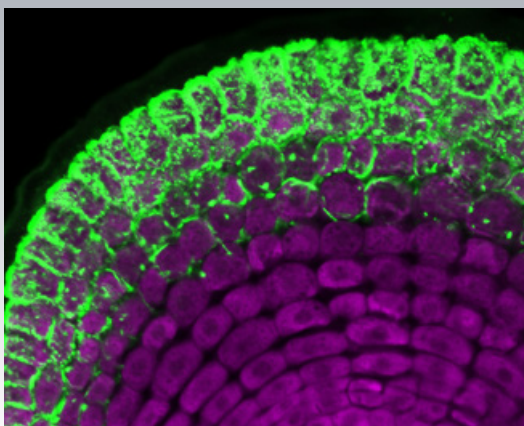
Our overall aim is to develop a Foundational Science Infrastructure, drawing on ORNL's specific strengths and capabilities while partnering with our sister national laboratories to create complementary analytical tools and approaches. Our focus will include both lab-based instruments for detailed biomolecular characterizations and field-based systems for real-time monitoring, remote sensing, and automated sampling. These initiatives will bridge ORNL's **Grand Challenge Themes**. A detailed list of **Strategic Infrastructure Objectives** with 5-year and 10-year goals is given in Appendix E.



NEUTRON SCATTERING ILLUMINATES PLANT STRUCTURES

Scientists using small-angle neutron scattering, TEM, and SAXS have shown how a companion protein to the cellulose synthase enzyme interacts with microtubules, bundling the microtubules into hexagonal structures under salt stress. These formations help preserve plant growth. These insights can help researchers better modify plant structures and treatments to facilitate the conversion of cellulose into biofuels and bioproducts.

Figure 22. Atomic model of the N-terminal domain of the companion of the cellulose synthase 1 protein interacting with microtubules.



ORNL SCIENTISTS MAKE FUNDAMENTAL DISCOVERY TO CREATING BETTER CROPS

A team of scientists led by ORNL discovered the specific gene that controls an important symbiotic relationship between plants and soil fungi and successfully facilitated the symbiosis in plants that typically resist it. The team used supercomputing resources at the OLCF along with genome sequences produced at DOE's Joint Genome Institute to narrow down the search to a particular receptor protein. Once they identified the likely gene, the researchers validated their findings by engineering *Arabidopsis*, a plant that traditionally does not interact with the fungus *Laccaria bicolor*, to interact symbiotically with the fungus.

Figure 23. Confocal microscopy shows the fungus, *Laccaria bicolor*, in green, colonizing the root of a natural host, *Populus trichocarpa*.

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Appendix A:

Partnering Strategically for Success

ORNL's impact is amplified by its extensive partnerships. Located in Oak Ridge, Tennessee, the Lab is managed by a partnership between the **University of Tennessee (UT System and Battelle Memorial Institute (UT-Battelle))**, through a contract that includes several core universities. ORNL also engages with other universities, DOE national laboratories, federal entities, industry, and community partners to extend its impact. This Plan will strengthen existing partnerships and, when needed, build new ones to grow our ability to address the **Grand Challenge Themes**. For example, ORNL has been expanding its partnerships with core universities, including the University of Tennessee, Knoxville. The UT-Oak Ridge Innovation Institute (UT-ORII) provides collaborative and educational opportunities between the two institutions and has just founded a DOE and State of Tennessee funded **Circular Bioeconomy Systems** convergent research initiative (Fig. 15) that aligns with **Theme 4**.

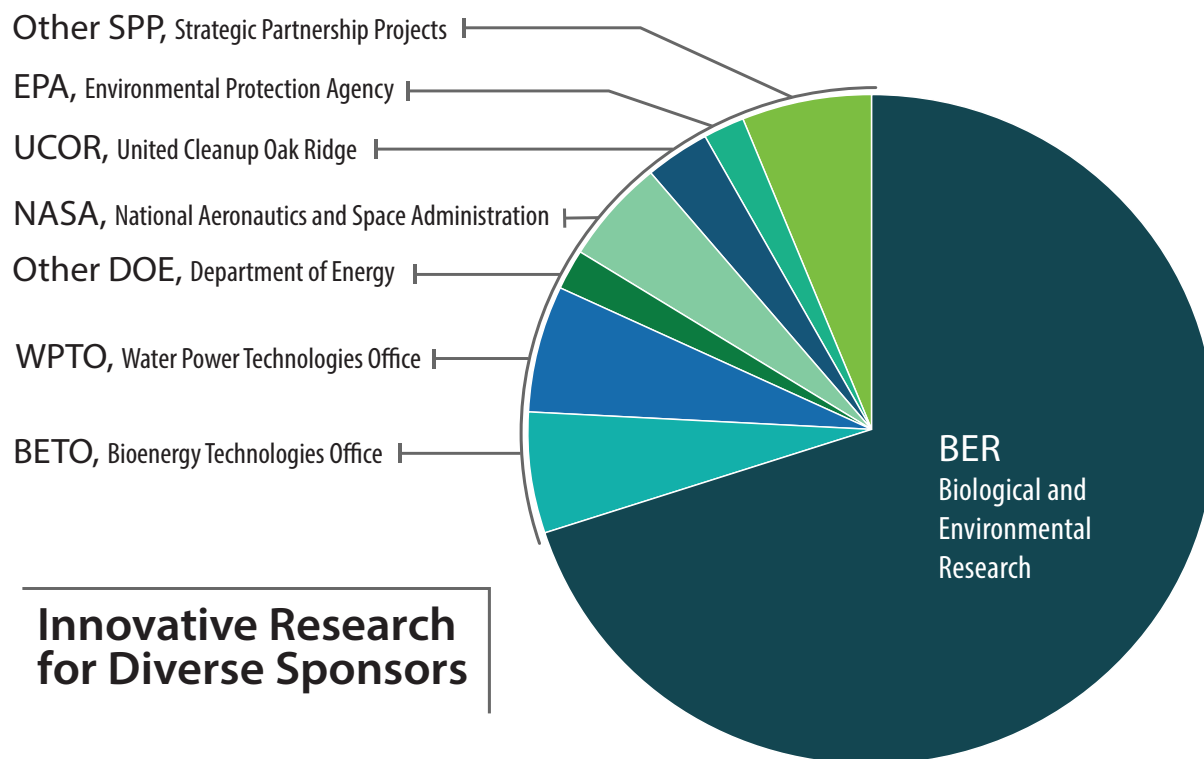
HUMAN HEALTH

ORNL strategically partners and conducts research with organizations outside of the Lab and DOE when it amplifies our ability to meet the DOE mission (Fig. A-1). Building on its scientific legacy in mammalian genetics and radiation risk assessment, **ORNL continues to make discoveries relevant to human health**. Researchers leverage the Lab's unique user

facilities as well as BESSD's multi-omics expertise, microbial science, systems and synthetic biology, mass spectrometry capabilities, analytics, synthetic chemistry, biophysical methods, and computational biology.

