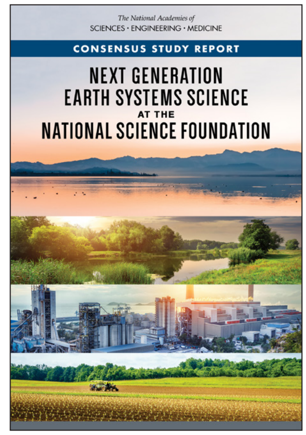
Consensus Study Report

SEPTEMBER 2021

HIGHLIGHTS



Next Generation Earth Systems Science at the National Science Foundation

The complex, dynamic interactions among natural components of the Earth system—the atmosphere, ocean, cryosphere, biosphere, and geosphere that cycle energy, water, nutrients, and other trace substances—have maintained life on our planet for billions of years. Our understanding of these interactions—and their importance for providing food, water, and secure habitat in a changing climate—has grown substantially over the past few decades.

However, today, the expansion of human technologies and activities have come to rival and even exceed the magnitude of natural processes in driving the behavior of the Earth's systems. Our understanding has struggled to keep pace with the rapidity of changes, the magnitude of human influences on them, the impacts on human and ecosystem sustainability and resilience, and the effectiveness of different pathways to address these challenges. Filling these knowledge gaps is urgent, because decisions made today will shape the future functioning of the planet's life support systems.

The National Science Foundation (NSF) has played a key role in Earth Systems Science for several decades, by funding research on atmospheric, ocean, hydrologic, geologic, polar, ecosystem, social, and engineering-related processes. Given the urgency of understanding human-driven changes in Earth systems, NSF will need to sustain and expand its efforts to achieve greater impact.

The time is ripe for an integrated approach that emphasizes research on complex interconnections and feedbacks between natural (e.g., physical, chemical, biological) and social (e.g., cultural, socioeconomic, and geopolitical) processes.

Next generation Earth Systems Science is aligned with NSF's dual mission to "promote the progress of science" by advancing fundamental understanding of the Earth's systems, and "advance the national health, prosperity, and welfare" by building the knowledge foundation vital to tackling Earth systems-related societal problems. As a next step, NSF is encouraged to adopt the following vision and role in support of next generation Earth Systems Science Research:

Vision: A next generation Earth Systems Science that explores interactions among natural and social processes that affect Earth's capacity for sustaining life, now and in the future.

NSF Role: To innovate, advance, and nurture systems approaches to discover how our planet functions and to inform how society can function as part of the Earth's systems for the well-being of communities, regions, the nation, and the world.

Key Characteristics of Next Generation Earth Systems Science

Next generation earth system science should encompass 6 key characteristics:

1. *Advance both curiosity-driven and use-inspired basic research on the Earth's systems across spatial, temporal, and social organization scales.* Fundamental research provides the foundation for understanding both how the Earth's systems function and their roles in supporting societies. Both curiosity-driven research and use-inspired basic research are key to unraveling the complex drivers, interactions, and feedbacks within and across the Earth's systems. A broad interdisciplinary approach is important to grapple with links among nonlinear processes that occur over a vast range of spatial and temporal scales. Use-inspired basic research is also crucial to guide management of societal challenges related to the Earth's systems, such as projections of water, food, and nutritional insecurity, ecosystem changes, growing fire risk globally, and impacts of pollution.

2. *Facilitate convergence of social, natural, computational, and engineering sciences to advance science and inform solutions to Earth systems-related problems.* Natural–social relationships are at the heart of many complex problems facing society and the Earth. Identifying and understanding these multi-directional relationships within and across natural, technological, and social systems in the context of the societal problem at hand involves a robust integrated science. Convergent research provides a means to develop that integrated science by framing research questions from a societal problem perspective; fusing knowledge and approaches from natural, social, computational, and engineering sciences at the outset; and incorporating perspectives of those within and outside of the scientific community.

3. *Ensure diverse, inclusive, equitable, and just approaches to Earth Systems Science.* Who participates in defining and studying the Earth's systems influences how well we understand these systems. Incorporating broad perspectives, values, and experiences into all stages of research—including from those who have been historically excluded from Earth Systems Science—and ensuring an inclusive healthy workplace culture will result in more relevant research questions, more new ideas, more creativity, and more capacity. It will also help ensure that scientific advances yield benefits to all sectors of society.

4. *Prioritize engagement and partnerships with diverse stakeholders to benefit society and address Earth systems-related problems at community, state, national, and international scales.* Stakeholders play important roles in advancing Earth Systems Science knowledge and using those insights to set policy and make practical decisions. For example, engaging stakeholders such as engineers, resource managers, nongovernmental organizations, and local communities in shaping research questions is essential for developing knowledge that can be put into practice at community and larger scales. Stakeholders may also co-produce knowledge with scientists, generating scientific discoveries and improving data products. Partnerships among government agencies and private companies expand the pool of knowledge, observations, and computational resources that will help advance next generation Earth Systems Science and speed innovation and solutions.

5. *Use observational, computational, and modeling capabilities synergistically to accelerate discovery and convergence.* The observational, computational, and modeling infrastructure must work collectively to support convergence in Earth Systems Science. Observations and monitoring reveal changes in the Earth's systems. Data from diverse sources are assimilated into models that represent natural- and social-system processes and their interactions across the Earth's systems. Computation provides the framework for putting together the complex pieces of Earth Systems Science, supporting data collection and analysis, generation of forecasts, and interpretation of model results.

