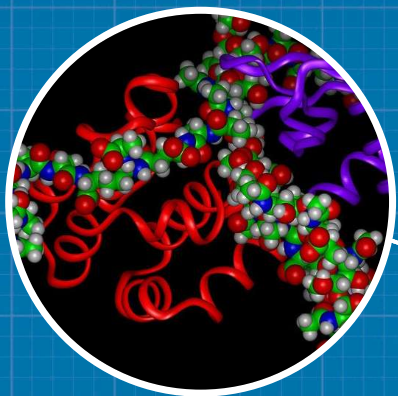
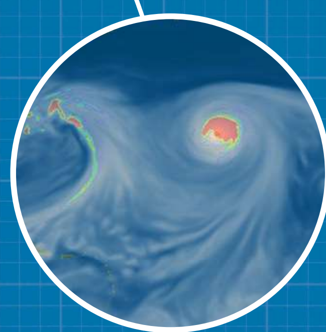


CHAPTER 7

Integrative Science



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Chapter 7

Key Findings and Recommendations

Key Findings

KF7.1 BER leads internationally in integrating climate observations and modeling, and its Atmospheric Radiation Measurement (ARM) user facility and Atmospheric System Research (ASR) program are international leaders of integrative science involving short-term field campaigns.

KF7.2 Sustaining leadership in the integration of the ARM, ASR, and Earth system modeling programs requires both maintenance of cutting-edge observational capabilities and continued access to adequate computational resources.

KF7.3 Additional leadership gains would be achieved by improving integration across the Energy Exascale Earth System Model (E3SM), the Program for Climate Model Diagnosis and Intercomparison, research in Regional and Global Model Analysis, ARM, and MultiSector Dynamics modeling efforts.

KF7.4 The DOE Bioenergy Research Centers (BRCs) exemplify interdisciplinary research ranging from detailed molecular analysis to ecosystem modeling.

KF7.5 DOE's Environmental Molecular Sciences Laboratory (EMSL), Joint Genome Institute (JGI), and light source user facilities, along with their numerous collaborators, are international leaders in integrating omics research, molecular and structural analysis, and systems biology.

KF7.6 BER is a leader in systems-level understanding such as the linkages between plant microbiomes and ecosystem function.

KF7.7 EMSL successfully integrates atmospheric science and physical chemistry with potential expansion into biological aerosols.

KF7.8 Citation analysis demonstrates integration success: BER-sponsored papers are 1.5 times more likely than non-BER papers to span two BER science areas and 3 times more likely to span three.

KF7.9 BER research could be further integrated by developing opportunities embodied in crosscutting user facility programs such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) project and the Facilities Integrating Collaborations for User Science (FICUS) initiative.

KF7.10 Integrating efforts across U.S. agencies is a formidable challenge leaving unrealized opportunities for further integration across BER's portfolio.

Recommendations

R7.1 Improve BER's capacity for integrative research within and beyond its research portfolio.

- **a.** Solicit support from the National Academies of Sciences, Engineering, and Medicine for synthesizing capabilities, needs, and opportunities across BER-relevant user facilities and field sites funded by DOE and other U.S. agencies to accelerate groundbreaking integrative research.
- **b.** Create sustained funding opportunities across BER, DOE, and other agencies (where possible) to advance a more integrated understanding of biological and environmental systems at multiple scales.
- **c.** Strengthen workforce capacity for integration by better supporting integrative research with targeted funding opportunities, particularly among early career researchers.

R7.2 Advance a more complete understanding of coupled human-natural systems in BER science areas.

- **a.** Include coupled human-natural system dynamics in BER funding opportunities.
- **b.** Launch a multiagency research program to improve integration across both the MultiSector Dynamics and Earth and Environmental Systems Modeling programs.
- **c.** Establish research sites for integrated long-term studies that span genomes to landscapes and the subsurface to atmosphere.

R7.3 Build international collaborations to strengthen BER's global leadership in the genomic, environmental, and climate modeling sciences.

- **a.** Work jointly with other U.S. agencies to develop an internationally coordinated effort that will provide public and private stakeholders with urgently needed climate and environmental data.
- **b.** Explore the potential for coordinating and promoting international collaborations that would leverage BER's investments in the genomic and environmental sciences, including the BRCs.

R7.4 Support integration through existing and new user facilities.

- **a.** Establish a computational synthesis center to support the pursuit of questions that demand targeted integration across disciplines and scales.
- **b.** Dedicate a cross-facilities operational budget to fund integrative science projects spanning multiple BER user facilities.

7 Integrative Science

7.1 Overview of Innovation in BER Research Integration

A key part of DOE's mission is addressing energy and environmental problems through transformative science and technology, which includes discovering and developing new energy systems and understanding and predicting their consequences at local to global scales. Enabling these advances are the fundamental scientific discoveries and tools delivered by the Office of Science. Implicit in DOE's mission is the need to understand the complex, multiscale interactions between energy systems and the environment. Attaining this knowledge requires an integrated research portfolio that promotes understanding and discovery across different subsystems of the overall energy system and enables sustainable prosperity through a vibrant bioeconomy.

As detailed in previous chapters, 45 years of BER science has helped reveal the importance of integration across different disciplines, modes of analysis, and spatial and temporal scales. Valued parts of this understanding derive from coordination with complementary research performed by other DOE programs, U.S. science agencies, the private sector, and strategically chosen international partners. The need for integrated approaches to meet energy and environmental challenges has become especially apparent internationally, with the expansion of coordinated research programs in the European Union (EU), China, Australia, and elsewhere. Many Americans today can recall DOE's origin as an executive branch agency. Enabling the full fruition of future BER research now requires a fundamental widening of perspective, scoping out from a focus on delivering long-term advances within well-delineated mission areas to a comprehensively broader strategy that actively and simultaneously stimulates scientific integration—across BER, U.S. agencies, and in collaboration with international and private-sector partners.

Individual system components reside in a network of subsystems interlinked to comprise larger systems, each with emergent properties difficult to characterize without a fundamental understanding of how components interact across subsystem interfaces. The ability to understand, predict, and ultimately manage the outcomes of these interactions depends crucially on integration—research that reveals the ways that subsystems interact to produce different outcomes. A foundational premise of systems science is that the whole is greater than the sum of the parts, which often are not additive. Therefore, understanding the whole requires integrative research.

This chapter begins by discussing the realization of and further potential for integration across BER's research portfolio. BER integration leadership is then examined using citation analyses, three examples of BER success, and one example of a lost opportunity. Then, three areas are highlighted in which global competition challenges current BER leadership in integrative science. The chapter concludes with recommendations for strengthening BER's leadership into the future. Discussions throughout draw on evidence gathered from citation analyses and multiple interviews with leading national and international experts.

7.2 BER Leadership

7.2.1 Citation Analysis Results

A topical analysis of more than 150,000 publications that were identified independently in Chapters 2–5 (to assess leadership in four BER science areas) indicates that BER is no stranger to integration. Among these publications, BER-supported articles are 1.5 times more likely than non-BER articles to contribute to two of the four science areas and 3 times more likely than non-BER articles to contribute to three of the four science areas (see Fig. 7.1, p. 106). In total, over 18% of BER-supported publications spanned at least two science areas.