ORNL work in the **biomedical field**, including SARS-CoV-2 inhibitor molecule design, computational immunology and pathology projects, epidemiological modeling, and integrated biomedical systems biology, has involved partners from the **U.S. Veteran's Administration, the National Institutes of Health (NIH), the UT Health Science Center in Memphis, Georgetown Medical Center, St. Jude Children's Research Hospital, and many academic partners**, and COVID-related research through the DOE **National Virtual Biotechnology Laboratory (NVBL)**. BESSD also uses its broad expertise in human health risk assessment, ecology, radiation protection, and toxicology to develop and support widely used tools and data for the **EPA's Superfund program**. **These partnerships help build biological capabilities and expertise that can be leveraged in Themes 3 and 4.**

Another **UT-ORII** convergent research initiative for **Development and Advancement of Radiopharmaceutical Therapies** has been established to develop a pipeline for radiotherapeutics based on ORNL's unique status as a key producer of stable isotopes. The pipeline will extend from isotope production and chemistry to nanotechnology targeting vectors/novel chelators, to



Innovative Research for Diverse Sponsors

Figure A1. Multiple sponsors support directorate research.

bioassessment platforms/integrated cellular effects and nanotechnology, and to next-generation radiotherapeutics and technologies. We also see opportunities to reach out to new partners in human health research to take advantage of **ORNL's HPC infrastructure, including the OLCF** (App. C) and other unique resources for faster experimental and clinical workflows. There are opportunities to serve industry as a virtual user center for scientific research, to explore the human microbiome, accelerate precision medicine treatments, address emerging pandemics and biothreats, and to develop materials for human health. These opportunities have the potential for DOE-NIH alignment and partnerships that could address challenges such as mitigating the impacts of extreme environmental disturbance on human health.

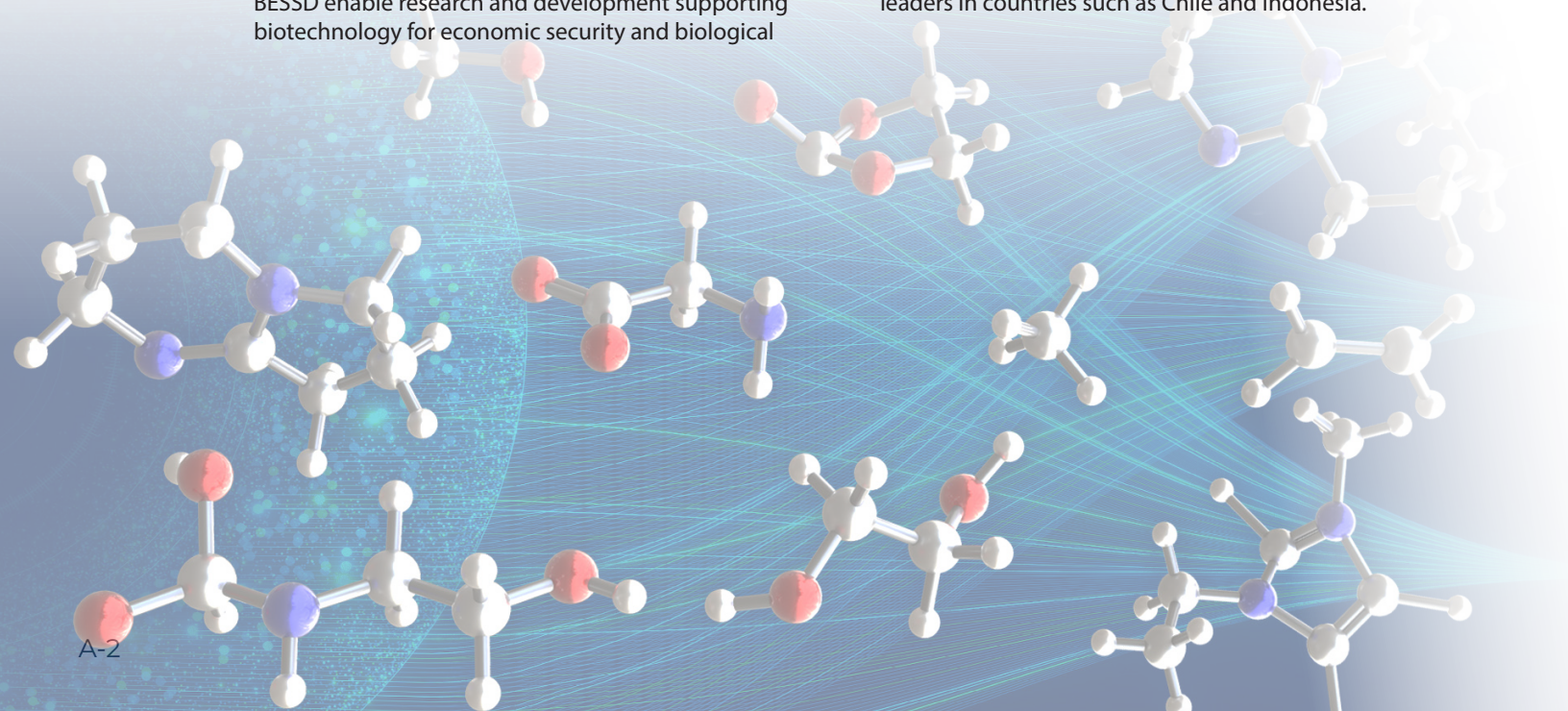
BIOSECURITY

BESSD strategically partners to address national security challenges in the biosciences. Capabilities developed for bioenergy research through the DOE **Biological and Environmental Research program (BER)** and the DOE **Bioenergy and Technologies Office (BETO)** have been leveraged to support food and agricultural biosecurity projects and risk assessments spurred by the **Securing our Agriculture and Food Act** and other legislation. ORNL's response to the COVID-19 pandemic through the NVBL has been foundational for current efforts in the DOE **Biopreparedness Research Virtual Environment**, (BRaVE), program. Bioinformatic and geospatial analysis of massive datasets using HPC enables network and pathway analyses that support the **Global Health Security Strategy** issued this year. Analyses of dual-use biotechnology assists the activities of the **National Nuclear Security Administration (NNSA)** focused on biological nonproliferation, the **National Biodefense Strategy**, and the safe use of Artificial Intelligence (AI). Systems biology and synthetic biology capabilities in BESSD enable research and development supporting biotechnology for economic security and biological

detection. With support from BER, the ORNL-led **Secure Ecosystem Engineering and Design (SEED)** Science Focus Area engineers biocontainment measures for a sustainable bioeconomy. ORNL biosecurity research and development is sponsored by DOE and Strategic Partnership Projects from the **Department of Defense (DOD) Defense Advanced Research Projects Agency, Defense Threat Reduction Agency, Strategic Environmental Research and Development Program, the United States Army, the Department of Homeland Security, and U.S. Food and Drug Administration.**

LOCAL PARTNERS AND COMMUNITIES

BESSD has an increasing focus on the southeastern region of the U.S., with partners that include the **Tennessee Department of Environment and Conservation**, the **USDA Forest Service Southern Research Station**, the **Tennessee Valley Authority**, **EPA Region 4**, and the **Eastern Band of the Cherokee Indians**. We have growing relationships with **Historically Black Colleges and Universities and Minority-Serving Institutions** through student programs and advisory committees. Nonprofits in the southeast, such as the **Southeast Energy Efficiency Alliance** in Atlanta, engage with our projects on advisory committees and workshop planning. Because of the growing need for co-production of knowledge, the necessary engagement of communities and stakeholders in energy and environmental projects, and the emphasis on energy and environmental justice, we expect collaborations with nonprofits to increase in the future. Although we have always engaged academia, industry, utilities, and federal agencies in our projects, we are beginning to engage additional sectors, such as the energy and environmental nonprofits described above, municipalities, and labor unions. Our international work on the interagency **Net Zero World** program focuses on engaging local partners and women leaders in countries such as Chile and Indonesia.



THREE COMPANIES LICENSE ORNL-DEVELOPED TOOLS FOR MICROBIAL ENGINEERING

Developing precise, efficient, and high-throughput genetic engineering tools is critical to achieving many goals, such as making biofuels and bioproducts, recycling mixed plastics, and aiding soil carbon storage. ORNL's Adam Guss leads development and application of these tools, known as the **Serine recombinase-Assisted Genome Engineering (SAGE)** toolkit. SAGE allows quick insertion of new genes into virtually all microorganisms, including newly domesticated microbes. These non-model microbes, previously so challenging to work with, can be modified in days with SAGE compared to the tailoring process that can take weeks when using existing methods. Through its speed and ease of use, SAGE biotechnology is fostering both fundamental discovery science and new product development for the growing bioeconomy. To date, three companies have licensed the technology for use in their microbial strains of interest, and many projects across the national laboratories and partner universities are employing SAGE to advance DOE science missions.



Figure A2. Adam Guss began adapting the SAGE gene editing tool to modify microbes in graduate school. Today, SAGE is rapidly accelerating the design of custom microbes for a variety of applications.



Figure A3. The EPA approved the registration and use of a renewable gasoline blendstock developed by Vertimass LLC and Oak Ridge National Laboratory that can significantly reduce vehicle emissions when added to conventional fuels.

EPA APPROVES RENEWABLE GASOLINE BLENDSTOCK DERIVED FROM ORNL INVENTION

EPA recently approved the registration and use of a renewable gasoline blendstock developed by Vertimass LLC and ORNL that can significantly reduce the emissions profile of vehicles when added to conventional fuels. The EPA approved the blending of up to 20% of the **VertiGas20** green gasoline product with conventional gasoline. The low-cost, biomass-derived product is made from renewable ethanol produced by a method called **Conventional Alcohol Deoxygenation and Oligomerization, or CADO**, a technology originally invented at ORNL. The Lab, along with Technip Energies, assisted Vertimass in optimizing the novel catalyst and production method, and Vertimass is now ready to fully commercialize it. Use of the blendstock could eliminate 560 billion pounds of new CO₂ accumulation in the atmosphere as it replaces a portion of the fossil fuels required for conventional gasoline production. Vertimass also aims to use the technology in developing renewable propane and chemical feedstocks to decarbonize other industrial sectors, including the production of plastics, nylon, paints, and detergents.

CENTER FOR BIOENERGY INNOVATION R&D SUPPORTS NEXT-GENERATION BIOFUELS STARTUP TERRAGIA

Using a best-of-nature approach developed by researchers working with CBI at ORNL, startup company **Terragia Biofuel** is targeting commercial biofuels production that relies on renewable plant waste and consumes less energy. Terragia is scaling up several licensed technologies resulting from collaborative R&D led by Dartmouth and ORNL scientists through DOE's CBI. The company is also a partner in CBI, a DOE Bioenergy Research Center that brings together some 250 scientists from 17 partner institutions to develop bioenergy-relevant plants, microbes, and processing methods for sustainable biofuels production. Terragia will use an engineered bacterium, *Clostridium thermocellum*, which tolerates high temperatures and can eat away at plant material in bioreactors, to convert cellulosic biomass in a one-step consolidated bioprocessing method without the addition of costly enzymes or thermochemical pretreatment used in traditional ethanol production. The method can utilize crop and forest residues as well as purpose-grown, nonfood perennial crops like poplar trees and switchgrass to produce "wet" ethanol, containing 20% water, that is then converted into low-carbon blendstock fuels for jet engines. The technology can be bolted onto existing ethanol refineries to help meet the demand for billions of gallons of clean liquid fuels needed to reduce emissions from airplanes, ships, and long-haul trucks.

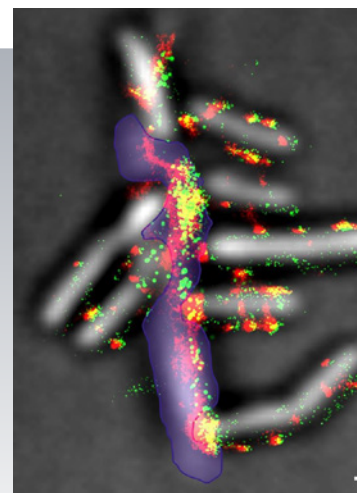


Figure A4. An engineered bacterium, *Clostridium thermocellum*, breaks down biomass.