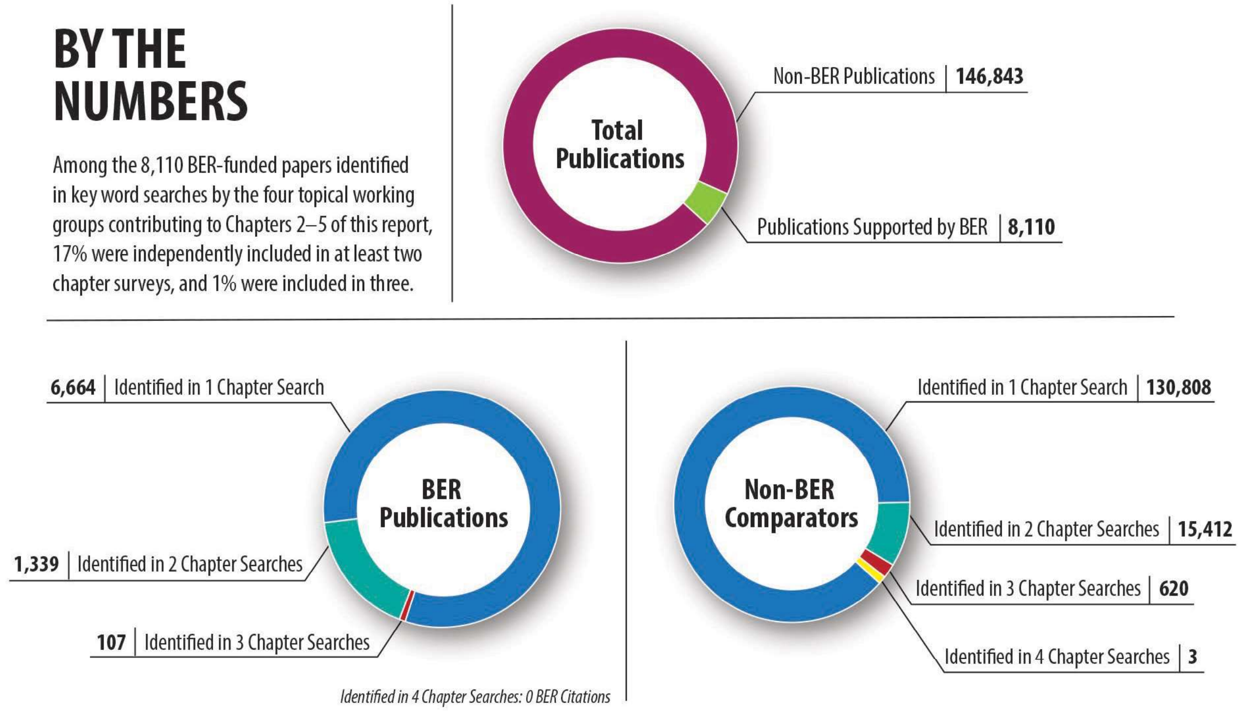

Fig. 7.1. BER Publications Cross Multiple BER Research Areas More Frequently than Non-BER Publications. A review of all BER and non-BER publications analyzed for this report (four separate topical areas for Chapters 2–5) indicates that BER publications are more likely to span two to three areas than non-BER counterparts.

7.2.2 BER Exemplars

This section highlights three successful examples of BER leadership in cross-disciplinary integration: (1) the Bioenergy Research Centers (BRCs), (2) grand challenge research efforts in biogeochemistry and membrane biology at the Environmental Molecular Sciences Laboratory (EMSL), and (3) the climate modeling and MultiSector Dynamics programs. Also featured is a counterexample from the Facilities Integrating Collaborations for User Science (FICUS) program that demonstrates the need for further effort. Examples are drawn from interviews with leading researchers who provided opinions about the current integration status across BER's portfolio and ideas for promoting further integration, including international efforts. Interviewees were chosen among thought leaders across a geographically diverse pool that spans the breadth of BER's research portfolio and institutions, including both university- and national laboratory–based individuals at multiple career stages and with broad knowledge of international programs.

Success Story 1: Integrated Research in Bioenergy—the BRCs

Bioenergy research—as pursued by BER—is inherently integrative, providing foundational knowledge to sustainably produce, deconstruct, and convert plant biomass to a range of fuels, chemicals, and other bioproducts that are otherwise produced from fossil fuels. The bioenergy pipeline stretches from field to product and thus requires expertise from plant, microbial, chemical engineering, and environmental sciences and spans scales from the molecular to landscape.

Ultimately, this knowledge must be integrated to supply industry with the fundamental science underlying effective biomass crops; agronomic practices; and biomass processing, deconstruction, conversion, and separation technologies. Together, this knowledge delivers economically viable alternatives to current fossil fuel–based products that in turn provide valuable climate and economic benefits.

Fig. 7.2 Snapshot of Collaborative Efforts Within the Great Lakes Bioenergy Research Center. GLBRC exemplifies the collaborative reach of DOE's Bioenergy Research Centers, as demonstrated by the center's publications. More than 60% of GLBRC papers since 2017 involve collaborations with multiple coauthors from non-BRC institutions across the country (green) and world (orange). [Courtesy GLBRC]

Interviewees agreed that BER's BRC program exemplifies the integration needed to advance a future bioeconomy. The BRCs have collectively excelled in driving multidisciplinary, multi-institutional collaborations on common science problems that are often difficult to arrange on an *ad hoc* basis among independently funded principal investigators (PIs). Underpinning these qualitative assessments are BRC publication metrics showing a high proportion of collaborative papers that cross laboratory and institutional bounds, both U.S. and international. For example, more than 60% of publications from the Great Lakes Bioenergy Research Center (GLBRC) are coauthored by multiple PIs from different laboratories; a similarly high proportion of these papers include coauthors from geographically dispersed non-BRC institutions (see Fig. 7.2, this page). The scientific value of such collaborations is underscored by the tendency of these multi-investigator papers to appear in journals with higher impact factors (see Case Study: DOE Bioenergy Research Centers, p. 16).

Success Story 2: User Facilities as Integrative Research Hubs

BER funds three unique user facilities integral to advancing its research objectives: the DOE Joint Genome Institute (JGI), Atmospheric Radiation Measurement (ARM) user facility, and EMSL (see Ch. 6: Enabling Infrastructure, p. 83). BER recognizes the value of these facilities as scientific hubs that can unite facility expertise and capabilities with teams of scientists from across the nation to tackle some of the program's biggest research challenges. For example, in the early 2000s, BER formally launched two grand challenge research efforts at EMSL—one in biogeochemistry and the other in membrane biology—to foster innovation and discovery through large multidisciplinary teams collaborating on EMSL-anchored research. These 3- to 5-year grand challenges brought together multidisciplinary teams of scientists from more than 20 U.S. institutions to investigate significant questions in energy and the environment. The membrane biology effort (see Fig. 7.3, p. 108) focused on membrane proteins in cyanobacteria, important photosynthetic microorganisms in the world's oceans. The biogeochemistry effort probed the fundamental question of how subsurface metal-reducing bacteria interact with and transfer electrons to the mineral surfaces on which they live. By all measures, these efforts successfully demonstrated integrative team science using a BER facility as a research hub. Raymond

Fig. 7.3. Team Science Success in Tackling Grand Challenges. Integrative efforts that unite DOE user facility capabilities and the expertise of principal investigators from different laboratories and institutions have been an effective (if infrequent) strategy within BER to address key biological and environmental questions as part of multiyear research projects. An example is the membrane biology grand challenge project at the Environmental Molecular Sciences Laboratory (EMSL) in the 2000s, which assembled a multidisciplinary team of researchers, including those pictured here. [Courtesy EMSL]

Orbach, director of DOE's Office of Science from 2002 to 2009, lauded both projects' success, stating that "EMSL is already one of the Department of Energy's most successful national user facilities, so it is a fitting place to attempt such ambitious grand challenges, where we can pair large groups of our most talented scientists with our most sophisticated analytical tools to look at very specific and vexing scientific problems. We are hopeful that this approach will become a model for collaborative research at EMSL and other DOE facilities."

Success Story 3: Climate Observations, Modeling, and MultiSector Dynamics to Advance Climate Science Integration

BER has been a lead supporter of U.S. and international research to better understand the longer-term and large-scale impacts of energy use on Earth systems (and vice versa) over the past few decades (see Ch. 5: Climate Science, p. 63). A major aspect of this leadership is BER support of integrative innovations across (1) modeling, observational, and experimental information and insights; (2) disciplinary research programs; and (3) spatial and temporal scales of analysis. The ARM and Atmospheric System Research (ASR) programs' integration of ARM and other measurements to advance global climate observations and modeling is a key example of integrative science leadership (see Ch. 5 and Ch. 6).