Appendix B: Leveraging DOE Capabilities for Science and Innovation

Groundbreaking science at ORNL is enabled by cutting-edge DOE user facilities and capabilities. In addition to Oak Ridge facilities, BESSD researchers leverage those at other national laboratories and collaborate with partners in academia and industry through a range of programs, projects, and consortia including instrumentation and expertise at the **Environmental Molecular Sciences Laboratory** at PNNL and the **Joint Genome Institute (JGI)** at LBNL. These facilities play a vital role in our science, offering diverse imaging and analytical capabilities and generating volumes of genomic data to advance discoveries spanning genes to ecosystems. Discoveries are also fostered by the team-oriented, collaborative research that our staff leads and contributes to through DOE's many Science Focus Areas.

BESSD scientists use DOE light sources such as the **Advanced Photon Source** at Argonne National Laboratory, the **National Synchrotron Light Source II** at Brookhaven National Laboratory (BNL), and the **Stanford Synchrotron Radiation Light Source** at Stanford Linear Accelerator Center (SLAC) to study materials and biological structures from the atomic scale, through the mesoscale, to the plant rhizosphere macroscale, complementing unique information provided by ORNL SNS and HFIR neutron user facilities (App. C). One of many examples is the use of X-ray and neutron small angle scattering together with HPC to determine morphological changes in biomass as it undergoes pretreatment for conversion to biofuels (Ref. 19).

Collaborations across **DOE's Bioenergy Research Centers** are speeding up breakthroughs that support the growing bioeconomy. The team science conducted through CBI is complemented by efforts at the four other centers, as they share knowledge and resources to break down barriers to a robust bioenergy industry, through shared research objectives. Using DOE capabilities such as the testbeds at the **Advanced Biofuels and Bioproducts Development Unit** at LBNL, researchers are expediting the commercialization of next-generation biofuels, biochemicals, and bioproducts. BESSD also contributes to bioenergy innovations by participating in six multi-laboratory consortia supported by BETO.

In addition to HPC capabilities housed at ORNL (including the Oak Ridge Leadership Computing Facility, App. C), BESSD scientists use resources at the Argonne Leadership Computing Facility and the National Energy Research Scientific Computing Center at LBNL to accelerate scientific discovery. Our researchers contribute to DOE's E3SM,

which requires these world-class computing facilities to execute complex simulations of future climate that can inform regional, national, and global mitigation strategies.

Insights from new data are informing improvements to Earth system models. Sensors deployed across North, Central, and South America through DOE's **AmeriFlux** Network are generating data and new understanding of critical links between terrestrial ecosystem processes and climate responses. Our researchers not only use these data, but also contribute to the leadership of the network by co-chairing the AmeriFlux Science Steering Committee. These premier capabilities enable scientific discoveries and innovations that advance DOE missions, focusing on some of the most urgent issues of our time.

Although understanding how cells, plants, and ecosystems will respond to environmental change is a pressing challenge, quantifying how genes function and influence a plant's phenotype is a complex and time-consuming process. To accelerate discovery, **ORNL has invested in, built, and now operationalized APPL for high-throughput phenotyping of plant systems and their response to environmental change, a major additional science capability.** The APPL tram system autonomously circulates up to 520 soil-plant units daily through a greenhouse using a robotic loop, whereby the plants are 3D imaged using a suite of remote sensing and spectroscopic measurement methods and are also subjected to manipulations (such as changes in soil moisture, air temperature, and nutrient delivery). ORNL is currently using APPL image data, analyzed by AI, to extract phenotyping data to identify genes in *Populus* and switchgrass that enhance growth, photosynthesis, and nutrient use efficiency in normal and drought conditions; to discover how microbial inoculants enhance resilience in the face of stresses; and to determine how these noninvasive imaging methods relate to ground-truth measures of metabolites, photosynthetic CO₂ capture, and volatile organic compounds. We see APPL as having potential to be used as a shared-facility capability for the broader biological and environment research community to collect data that will be highly complementary to X-ray and neutron imaging data collected at DOE light and neutron sources, data that will be provided by the planned **Microbial Molecular Phenotyping Capability (M2PC)** at PNNL, ORNL's automated **SMART Field experiments**, and a potential future **Plant Transformation Facility**.

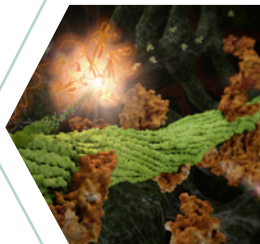
Appendix C: Leveraging ORNL Research Facilities and Capabilities

ORNL's world-class scientific user facilities and diverse research capabilities support transformational science.



Figure C1. Leveraging ORNL facilities and capabilities to advance DOE missions.

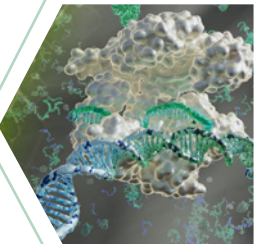
Select BESSD Projects



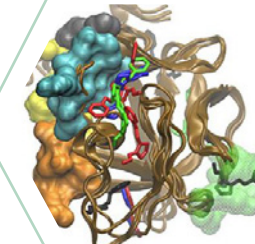
Biomass Deconstruction—Examining the effects of solvents on plant cell walls and microbial membranes to optimize biofuels production



Biomass deployment strategies—Aligning market feasibility, ecosystem services, and equity to optimize and ensure sustainability and fair economic opportunities



Biosecurity—Applying biosciences to National Security programs to identify and mitigate threats to agriculture, bioeconomy, ecosystems, and human health



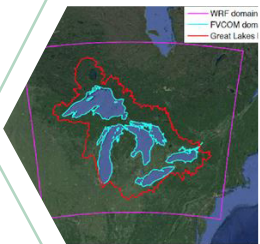
Center for Molecular Biophysics—Analyzing and understanding the function of biologically-relevant molecular systems by employing high-performance computer simulations in combination with biophysical experiments



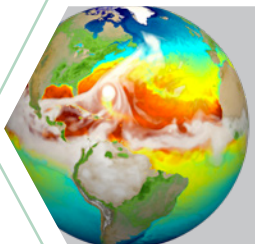
Circular Bioeconomy Convergent Research Initiative—Using emerging science to produce materials from sustainable carbon sources and enable a shift toward low-energy and low-carbon-intensity agriculture and manufacturing



Coastal Observations, Mechanisms, and Predictions Across Systems and Scales – Field, Measurements, and Experiments—Developing a predictive understanding of the shift between aerobic and anaerobic conditions at land–water interfaces



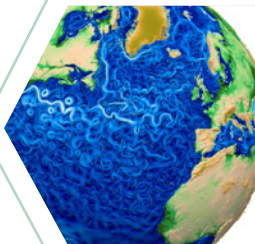
Coastal Observations, Mechanisms, and Predictions Across Systems and Scales – Great Lakes Modeling—Developing a fully coupled regional Earth system model centered around the Ohio Portage River basin



Earth System Grid Federation 2 US—Archiving and distributing model output from international sources to inform global and regional climate change assessments



eDNA—Analyzing environmental DNA from water samples to monitor the presence of endangered fish populations



Energy Exascale Earth System Model—Informing and improving the land model for DOE's Earth system modeling, simulation, and prediction project



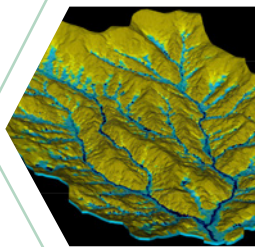
Free Air CO₂ Enrichment Model-Data Synthesis—Improving models to reflect accurate terrestrial ecosystem responses to elevated atmospheric CO₂



Hydropower Market Report—Highlighting market developments and high-level trends in the nation's public and private hydropower fleet



HydroSource—Providing U.S. energy–water data, visualizations, and analytics tools to support clean energy development



IDEAS – Watersheds—Accelerating watershed science through a community-driven software ecosystem



Integrated Multisector Multiscale Modeling—Leading urban modeling for the IM3 project exploring how human and natural landscapes co-evolve in the short- and long-term



Microbial engineering for the bioeconomy—Modifying microbes to produce valuable fuels and chemicals from renewable resources and to break down and upcycle plastics



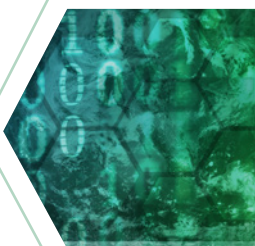
Next Generation Ecosystem Experiments Tropics—Filling the critical gaps in knowledge of tropical forest–climate system interaction for better predictive models



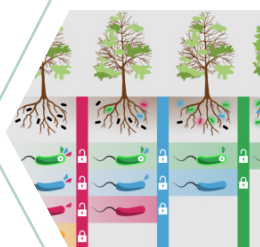
Next-Generation Ecosystem Experiments (NGEE) Arctic—Advancing predictive understanding of the structure and function of Arctic terrestrial ecosystems in response to climate change



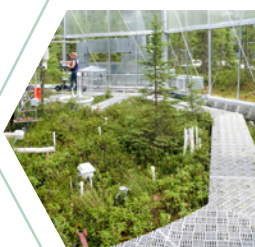
Plant-Microbe Interfaces—Elucidating interactions between plants and micro-organisms critical to plant and ecosystem health, resilience, and carbon storage



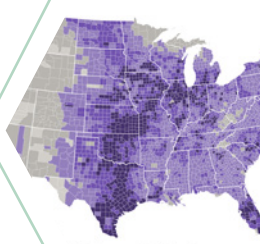
Reducing Uncertainty in Biogeochemical Interactions through Synthesis and Computation—Evaluating representations of key ecosystem processes to reduce uncertainties in Earth system models



Secure Ecosystem Engineering and Design—Developing biodesign strategies and tools for beneficial alterations and prevention of undesirable changes to critical ecosystems



Spruce and Peatland Responses Under Changing Environments (SPRUCE)—Assessing northern peatland ecosystems' response to temperature increases and exposures to elevated atmospheric CO₂ concentration



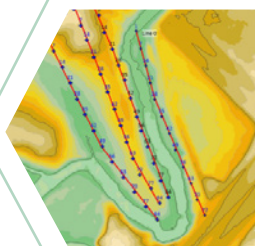
Sustainable biomass resources—Providing essential assessments of biomass resources to guide decision-makers in supporting decarbonization and a growing bioeconomy



TRITON inundation modeling—Studying flood impacts using a GPU-accelerated hydrodynamic model and the Oak Ridge Leadership Computing Facility



Urban Integrated Field Laboratories—Informing equitable climate and energy solutions to strengthen community-scale resilience in cities across the nation

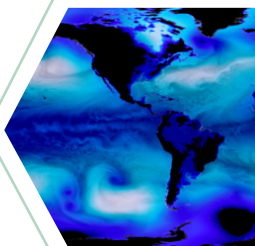


Watershed Dynamics and Evolution—Advancing predictive understanding of how processes controlling watershed function operate under a range of hydrologic conditions

Centers and Institutes



Center for Bioenergy Innovation—Accelerating domestication of bioenergy-relevant plants and microbes to enable high impact, value-added fuels and coproduct development at multiple points in the bioenergy supply chain



Climate Change Science Institute—Translating data, knowledge, and applied understanding of climate change science into equitable and sustainable solutions for our communities, the nation, and the world

Laboratory Investments in Research and Development

The Laboratory Directed Research and Development (LDRD) program at ORNL supports cutting-edge research that stimulates exploration at the forefront of science and technology. LDRD includes components that develop new capabilities in support of ORNL's research initiatives, innovative ideas that have the potential for enhancing the Laboratory's core scientific and technical disciplines, and fellowships for outstanding scientists and engineers to achieve experience in areas of national importance. LDRD projects are led by ORNL research staff members and often involve collaborations with university researchers.