Two ongoing, interrelated BER modeling-based programs are particularly notable for successfully integrating research and multidisciplinary information from different projects: the Energy Exascale Earth System Model (E3SM) and the MultiSector Dynamics research program. E3SM integrates advances in Earth system modeling and human systems modeling. For example, the Global Climate Analysis Model (GCAM) developed at Pacific Northwest National Laboratory (PNNL) accounts for dynamic land-use modeling coupled with evolving socioeconomic conditions to better understand the interplay between land use, water use, and the role of human-Earth interactions (see Ch. 5: Climate Science, p. 63). The MultiSector Dynamics research program supports teams of interdisciplinary researchers who are integrating models across multiple scales (global to regional) and sectors (see Fig. 7.4, p. 109). This work is examining how different stressors interact across energy, water, land, and socioeconomic sectors and how they could adapt—especially in response to plausible extreme values in external drivers (e.g., weather, sea levels, and baseline demographics) and internal conditions (e.g., power plant characteristics, irrigation infrastructure, and the locations of people and economic activities).

Opportunity to Strengthen Integration: FICUS

While several integration successes illustrate projects that have advanced BER goals, some counterexamples highlight situations where a lack of integration has led to lost opportunities. Initiated in 2014, the FICUS program inherently reflects BER's interest in integrative science. Through this program, multidisciplinary researchers can simultaneously access resources and user facilities across the DOE enterprise. These include (1) BER's JGI, EMSL, and ARM; (2) the National Energy Research Scientific Computing Center supported by DOE's Advanced Scientific Computing Research program; and (3) beamlines and instruments at the DOE light and neutron sources operated by the Basic Energy Sciences program. Awards linking

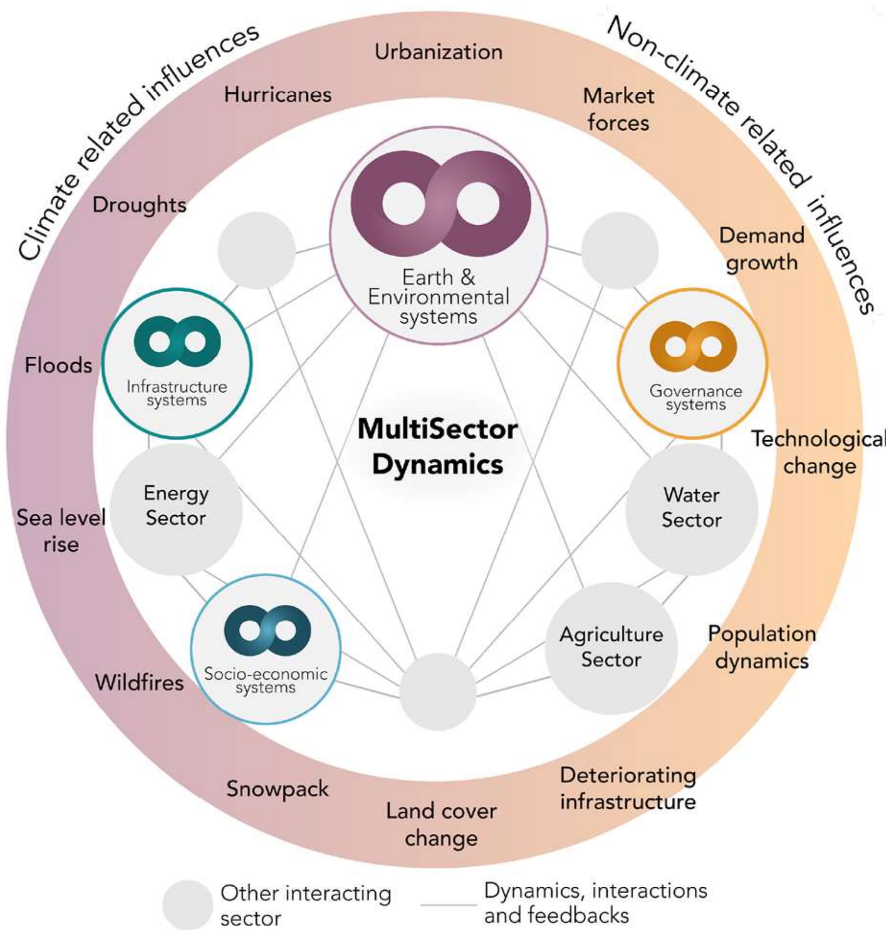

Fig. 7.4. Scope of the BER MultiSector Dynamics Research Program. Sectors are complex "systems of systems" that shape themselves through their dynamic interactions and feedback with broader Earth, environmental, infrastructure, and socioeconomic systems. [Reprinted with permission from Reed, P., et al. 2022. "MultiSector Dynamics: Scientific Challenges and a Research Vision for 2030, A Community of Practice Supported by the United States Department of Energy's Office of Science." *Zenodo*.]

EMSL and JGI's respective capacities for molecular characterization and genomic sequencing have proved the most popular category in the FICUS program. The highly competitive program supports many aspects of DOE mission research, as well as projects funded by other sponsors such as the National Science Foundation (NSF).

Because FICUS encompasses facilities from both BER's Earth and Environmental Systems Sciences Division (EESSD) and Biological Systems Science Division (BSSD), the program could serve as a key point of cross-division integration and collaboration. However, an analysis of funded FICUS projects indicates that none involved interdivisional research. Also, very few focused on flagship EESSD studies—including the Spruce and Peatland Responses Under Changing Environments (SPRUCE) project and the Next-Generation Ecosystem Experiments (NGEEs) in the Arctic and tropics. Similarly, few FICUS projects involve national laboratory–led Science Focus Areas (SFAs), such as the Watershed Function SFA and Belowground Biogeochemistry SFA. Instead, nearly all EMSL-JGI FICUS projects are oriented toward BSSD topics, and most project PIs are associated with BSSD research awards.

BERAC conducted several interviews with BER and JGI-EMSL FICUS awardees to discuss how the program could better support cross-BER integration and scaling from molecular to ecosystem models. These researchers pointed out that ideas spanning BER mission scope do not find an easy path to funding. For example, if a study sought to use a predictive understanding of microbiomes to inform mechanisms in ecosystem models, it would likely need to de-emphasize the ecosystem modeling component to be fundable in BSSD, and vice versa in EESSD.

The separation of BSSD and EESSD research is also geographic. With the exceptions of two sites (Luquillo Experimental Forest in Puerto Rico and SPRUCE in northern Minnesota), BERAC was not able to identify sites with ongoing work funded by both divisions. In the rare instances where PIs have successfully bridged the breadth of BER mission space, the onus is on the researcher to find a way to link capabilities from different DOE user facilities and resources such as EMSL, JGI, the Advanced Light Source, the National Microbiome Data Collaborative, and the Environmental System Science Data Infrastructure for a Virtual Ecosystem. As such, the Working Group sees a ripe opportunity in the FICUS program to link more purposefully across scales; integrate empirical and modeling research; and develop protocols for archiving and associating diverse molecular, biogeochemical, and model output data streams.

7.3 Global Competition

The international scientific community recognizes the value and need for integration. In many countries, funding has flowed to large projects seeking to integrate across disciplines, geographic scales, and borders. Three efforts in particular stand out as examples of international leadership quickly gaining ground on U.S. integrative science efforts.

7.3.1 International Integrated Biology Efforts

Expert interviews pointed to several international research agencies that have developed programs that target integrated biological research; these may serve as illustrative examples for future BER programs. For example, the Research Council of Norway recently considered a Norwegian Center for Microbiome Research that focuses on how microbiomes in diverse systems (e.g., agricultural soil, the rhizosphere, domesticated animals, and engineered ecosystems) affect fluxes of methane and nitrous oxide. The Australian Research Council Centre of Excellence is evaluating a multi-institutional effort in Soil Carbon Systems, with a scope and complexity on par with a BRC. Finally, in Germany, the DFG (German Research Foundation) established so-called Priority Programmes, which provide coordinated 6-year funding for promising research topics. DFG-funded projects must be designed to promote interdisciplinary and multilocation collaboration and networking. The funding scheme includes support for researchers, including early career scientists, and instrumentation. Examples of recently funded DFG Priority Programmes relevant to BER include:

- Emergent Functions of Bacterial Multicellularity
- New Concepts in Prokaryotic Virus-Host Interactions—From Single Cells to Microbial Communities
- Systems Ecology of Soils
- Rhizosphere Spatiotemporal Organisation—A Key to Rhizosphere Functions

The rhizosphere project brings together researchers from several European countries with expertise in rhizosphere research, soil chemistry, plant genomics and physiology, soil microbiology, soil physics, exudate analysis, image and pattern analysis, and modeling. This team is identifying spatiotemporal patterns and underlying mechanisms in plant roots, nearby microbial communities, and soil minerals. They have published several outstanding articles that cross traditional disciplinary boundaries.