Artificial Intelligence—Ensuring secure, trustworthy, and energy-efficient AI in the service of scientific research and national security

- **ORBIT—**Developing an AI foundation model for Earth system predictability

INTERSECT (Interconnected Science Ecosystem)—Employing a common infrastructure to connect high-performing, self-driving laboratories across ORNL through a system of systems approach

- **SMART Plant Field Systems—**Developing autonomous, robotic technologies for belowground monitoring and sampling with edge computing capabilities

Accelerating Radiotherapeutics Through Advanced Molecular Constructs—Enable technological advances in the design, synthesis, and characterization of molecular cages to enable the targeted transport of therapeutic radionuclides to cancer sites

Bringing a Digital Underground to the Advanced Plant Phenotyping Laboratory—Adding new capabilities to APPL that allow imaging of the belowground rhizosphere

Circular Bioeconomy Systems—Developing the technologies and capabilities for production of bio-based energy, products, and materials for a sustainable, circular bioeconomy

CCSI STARS—Combining ORNL and university partner expertise for projects addressing climate change in the U.S. Southeast

Enzyme Engineering—Engineering enzymes with the latest AI and characterization tools for materials science applications

Integrative Studies of Complex Biological and Environmental Systems—Developing capabilities to assess and enhance biosystem resilience to extreme climatic events

NetZero-ARMADA (Action-Relevant Modeling and Decision Analysis for a People and Nature Inclusive Energy Transition)—Identifying high-resolution pathways to net-zero carbon for regions and communities by deploying action-relevant modeling and decision analysis

Pilot Project: Pioneering Multiscale Biological and Environmental Solutions for a Sustainable Earth—Designing an integrated, multiscale observation-experiment-data-model framework for natural and managed systems

Transformational Decarbonization Initiative—Supporting crosscutting science and technology to address the challenge of decarbonizing the U.S. energy system to address climate change

- **SoilCosm Phenotyping to Counteract Priming for Sequestration—**Analyzing belowground biogeochemical processes using instrumented soil incubation systems

LDRD Seed Awards—Protein Engineering to Multiplex Gas Biosensors, Tracking Disturbance Signals Along River Networks, and Impact of Carbonaceous Particles on Mixed-Phase and Ice Cloud Processes

LDRD Early Career Awards—Joanna Tannous: "Harnessing Fungi to Enhance Soil Carbon Sequestration" and Brian Sanders: "Contrast Probes for Non-Invasive Imaging of Plant Microbe Soil Systems"

Appendix D: Advanced Computing and Data Science

STRATEGIC INFRASTRUCTURE OBJECTIVE 1:

Create reconfigurable and scalable data systems for integrated biological and environmental research.

TECHNICAL AND KNOWLEDGE GAPS

In the next decade, the need for reconfigurable and scalable data systems for integrated biological and environmental research will significantly increase. However, there are substantial technical and knowledge gaps that must be addressed to meet this demand. Currently, the absence of standardized protocols and interoperability among various data systems obstructs the smooth integration of diverse datasets. This issue directly impacts our ability to improve data management, accessibility, interoperability, and analysis, which is a key focus of our approach. Secondly, there is a scarcity of expertise in handling and interpreting large-scale, intricate data. This gap hinders our ability to develop a predictive framework that can establish a connection between changes in metabolism and their impact on the ecosystem. Lastly, the swift advancement of technology surpasses the development of robust, adaptable data systems. This gap affects our ability to develop coupled data storage and decision-making capabilities appropriate for the range of temporal and spatial scales needed to address scientific problems. Addressing these gaps is vital to fully exploit the potential of these data systems in propelling biological and environmental research forward.

APPROACH

We will improve data management, accessibility, interoperability, and analysis with a focus on faster analysis and integration of biological and environmental data. Developing a predictive framework that can establish a connection between changes in observed parameters and their impact on the experimental environment is another focus. We will develop coupled data storage and decision-making capabilities appropriate for the range of temporal and spatial scales covered by our science. We will also investigate methodologies to make experimental and observational data public and available to models, through data assimilation and uncertainty quantification, in near-real-time.

5-YEAR GOALS

- Develop a demonstrative system that makes data (from observations, experiments, and relevant online sources) available to models through autonomous data collection, assimilation, assurance, and analysis, in near-real-time.
- Define common components in autonomous data workflows and pipelines to enable experimental and observational decision-making (i.e., decisions to sample a parameter, change frequency of parameter data collection, etc.) for select projects.
- Leverage AI expertise to design and test a Retrieval-Augmented Generative system for data management.
- Integrate specific projects with the Retrieval-Augmented Generative system for project-specific, autonomous data management.

10-YEAR GOAL

- Leverage the Retrieval-Augmented Generative system and large language model (LLM)–based utilities (developed via Objective 3) to establish a highly customized autonomous data management system to facilitate biological and environmental research.

Build a multiscale modeling and data analysis capability with high-performance computing systems, including exascale computers, to accomplish environmental and biological research at extreme scales.

TECHNICAL AND KNOWLEDGE GAPS

We possess a diverse range of capabilities for utilizing HPC systems for multiscale data analysis. However, to fortify our leadership position in an integrated, kilometer-scale modeling capability using DOE's exascale computer, strategic investment is required. This investment encompasses dataset preparation, model interface design, and performance optimization, along with scalability demonstration with exascale computers.

APPROACH

We will collaborate with the Grand Challenge Theme leadership to delineate project scope, which includes data preparation, simulation, and analysis, to advance Exascale computer-ready applications. Concurrently, we will formulate technical and recruitment strategies, as well as implementation plans for **Grand Challenge Themes**.

5-YEAR GOALS

- Demonstrate the integration of the kilometer-scale ELM with the ATS or other hydrology models for the North American region.
- Develop an extreme-scale toolkit for visualizing and analyzing results from these same kilometer-scale coupled models.
- Design AI foundation models for environmental modeling with billions of parameters to handle hundreds of variables.
- Develop a computational framework that leverages HPC, including exascale computing, for model parameterization and structural uncertainty quantification.
- Use exascale computing, AI foundation models, and uncertainty quantification technology to improve our understanding of the primary mechanisms that regulate carbon storage in terrestrial ecosystems and water cycle dynamics.

10-YEAR GOAL

- Develop a comprehensive capability with exascale computing, AI foundation model, and uncertainty quantification technology to support integrated kilometer-scale simulations from the ELM coupled with the ATS. This will enhance our understanding of the primary mechanisms that regulate carbon storage in terrestrial ecosystems and water cycle dynamics under the conditions of ongoing climate change. It will also shed light on potential scenarios for climate change mitigation.

Generate context-aware, trustworthy large language models as a foundational capability to facilitate biological and environmental research.

TECHNICAL AND KNOWLEDGE GAPS

We have begun to incorporate AI and ML into biological and environmental systems research, yet we lack the necessary strategies and expertise to fully exploit AI's potential in all aspects of model–data–experiment integration. AI foundation models can accelerate simulations by a factor of one thousand, paving the way for comprehensive uncertainty quantification analysis and future climate projections and mitigation. LLMs exhibit remarkable efficiency in reducing time-consuming tasks in daily scientific research, including customized data collection, code generation, and data analysis and archiving. Given that existing LLMs are based on generic information, there is a need to create a curated information archive (consisting of papers, websites, technical reports, and data resources for BER research), fine-tune the LLM for user-friendly responses, and engineer prompts to enhance communication with the model for generating trustworthy responses.