7.3.2 Emerging Competitors in Genomic Science

All interviewees pointed to BER's leadership in genomics as a major strength, specifically referencing JGI, which was founded in 1997 to perform sequencing work for the Human Genome Project (HGP). Since then, JGI has contributed substantially to the scientific community's understanding of plant and microbial genomes. In comparison, the Beijing Genome Institute (BGI), founded in 2003, also played an HGP role and gained early attention for its completion of the rice genome. While JGI largely limits its efforts to plants and microbes, BGI has a wider purview that includes animal and disease genomics. BGI is the largest among many strong international competitors to BER's preeminence in genomic science. In fact, several interviewees believe that these competitors are beginning to outpace the United States, but the group's consensus is that JGI, as a user facility, still leads globally in plant and microbial genomic science.

Beyond RNA and DNA sequencing, JGI, EMSL, and BER's structural biology and imaging resources, along with their numerous collaborators, have contributed significantly to advances in systems biology and the understanding of living systems and communities. EMSL has developed unique capabilities that greatly support the BER research community, notably a method for single-cell proteomics. Various BER-supported beamlines and resources at DOE light and neutron sources provide a strong underpinning for BER-relevant structural biology studies, enabling mechanistic insights through an understanding of structure. However, rapid advancements in genomics are quickly rendering once cutting-edge technologies routine or obsolete. Continued efforts thus are needed to ensure that the BER community retains access to innovative technologies and that BER-supported user facilities remain relevant. BSSD and user facility efforts to support synthetic biology research are laudable and offer a good example of the need to tailor research foci within the division as the science evolves. However, several experts raised doubts as to whether BER capabilities could remain cutting-edge as new innovations in genomic technologies emerge.

Because genomic technologies generate "Big Data," support for computational and informatic resources must be an integral part of the overall genomics portfolio. Although BER continues to provide strong support for these resources for microbial genomics, similar resources for plant genomics lag, despite BER's clear leadership in generating plant genomics data.

Interviewees were also in agreement that BER is an established international leader in the growing area of microbiome analysis. Indeed, the importance of the microbiome in human and animal health, plant health and performance, and environmental sustainability is increasingly coming into focus, along with a better understanding of the dynamics of microbial communities in general. Continued and expanded support for microbiome research is required to deepen these insights.

7.3.3 Europe's Destination Earth

On an international level, the European Commission's Destination Earth (DestinE) project stands out as an ambitious new program to supply member countries with interactive climate impact and mitigation strategy tools. Using the concept of digital twins, the DestinE project is integrating continuous observation, modeling, and high-performance global simulations to forecast scenarios of extreme weather events and natural disaster evolution under differing adaptation strategies. The DestinE project will be jointly executed by the European Space Agency, the European Centre for Medium-Range Weather Forecasts, and the European Organization for the Exploitation of Meteorological Satellites to meet three major milestones:

1. Deliver two digital twins focused on extreme natural events (see Fig. 7.5, p. 112) and climate change adaptation on an open-core digital platform by 2024.
2. Integrate additional twins addressing sector-specific targets (e.g., ocean) by 2027.
3. Converge twins on the shared digital platform by 2030.

DestinE will initially focus on serving public stakeholders but will later serve a larger range of users.

The DestinE initiative represents the most ambitious international effort yet undertaken to bring together high-resolution weather and climate forecasts with integrated assessment and environmental science.

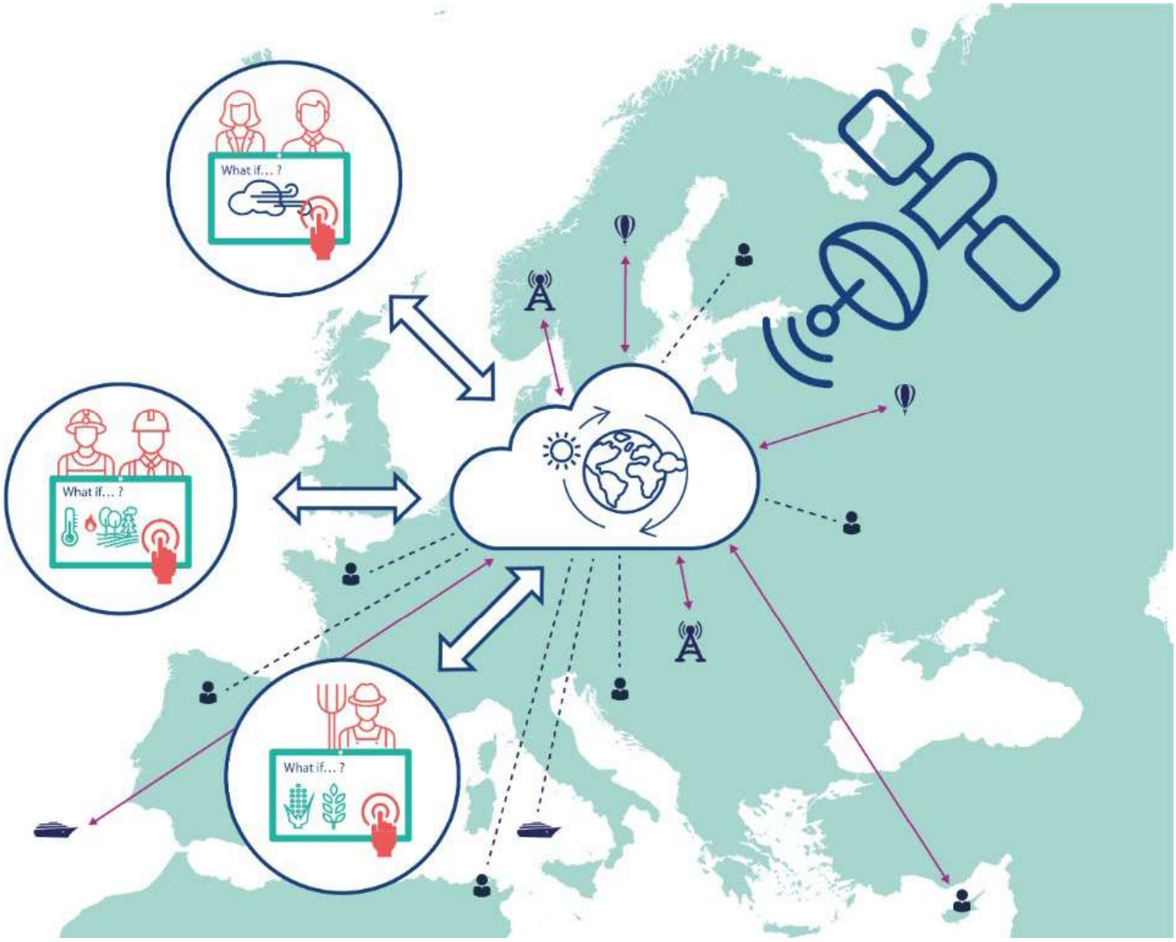

Fig. 7.5. DestinE's Extreme Natural Disasters Digital Twin. This capability will allow decision-makers to more precisely anticipate extreme natural events (e.g., flooding, droughts, and forest fires) and assess risk management strategies for civil protection, agriculture, energy, and transport. [Courtesy European Commission via a Creative Commons license, CC-BY-NC-ND-4.0]

Planning for the project began in 2019 with stakeholder meetings. These meetings highlighted the need for delivering accessible and timely operational weather, climate, and ecosystem data from a central and reliable government source and providing the precise information types needed by both public and private entities for risk-conscious decision-making. The project has selected three European global models as the initial foundation for its operational simulation framework. DestinE will deliver interactive kilometer-scale weather and near-term climate forecasts that rely on continuous data assimilation not only to obtain the most complete and accurate initial conditions but also to improve physics by studying bias correction. At this point in DestinE's development, no involvement in the Coupled Model Intercomparison Project (CMIP) is planned.

7.4 Strengthening BER Leadership in Integrative Science

This section provides 10 recommendations for strengthening BER's leadership in integrative science within and across the science domains comprising its research portfolio. Recommendations are based on an analysis of existing capacities, interviews with leading

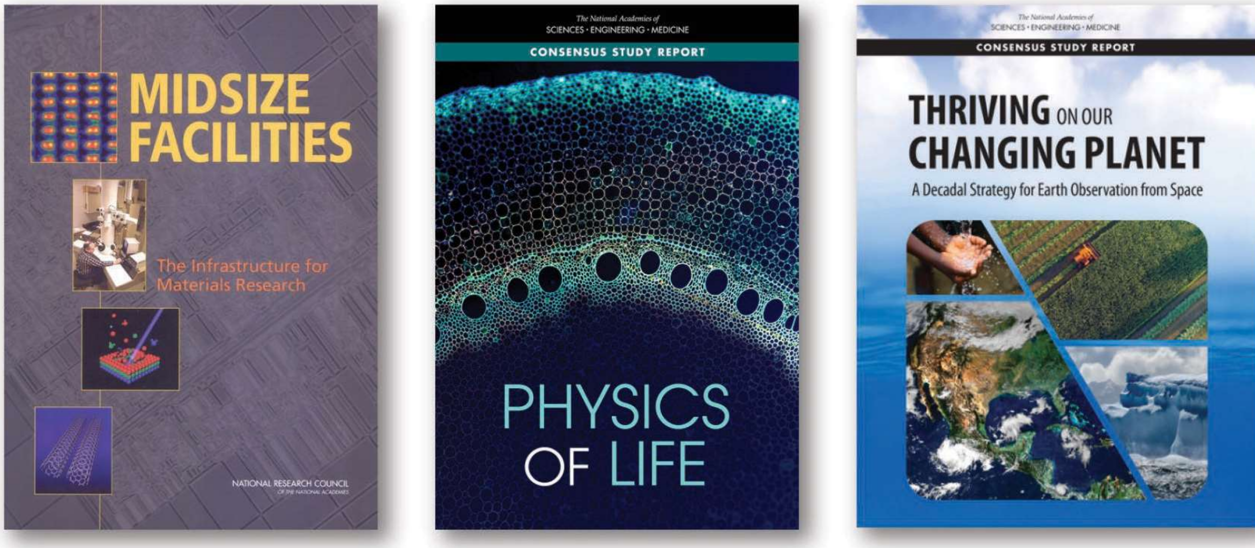

Fig. 7.6. Leadership Coordination and Community Engagement Can Accelerate Integrative Research and Maximize Investment Impact. Examples are shown of recent research reports jointly supported by other DOE offices, peer national agencies, and the National Academies of Sciences, Engineering, and Medicine. [Courtesy The National Academies Press]

scientists, and consideration of findings and recommendations in other chapters; they are grouped into four categories: (1) improving BER's capacity for integrative research, (2) incorporating human agency into the biophysical research for which BER is well known, (3) building international collaborations, and (4) supporting integration through user facilities.

7.4.1 Improving BER's Capacity for Integrative Research

> *Recommendation 1: Solicit support from the National Academies of Sciences, Engineering, and Medicine (NASEM) for synthesizing capabilities, needs, and opportunities across BER-relevant user facilities and field sites funded by DOE and other U.S. agencies to accelerate groundbreaking integrative research.*

To maximize investment impacts, BER's strategy and roadmap for its capabilities should be explicitly coordinated with other DOE offices and peer national agencies. The foundation for such coordination and synthesis of opportunities can draw upon NASEM's successful model for interagency coordination and the use of robust community engagement to collect valuable feedback for long-term planning and coordination at the national level. NASEM reports are not binding on agencies but instead provide a documented foundation for interactive long-term planning across diverse agency investments, commonly with strong community buy-in. One example is a NASEM report jointly supported by NSF and DOE titled "Midsize Facilities: The Infrastructure for Materials Research" (National Research Council 2006; see Fig. 7.6, this page). This one-time document has a much narrower technical scope than the scope collectively represented by BER facilities, so a similar exercise for them would likely necessitate more than one report. Producing such reports would require robustly addressing critiques that suggest formalizing the long-term planning process for facility formation and evolution, as documented in BERAC's 2022 Committee of Visitors report to BSSD (BERAC COV 2022; see also Ch. 6: Enabling Infrastructure, Section 6.4 Future Opportunities, p. 99). Establishing the full breadth of facilities and capabilities to be addressed by the report process could itself provide much-needed multiagency gap-filling and facility right-sizing exercises.

BER facilities contribute to diverse research funded by multiple U.S. agencies. These wide-ranging research domains span, for example, atmospheric science—which is funded by DOE, NSF, NASA, and the National Oceanic and Atmospheric Administration—to biological physics supported by DOE, NSF, and the National Institutes of Health (NIH; NASEM 2022b). The expansive extent of these contributions motivates the need to establish an appropriately broad multiagency stewardship protocol for facilities and capabilities. Initiating multiagency horizon-scanning exercises for facility investment opportunities with National Academies support can potentially surmount long-standing barriers to integrate science areas that have historically posed formidable challenges, such as land-atmosphere interactions (see Ch. 4: Environmental System Science, p. 43).

Recommendation 2: Create sustained funding opportunities across BER, DOE, and other agencies (where possible) to advance a more integrated understanding of biological and environmental systems at multiple scales.

Prior chapters document the considerable expertise and leadership of BER science within the Biological Systems Science Division and Earth and Environmental Systems Sciences Division, ranging from fundamental systems biology to climate modeling. Of course, neither domain stands alone. Within each portfolio there are cross-cutting questions whose answers demand integrative research across and within the two divisions. Within BSSD, for example, a substantial investment in microbiome research advances an integrated understanding of plant-microbe interactions at the genomic level, with the aim of improving plant resilience to biotic and abiotic stresses. This research requires integrating environmental science at field to ecosystem scales.

Similarly, within EESSD, advancing an understanding of complex interrelations among hydrological, biogeochemical, and ecological processes requires genome-level knowledge of the microbial processes that underlie larger-scale responses. Projects like the NGEEs, SPRUCE, and several SFAs provide place-based opportunities to conduct integrative research toward understanding interrelationships within individual ecosystems and landscapes.

For more than a decade, BER has identified understanding biological systems across scales as a grand challenge. However, multiple interviewees observed that the program appears to lack a concerted effort to address this challenge head-on. There are substantial unrealized opportunities for cross-program, cross-laboratory, and cross-agency interactions. For example, several experts noted that relatively few opportunities exist for BSSD-funded scientists to meaningfully participate in EESSD-led place-based projects and, consequently, to connect genome-level organismal science with the biogeochemical and other processes that biological systems fundamentally influence. Within the NGEE program, for instance, one expert noted the difficulties that face proposals with a too-strong genomics focus (e.g., linking soil microbial community structure to biogeochemical function). Likewise, EESSD-funded scientists have few opportunities to meaningfully participate in BSSD-led bioenergy programs, despite the central importance of climate, biogeochemical, and ecological outcomes to a sustainable bioenergy future. As discussed in Ch. 2: Bioenergy and Environmental Microbiomes (see p. 11), the genome-based foundation for sustainable bioenergy development is multiscaled and complex, encompassing the functions of atoms in protein structures, the systems biology of bioenergy crops and their microbiomes, and feedstock conversion technology. However, current research does not equally address the field- and landscape-based portions of the bioenergy pipeline. They are crucial, though, for the technoeconomic and life cycle modeling that will reveal tradeoffs needed to fully evaluate the potential for transitioning energy systems from fossil fuels to sustainable bioenergy sources.

The need for integration across the BER portfolio is not limited to a single grand challenge. Targeting integrative science in each of the grand challenge areas identified in BER's divisional strategic plans and BERAC reports (BERAC 2010, 2013, 2017, 2018; U.S. DOE 2018a, 2021a) would accelerate efforts to achieve a more-integrated science understanding within and across BER mission areas. Moreover, integrative research is needed not only within BER but also between BER and other DOE programs and federal agencies. For example, BER could strengthen collaborations with DOE programs such as Energy Efficiency and Renewable Energy, Fossil Energy and Carbon Management, and Advanced Research Projects Agency–Energy (ARPA-E) and with federal agencies including the U.S. Department of Agriculture (USDA) and NOAA. This integrative approach could speed the translation of fundamental science (advanced by BER) into applied solutions. Other programs operate in different mission spaces that can complement BER research and vice versa. Thus, intentional integration holds the potential for promoting the unintentional synergies that often arise serendipitously when diverse approaches and intellects address common problems.