APPROACH

Collaborating with the four **Grand Challenge Themes** will be essential to establish an autonomous workflow for data collection, storage, dissemination, and use. We will develop and utilize customized, purpose-driven language learning models (LLMs) to advance our science. We will establish a comprehensive Retrieval-Augmented Generative System for environmental and biological research that will serve as the backbone for knowledge integration and enable AI-generated, science-backed, trustworthy responses.

5-YEAR GOALS

- Establish autonomous workflows for data collection, generation, analysis, and archiving in collaboration with the **Grand Challenge Themes**.
- Refine LLMs to generate scripts and utilities customized for domain-specific requests.
- Develop an LLM utility to assist users in understanding the code structure and coding patterns.
- Develop and launch a comprehensive Retrieval-Augmented Generative System for environmental and biological research.
- Achieve significant improvements in code cleanup, documentation creation, and learning from exemplary code to generate similar code segments for user review.
- Begin integrating the new system into existing research and data analysis workflows.

10-YEAR GOALS

- Fully integrate the Retrieval-Augmented Generative System and LLM-based utilities into all relevant research and data analysis workflows.
- Significantly improve the speed, accuracy, and efficiency of research and data analysis, and explore ways to further advance them.

Appendix E: BIOLOGICAL AND ANALYTICAL TOOLS

STRATEGIC INFRASTRUCTURE OBJECTIVE 1:

Advance high-performance mass spectrometry integrated with separation and/or imaging capabilities.

APPROACH

Our focus will be on developing analytical capabilities with biological science objectives. A key question we will address is: how can mass spectrometry be leveraged to resolve molecular and biochemical complexity above- and belowground while capturing dynamic functional diversity?

5-YEAR GOALS

- Achieve higher-throughput automated measurements of proteins and metabolites and better integration of various omics approaches by:
 - Creating a suite of mass spectrometry capabilities tailored to samples and analytical needs.
 - Acquiring sample prep and handling infrastructure to enable centralized and state-of-the-art capabilities.
 - Developing edge computing processes for connecting high-value equipment to data storage and analysis capabilities.

10-YEAR GOAL

- Attain comprehensive characterization and integration at the systems biology level across all molecular machinery (genome, transcriptome, proteome, metabolome, interactome) and structure–function relationships for complex biological systems.

STRATEGIC INFRASTRUCTURE OBJECTIVE 2:

Develop advanced microscopy and imaging methods for high-resolution imaging across time and space and for living systems.

APPROACH

We will develop molecular tags that are compatible with quantum imaging and biological systems. Across imaging modalities, we will improve data storage, data analysis, and mechanisms to integrate the spatial, temporal, environmental, and biological data needed to realize the potential of systems science.

5-YEAR GOALS

Acquire new instrumentation for atomic force microscopy to enable high-resolution characterization of biomolecules and single cells.

- Integrate optical microscopy with other analytical modalities to provide highly correlated systems biology datasets.
 - Develop solutions to bottlenecks in data transfer, storage, and analyses to provide timely feedback.

10-YEAR GOALS

- Validate quantum imaging approaches to reduce phototoxicity and enable longer-term monitoring of living biosystems.
 - Advance systems-level characterization of biological systems using multiscale and multi-modal approaches.

STRATEGIC INFRASTRUCTURE OBJECTIVE 3:

Apply synthetic biology to customized transformation and manipulation of microbial and plant genomes.

APPROACH

We will implement new automated high-throughput microbial transformation systems toward methods development, optimize computational resources to streamline data analysis, and develop a standardized data management/data sharing system, including a centralized DNA sequence and strains database to restructure our research efforts and provide data for AI and ML efforts toward genotype to phenotype discovery.

5-YEAR GOALS

- Reduce cycle times for standardized application of synthetic biology tools across model and non-model systems.
- Develop a centralized database for data sharing, strains, and sequences for streamlined engineering and AI/ML efforts for engineering and genotype–phenotype discovery (in coordination with the **Advanced Computing and Data Science Crosscut**).

10-YEAR GOAL

- Establish routine application of advanced genetic tools in novel non-model plants and microbes and communities toward engineering targets.

STRATEGIC INFRASTRUCTURE OBJECTIVE 4:

Support high-throughput plant phenotyping via the Advanced Plant Phenotyping Laboratory.

APPROACH

We will continue to build state-of-the-art computational tools for broad image data analysis and release trait data at the completion of an experiment for a more real-time dashboard of current results. We will expand our analytic pipelines for all modalities with validation methods and unit checks using similar APIs to help researchers gain biological insights they cannot achieve any other way (in coordination with the **Advanced Computing and Data Science Crosscut**).

5-YEAR GOALS

- Utilize deep learning for direct inference from image data.
- Establish automated population-level studies, comparisons of mutants, and use of synthetic biology for biosensors pipelines.
- Integrate data with simulation models for model-experiment support and design build-test-learn cycles with synthetic biology.

10-YEAR GOAL

- Fully integrate the APPL with microcosms, mesocosms, and remote-sensing field imagery.

STRATEGIC INFRASTRUCTURE OBJECTIVE 5:

Advance methods to examine genome annotation via protein structural methods.

APPROACH

We will leverage and integrate existing expertise in metagenomics, bioinformatics, microbiology, and plant biology while expanding our expertise in supercomputing applied to modeling protein structure and function to improve gene and genome annotations, a current bottleneck in experimental biology. We will experimentally verify protein structures using DOE photon and neutron user facilities, including SNS and HFIR at ORNL, as required.

5-YEAR GOALS

- Implement genome-scale, AI-based, structure and function prediction approaches for bona fide gene annotation using supercomputing resources.
- Develop efficient computational pipeline for high-throughput annotation.
 - Expand/build experimental biochemistry capabilities to test predicted protein functions.

10-YEAR GOAL

- Achieve routine and highly accurate AI-based gene annotation across a broad spectrum of organisms, including microorganisms, fungi, and plants.

STRATEGIC INFRASTRUCTURE OBJECTIVE 6:

Develop remote sensing approaches with real-time integration.