Recommendation 3: Strengthen workforce capacity for integration by better supporting integrative research with targeted funding opportunities, particularly among early career researchers.

A vibrant and multidisciplinary scientific community provides the foundation for BER research and must be supported and continually renewed to maintain global leadership. Early career researchers often continue to pursue science problems similar to their postdoctoral research when they start their own independent laboratories. Promoting integrated approaches to address BER grand challenges will help BER capture the research interests of this young cohort of scientists early in their careers. To accomplish this goal, BERAC recommends establishing a grant program modeled after the NIH Pathway to Independence Award (K99/R00). Such a program would specifically target postdoctoral researchers to provide support for initiating integrative BER-relevant research projects that they can continue when they establish their independent laboratories.

7.4.2 Advancing a More Complete Understanding of Coupled Human-Natural Systems in BER Science Areas

Recommendation 4: Include coupled human-natural system dynamics in BER funding opportunities.

Several experts expressed significant concern that BER is lagging behind national and international peer programs in addressing coupled human-natural systems science (see Ch. 4: Environmental System Science, p. 43). Integrating genomic and environmental findings with the human domain is crucial for effectively upscaling fundamental knowledge of biological and environmental systems to information levels that industry and society can use. The same need is equally true for building bioenergy and bioproduct components for the emerging bioeconomy and for understanding the environmental impacts and consequences of climate adaptation and mitigation options. Developing pragmatic, useable solutions requires an integrative understanding of biological and environmental systems that includes society. The current BER portfolio largely lacks this integration, except for the inclusion of economic science in BER-funded MultiSector Dynamics modeling (formerly "integrated assessment modeling"). The MultiSector Dynamics program provides a point of comparison, as well as a source of information and insights, for E3SM-level work, which the research community is now beginning to leverage.

BERAC's proposal for a "scale-aware network of energy sustainability testbeds" in the 2017 BER Grand Challenges report focuses on Earth and human trends and interactions across geographic scales and time horizons (BERAC 2017; see Fig. 7.7, p. 116). Implementing similar approaches into current BER research provides context for appreciating what the program has accomplished since 2017 and motivation for understanding why it needs to aggressively pursue this research direction even more. For example, strengthening the portfolio's human-Earth systems science component will enable the scientific community to fully understand the causes and effects of extreme events (which likely will become more severe in the years ahead) and devise ways to better anticipate and adapt to them. BER leadership would be instrumental in coordinating this effort with other U.S. agencies, the private sector, and carefully selected international partners.

The integration challenge becomes critically important in the face of rapid climate change affecting ecosystem resilience and sustainability. It is now clear that policy changes will not occur

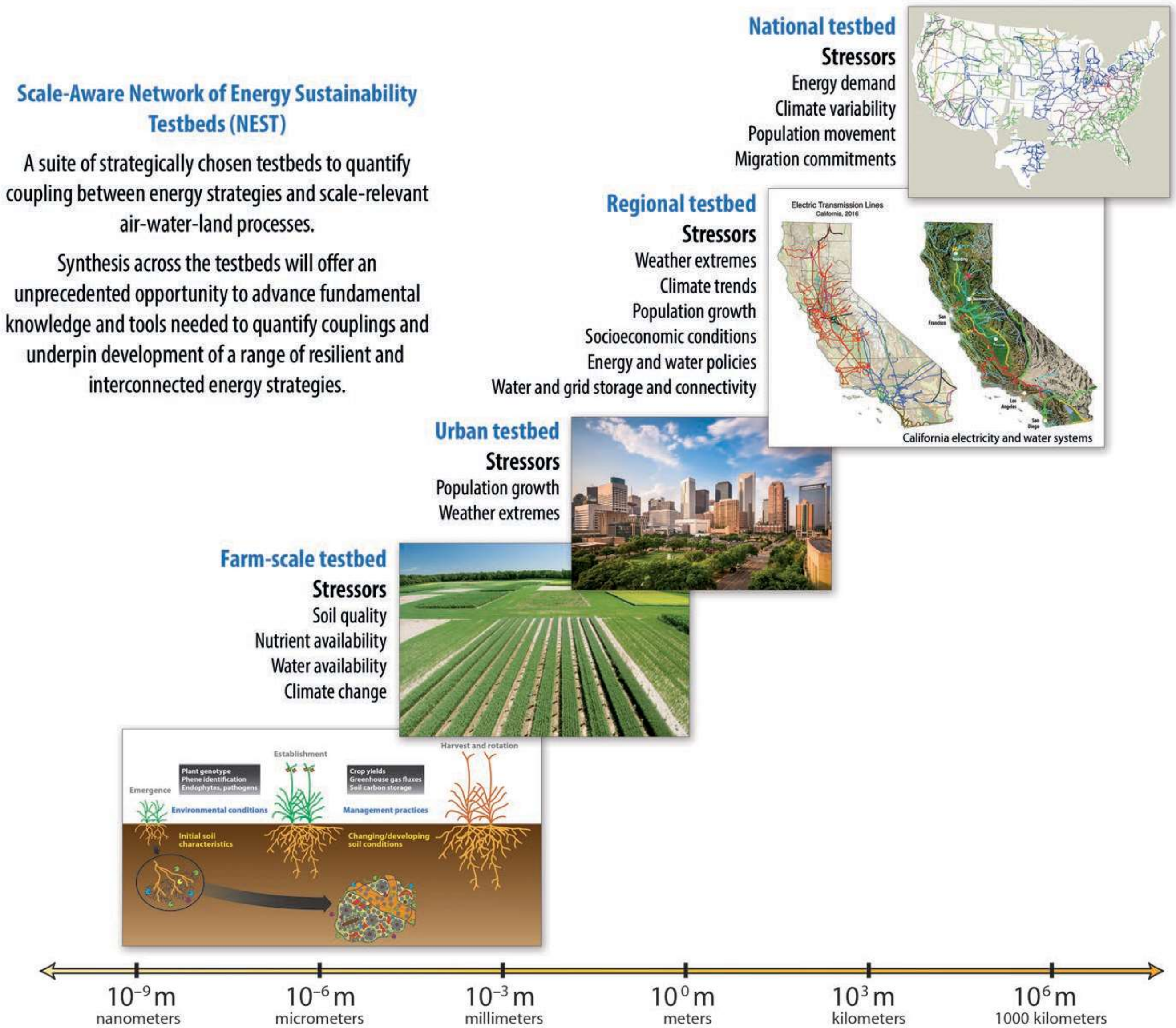

Fig. 7.7. Proposed Network of Energy Sustainability Testbeds. These testbeds comprise a suite of strategically distributed study sites chosen to span a range of scales, each relevant to a particular energy strategy and associated air-water-land forcing. Each testbed could be used for experiments, observations, and modeling to address a unique set of questions. Synthesis across the testbeds could offer an unprecedented opportunity for advancing the fundamental knowledge and tools needed to develop a range of resilient and interconnected energy strategies. [From BERAC 2017]

rapidly enough to prevent significant, negative climate impacts on ecological functions and environmental outcomes. Among other effects, these impacts threaten ongoing efforts, many led by BER, to develop a bioeconomy based on bioenergy crops. Addressing these challenges requires greater action to integrate and coordinate human-natural system science efforts. Clear opportunities exist for cross-agency collaborations, especially with agencies that have a history in fundamental coupled human-natural system dynamics (e.g., NSF) and stakeholder dynamics (e.g., USDA).

Recommendation 5: Launch a multiagency research program to improve integration across both the MultiSector Dynamics and Earth and Environmental Systems Modeling programs.

Feedback from experts indicated a consensus that much could be gained from pursuing even greater integration across climate modeling, analysis, observations, and integrated assessment. Such an approach would span E3SM, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), the SFAs in the Regional and Global Model Analysis and MultiSector Dynamics programs, and ARM. For instance, interviewees suggested improving two-way communication between the climate modeling community and the integrated assessment and MultiSector Dynamics community (e.g., in the physical, behavioral, and economic dimensions of climate damages).

PNNL's GCAM team has long been a leader in integrated assessment modeling (IAM), both in the United States and internationally. However, several European teams are now established and competitive in this area thanks to sustained funding from Horizon Europe and its predecessor, the Horizon program. Historically, scientific teams at the U.S. National Center for Atmospheric Research (NCAR) and the U.K. Hadley Center have led in integrating Earth systems models and integrated assessment models. Nonetheless, BER work on ESM-IAM-MultiSector Dynamics integration challenges is likely to continue advancing the state of scientific understanding in all three communities while simultaneously identifying critical Earth and human system interactions and feedbacks that cannot be studied in isolation within each individual community. Looking ahead, one expert suggested that a program as broad as BER could explore fully coupling impact models with kilometer-scale ESMs. Since the program currently supports both types of work, such efforts could be integrated with activities in other U.S. agencies (e.g., NCAR's WRF-Hydro modeling system). Ultimately, any attempts to achieve this kind of fine-scale integration requires input from the MultiSector Dynamics community, as efforts to understand and manage individual impact sectors often involve interacting changes across many sectors and geographies.

The rest of the world has accelerated these research frontiers through innovative research programs, such as Horizon 2020, sponsored by the European Commission. Among other achievements, this program has placed the energy sector's role in Earth system evolution into an even broader context (see Fig. 7.8, p. 118). Horizon Europe also is a major funder of the Destination Earth project (see Section 7.3.3, p. 111), thus contributing to groundbreaking integration of cutting-edge, high-resolution global simulations and human-Earth system decision-making tools.

To advance its research strategy in this direction, BER should play a major role in establishing a comprehensive long-term research program in integrative human and Earth systems analysis across relevant U.S. agencies, coordinating and collaborating with the private sector and the international research community as necessary. This effort will require additional resources, but given the major societal challenges humanity faces, these resources will be invaluable to the research community and society at large.

Recommendation 6: Establish research sites for integrated long-term studies that span genomes to landscapes and the subsurface to atmosphere.

Place-based research also has the potential to create both direct and indirect opportunities for integration that can enhance understanding of human-natural system interactions. First vetted in the 2013 BER Virtual Laboratory report (BERAC 2013), the Integrated

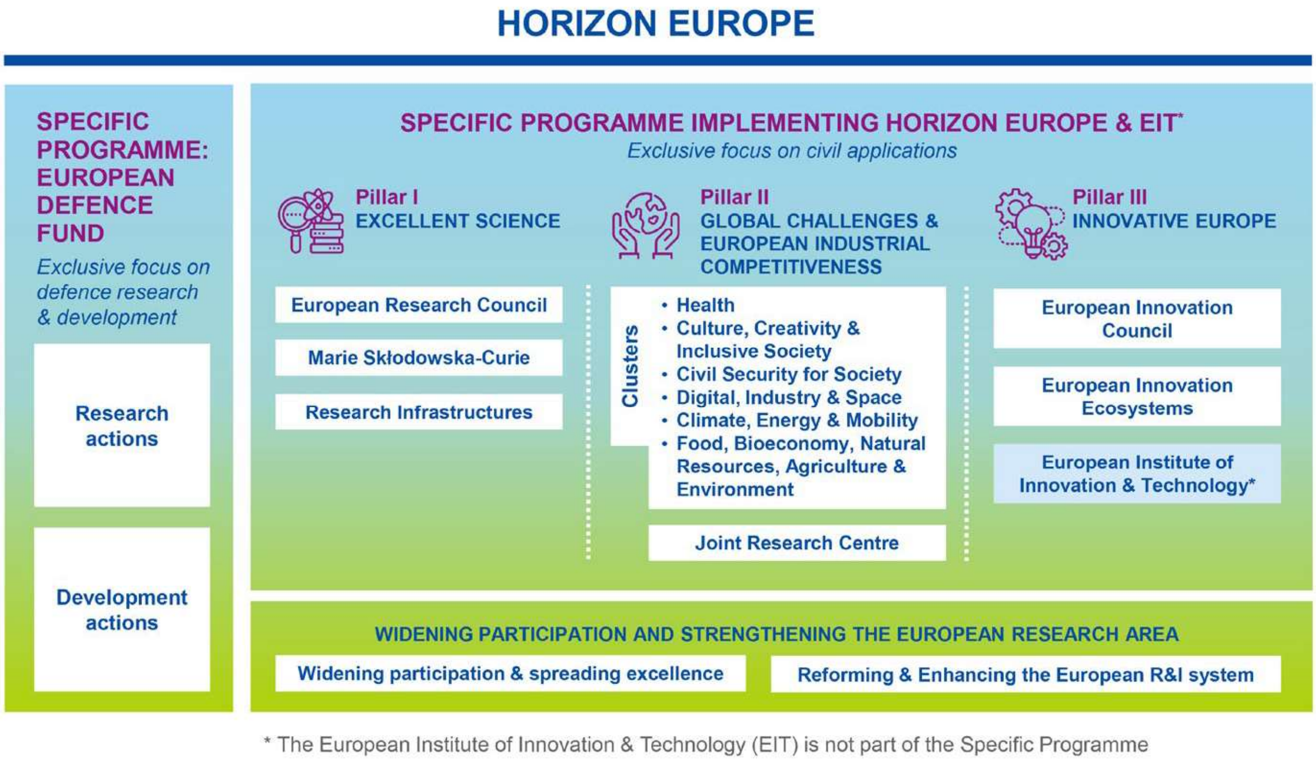

Fig 7.8. The European Commission's Horizon Europe. This program exemplifies a successful, high-level multiagency investment strategy for integrating MultiSector Dynamics and Earth system modeling. Horizon Europe's integrative strategy guides environmental policy, industrial development, and the bioeconomy through coordinated grant and infrastructure support. [Courtesy European Commission via a Creative Commons license, CC-BY-NC-ND-4.0]

Field Laboratories (IFLs) could bring together and expand laboratories in key representative ecosystems to focus on understanding and scaling fundamental biogeochemical, microbial, and plant processes that drive planetary energy, water, and biogeochemical cycles. Building on the success of earlier BER investments in study sites associated with integrated field research challenges, NGEE, AmeriFlux, and ARM programs, IFLs could explicitly engage BSSD and EESSD scientists in linking organisms and microscale processes to large-scale hydrological, biogeochemical, and climate processes.

The integrative power of conducting long-term research at single sites derives from both short-term disciplinary studies that together create a more complete understanding of site-level processes and from interdisciplinary studies intentionally designed to probe boundary-spanning relationships. Computational modeling then provides a means to test the understanding of linkages and extrapolate findings to future climates and locations elsewhere. Colocating such sites at or near long-term research sites established by other agencies could also provide some of the cross-agency integration called for in other recommendations. These agency sites include locations within the NSF National Ecological Observatory Network (NEON), NSF Long-Term Ecological Research (LTER) Network, and USDA Long-Term Agroecosystem Research (LTAR) Network (see Fig. 7.9, p. 119). BER's 2022 funding opportunity announcement (FOA) for Urban Integrated Field Laboratories (DE-FOA-0002581) is a nascent step in this direction.