APPROACH

We will develop a comprehensive ecological remote sensing program focusing on three primary areas: technology, systems-wide applications, and data-model integration. This will include novel remote sensing technologies and platforms that incorporate off-the-shelf sensors to enable real-time aerial and *in-situ* observations and new methods for estimating biological processes at various scales (in coordination with the **Advanced Computing and Data Science Crosscut**).

5-YEAR GOALS

- Build new remote sensing capabilities, focusing on ground to aerial drone scales.
- Test various drone technologies, including imaging spectroscopy, LiDAR, and thermal.
- Develop a framework for streamlined data processing and integration of cross-scale real/near-real-time observations from field, sub-orbital, and on-orbit sensors.
- Strengthen the collaboration with government space agencies (e.g., NASA and the European Space Agency) and the private sector to leverage advanced imaging and sensing technologies.

10-YEAR GOAL

- Establish a world-leading cross-scale remote sensing program with novel capabilities for scaling ground-based to orbital observations.

STRATEGIC INFRASTRUCTURE OBJECTIVE 7:

Research and development of bio-derived materials for a sustainable future.

APPROACH

ORNL has the advantage of being home to a fully functional Manufacturing Development Facility (MDF), which is a world leader in advanced manufacturing research and development and is driving the adoption of new materials, software, and systems for clean energy applications. One of its objectives is to use renewable and recyclable materials such as bio-derived materials used in construction/building, carbon fiber research, and much more. Bio-based materials, derived from renewable sources such as plants, algae, or even waste products, offer a compelling alternative to traditional petroleum-based materials. These materials are inherently sustainable, as they have the potential to reduce greenhouse gas emissions, minimize reliance on finite resources, and mitigate environmental pollution. Moreover, bio-based materials can often be biodegradable, further reducing their ecological footprint. Some challenges must be addressed in the area of developing bio-derived materials: for example, these materials may require specialized equipment, technologies, and sourcing strategies.

5-YEAR GOALS

- Research new bio-derived products, focusing on recycling and renewable technologies.
- Test various properties, including electrical, chemical, thermal stability, strength, and not limited to imaging and optical spectroscopy.
- Develop a framework for streamlined data processing and integration of cross-scale real/near-real-time observations from lab to pilot, and industrial scale up.
- Strengthen the collaboration with the private sector to leverage advanced technologies at ORNL.

10-YEAR GOAL

- Establish a world-leading cross-scale chemical, electrical, and structural sensing program with novel capabilities for bio-derived materials manufacturing and applications.

SUMMARY

The challenges of the 21st century—ranging from climate change and ecosystem health to sustainable energy production—demand a coordinated effort across multiple disciplines, organizations, and agencies. ORNL is uniquely positioned to lead such a multi-organizational initiative due to its world-class scientific contributions in microbial and plant sciences, spanning ecosystems, organisms, cellular processes, and genetics. Our reputation for scientific excellence is further supported by state-of-the-art infrastructure, including resources like the Frontier supercomputer, the SNS, and APPL.

Through established collaborations with leading scientists worldwide—such as in multi-organizational projects like NGEE Arctic, SPRUCE, FACE-MDS, and CBI—ORNL is poised to drive a vision that enables the scientific community to access groundbreaking tools and technologies. These advancements will support DOE's mission to further the most critical areas of biological research, addressing global challenges in energy, climate change, and ecosystem resilience.

Implementation and Resource Plan

We have developed a methodical Implementation Plan for the 10-year BESSD Strategic Plan to make our innovative ideas actionable. The implementation process relies on teams working together in an integrated way, especially the **Transformational Crosscutting Capability** teams with the **Grand Challenge** teams. It is action-oriented, based on finite implementation steps that continue to push our progress along. Finally, it is founded on continuing the strong communication, inclusivity, and cross-directorate collaboration that characterized the strategic planning process.

In a separate ORNL internal document, we outline a detailed Implementation Plan, which we briefly describe here. The Implementation Plan document describes how Theme Leads have worked with their teams to map out detailed 10-year plans of research to answer each Key Science Question. Some of these research plans can be achieved using current capabilities and technologies, but many will depend on progress in **Transformational Crosscutting Capabilities**. **Grand Challenge Theme** leads have discussed with **Transformational Crosscutting Capability** leads to understand this matrixed interdependency, and the new technologies and methodologies that must be developed to support progress with our Plan.

Support and resources are essential for success. ORNL supports BESSD with the allocation of Laboratory Directed Research and Development (LDRD) funds for program development, scientific research, strategic hires, early career scientist research, and capital equipment purchases (App. C). In addition, BESSD benefits from partnerships in large ongoing foundational LDRD initiatives and collaborative access to user facilities (App. C). Every decision that BESSD makes with respect to allocation of these resources will be guided by the principle of supporting the implementation and execution of our strategic plan and delivering on our commitment to DOE and the nation.

Appendix G:

List of Abbreviations

AGI	artificial general intelligence
AI	artificial intelligence
ATS	Advanced Terrestrial Simulator
BESSD	Biological and Environmental Systems Science Directorate
BMAP	Biological Monitoring and Abatement Program
CBI	Center for Bioenergy Innovation
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
ELM	E3SM Land Model
EPA	US Environmental Protection Agency
HFIR	High Flux Isotope Reactor
HPC	high-performance computing
JGI	Joint Genome Institute
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LDRD	Laboratory Directed Research and Development
ML	machine learning
ModEx	model-experiment
NGEE Arctic	Next-Generation Ecosystem Experiments – Arctic
NVBL	National Virtual Biotechnology Laboratory
OLCF	Oak Ridge Leadership Computing Facility
PMI	Plant-Microbe Interfaces
PNNL	Pacific Northwest National Laboratory
QC	quantum computing
SAGE	Serine recombinase-Assisted Genome Engineering
SANS	small-angle neutron scattering
SAXS	small-angle X-ray scattering
SFA	Science Focus Area
SMART Plants	Sensors, Machine vision, Automation and Robotics for Transforming Plants
SNS	Spallation Neutron Source
SPRUCE	Spruce and Peatland Responses Under Changing Environments
TEM	transmission electron microscopy
USDA	U.S. Department of Agriculture
UT-ORII	University of Tennessee-Oak Ridge Innovation Institute



This Plan represents the thoughts and aspirations of the Biological and Environmental Systems Science Directorate staff and colleagues from across Oak Ridge National Laboratory. The strategy was guided significantly by our Scientific Advisory Committee. The planning process was organized by our Planning Committee and spearheaded by the Theme and Crosscut Leads. Many staff contributed to the writing of this document.

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