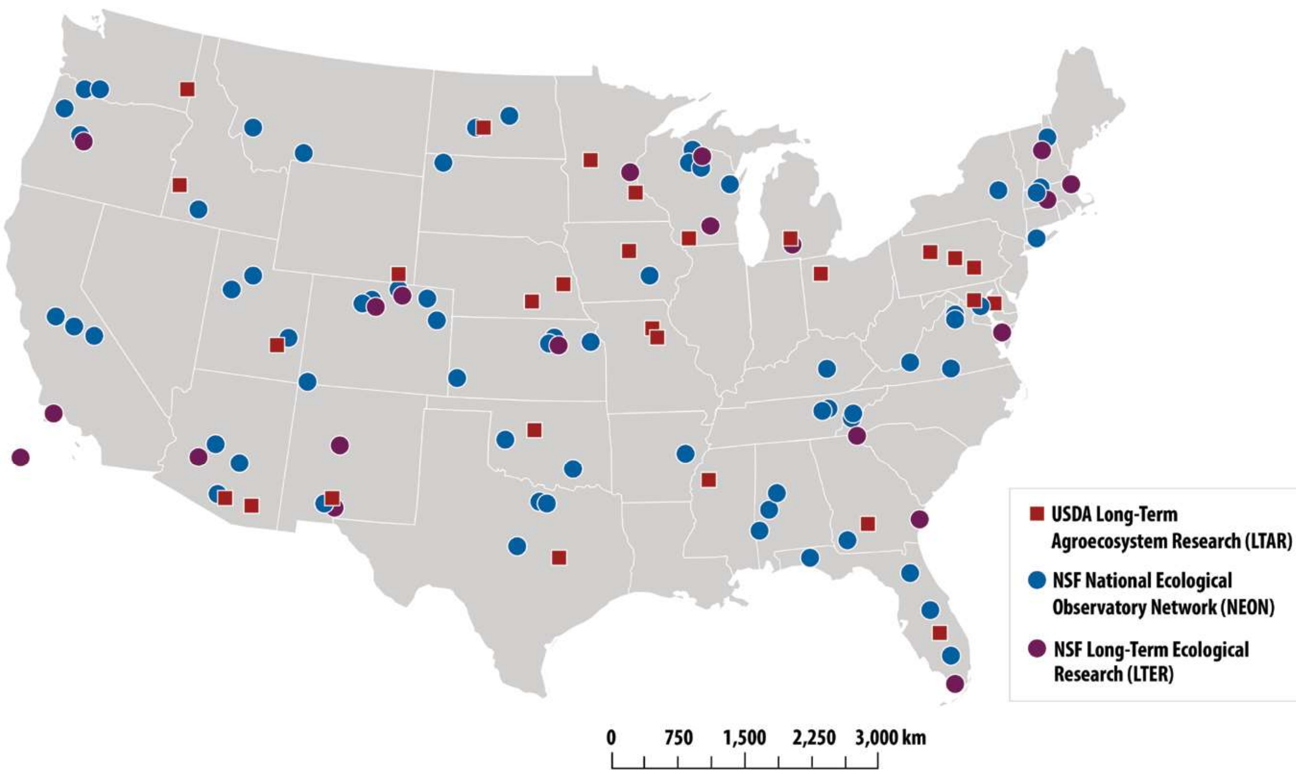

Fig. 7.9. Long-Term, Multi-Attribute Research and Observatory Networks. Distribution of conterminous U.S. sites in the National Science Foundation (NSF) National Ecological Observatory Network (NEON), NSF Long-Term Ecological Research (LTER) Network, and the U.S. Department of Agriculture (USDA) Long-Term Agroecosystem Research (LTAR) Network. DOE-supported research sites that could contribute to such networks include the AmeriFlux core sites (ameriflux.lbl.gov/sites/ameriflux-core-sites/). [Courtesy USDA]

7.4.3 Building International Collaborations to Advance Leadership in the Genomic, Environmental, and Climate Modeling Sciences

> ***Recommendation 7: Work jointly with other U.S. agencies to develop an internationally coordinated effort that will provide public and private stakeholders with urgently needed climate and environmental data.***

A U.S. multiagency-led initiative that effectively combines climate and environmental data to deliver integrative decision-making tools to public entities and industry would represent a maturation of decades of foundational science investment. Although historically useful, single-agency and sometimes duplicative U.S. efforts have not yet been effectively combined to provide the integrative science and decision support envisioned in a project such as Europe's Destination Earth. Currently, the United States seemingly has no comparable integrative strategic plan or funding allocations, but the competitive implications of trailing in this area are likely astronomical. In fact, the Financial Stability Oversight Council recently identified climate change as a potential threat to U.S. financial stability (FSOC 2021).

One expert warned that ceding the integration and interpretation of disparate climate information to private companies not only will duplicate future efforts but also risk unnecessary confusion because proprietary commercial projections are rarely open to scientific scrutiny (Fiedler et al. 2021). Yet BER cannot achieve such a degree of integration in an isolated fashion. To ensure BER's unique modeling capabilities are suited for the rapidly needed integration, BER should engage in multiagency planning as soon as possible.

Recommendation 8: Explore potential for coordinating and promoting international collaborations that would leverage BER's investments in the genomic and environmental sciences, including the BRCs.

As noted throughout this chapter, multiple international efforts aspire to advance the genomic and environmental sciences in ways related to efforts by BER. Though such efforts are almost always complementary rather than duplicative, they are rarely coordinated. A notable exception is FLUXNET, a global network of sites observing carbon, water, and energy exchange between ecosystems and the atmosphere, based originally on BER's AmeriFlux network, which is now a major collaborator. However, international collaborations for observational networks are uncommon but could yield significant synergies that might more rapidly advance BER science. BRC research, FICUS, and other BER programs might all benefit from coordination with international efforts to the extent they can be identified.

7.4.4 Supporting Integration Through Existing and New User Facilities

Recommendation 9: Establish a computational synthesis center to support the pursuit of questions that demand targeted integration across disciplines and scales.

Intentional integration can also arise by providing directed opportunities for cross-disciplinary synthesis. BER has a strong record of workshops and PI meetings that bring together scientists with diverse expertise and perspectives to assess the state of the science in a particular area and make recommendations for progress. Examples include the 2005 workshop that launched the BRCs (U.S. DOE 2006), the 2014 workshop that furthered BSSD investments in plant microbiome research (U.S. DOE 2014b), and various environmental science and climate modeling workshops leading to subsequent FOAs (science.osti.gov/ber/Community-Resources/BER-Workshop-Reports). Although invaluable for evaluating and establishing programmatic needs, these efforts also hint at the capacity for such workshops to synthesize existing cross-disciplinary knowledge in novel ways to rapidly move a field forward. BER could more aggressively pursue such integrative efforts, partly by establishing a user facility dedicated to computational analysis and synthesis, as suggested in past BER reports (BERAC 2018). Such a facility would enable targeted collaborations to synthesize and integrate disparate BER science areas while providing the visualization, computational, and training support that might not otherwise be readily available to users.

Several experts noted that the most exciting science often occurs at the interface of traditional science areas. Consequently, activities to increase such scientific "collisions" would be valuable, as would efforts to more effectively leverage the expertise of BER-supported researchers at universities, national laboratories, centers, and user facilities. Precedents for a facility aimed at these objectives exist in other domains—such as NSF's National Center for Ecological Analysis and Synthesis. Similarly, a BER facility could catalyze creative thinking that will accelerate the integration of genomics and environmental research to address questions that demand targeted integration across disciplines and scales.

Ultimately, this integrative effort would support development of the new bioeconomy and more robust ESMs. BER user facilities already have a strong track record for integration across empirical and observational domains (see Section 7.2.2, p. 106). A similar center providing advanced data visualization and computational support directed toward transdisciplinary integration could dramatically accelerate integration across BER science domains.

Recommendation 10: Dedicate a cross-facilities operational budget to fund integrative science projects spanning multiple BER user facilities.

BER user facilities are hubs of integration and could be further leveraged to enhance research that crosscuts BER programs. For example, while the FICUS program effectively facilitates and streamlines cross-facility access, it does not provide additional resources to those facilities to execute FICUS projects. As a result, the user facilities must balance budgets between FICUS projects and other user projects, thereby hampering integration efforts. Establishing a separate funding line solely for FICUS projects at the user facilities will alleviate funding pressures and lead to increased integration across BER facilities.

7.5 Conclusion

Emphasizing a more integrative BER portfolio, both internally and with external partners, is an opportunity to achieve urgently needed and comprehensive solutions to energy and environmental problems. Not capitalizing on this opportunity puts these solutions at risk. Within the Office of Science, transformative science and technology capabilities in climate change forecasting and mitigation, sustainable prosperity, and energy transitions are in danger of failing to advance critical U.S. research needs quickly enough. Moreover, all comprehensive solutions fundamentally depend on incorporating humans as drivers across systems and scales, thus requiring integration of human and natural systems science. The recommendations in this chapter are intended to enable BER to continue leading in areas in which it already excels. Perhaps more importantly, these recommendations provide opportunities to deliver the integration of transformative science and technology that is necessary for effectively translating BER science into solutions positioning the country to continue its global leadership in energy transitions and sustained industrial and economic development more generally. To be most effective, this integration is needed not only within BER but also across the myriad DOE programs and other agencies that share and amplify BER's mission.