6. *Educate and support a workforce with the skills and knowledge to effectively identify, conduct, and communicate Earth Systems Science.* The workforce in Earth Systems Science must maintain strong disciplinary knowledge and skills, while also developing interdisciplinary and transdisciplinary science skills and practices that will help tackle problems at the intersection of natural and human systems. Necessary skills and practices include systems thinking, integration and application of human dimensions, complex problem solving, computational and analytical skills, spatial and temporal reasoning, communicating to diverse audiences, and the ability to work ethically in diverse teams.

NSF should create a sustained next generation Earth Systems Science initiative that both furthers scientific understanding of the Earth's systems and supports solutions to Earth systems-related problems. An integrated initiative that incorporates the six key characteristics requires sustaining and expanding NSF's current practices. The objective is to harness existing capabilities and create new approaches by placing increased emphasis on use-inspired and convergence research while maintaining strengths in curiosity-driven Earth Systems Science; enhancing the participation of social, engineering, computational, and data scientists; and strengthening efforts to include diverse perspectives in the research and engage with stakeholders.

Opportunities and Barriers to Establishing Next Generation Earth Systems Science

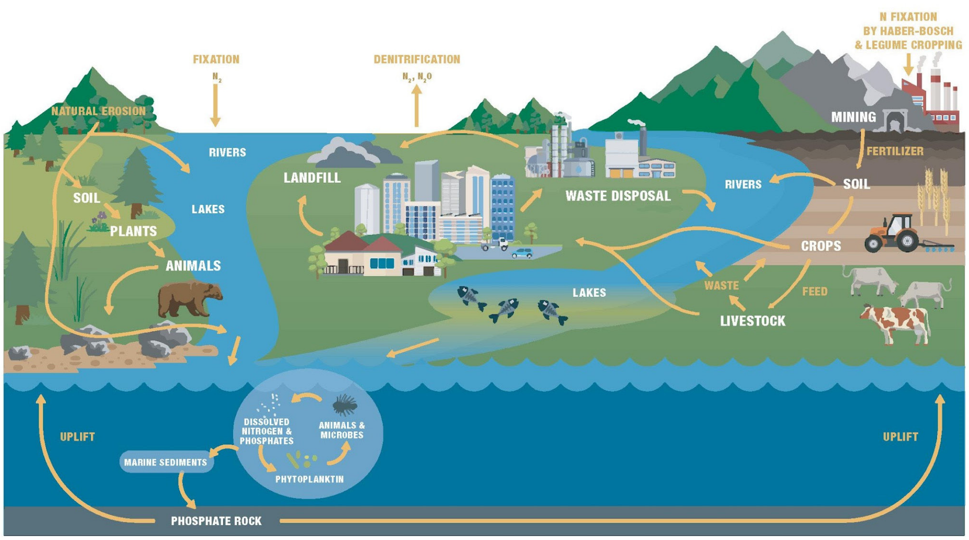
Our ability to deepen understanding of how the planet and societies function and to sustainably manage and adapt to future changes rests on knowledge found within and beyond science. NSF needs to create incentives for researchers to overcome different vocabularies, cultures, methods, professional incentives, and power differentials across diverse fields and stakeholder groups, many of whom have not been viewed as equal experts in Earth Systems Science. Currently, academic institutions bear the substantial time and cost of establishing and maintaining relationships with stakeholders, creating a barrier for early career scientists and institutions without substantial resources.

Another barrier to inclusive research is the legacy of exclusion in Earth Systems Science fields. Mechanisms that NSF could use to lower this barrier include supporting programs that produce and support diverse graduates in relevant fields (e.g., Minority Serving Institutions), hiring individuals with diverse perspectives in scientific leadership and program management positions, and encouraging their participation in review panels and research teams.

NSF should remove barriers to convergence research, including facilitating engagement with stakeholders and building transdisciplinary teams. Convergence research for next generation Earth Systems Science requires new modes of interaction across directorates, between scientists, within research teams, and with stakeholder partners. Transdisciplinary teams and relationships with stakeholders develop over longer time frames than a typical research project and may have to be maintained for many years.

NSF should integrate diversity, equity, inclusion, and justice in all aspects of next generation Earth Systems Science, including the determination of research priorities, evaluation of research activities, and development of the workforce. NSF's ability to achieve this goal requires innovative approaches in all phases of research projects, including research into how to structure programs that include co-production of knowledge and other forms of participatory knowledge. In addition to the critical need to foster diversity in scientific leadership, management, and the scientific community, NSF can incentivize scientists to consider diversity of research teams and address the implications of their research on different segments of society in the design, implementation, and outreach of research projects.

Using Next Generation Earth Systems Science to Tame Earth's Food-Driven Nutrient Cycles



In the past, nitrogen and phosphorus flowed according to natural laws, but these nutrients now flow largely according to small- and large-scale impacts of choices that humans and human institutions make about what foods are eaten, how and where that food is grown, and how various forms of waste are handled. Only a transformed Earth Systems Science will be sufficient to guide society toward a more sustainable use of nutrients.

Observing and Computational Infrastructure

Leveraging synergies among observing and computational facilities and infrastructure is critical for supporting convergence research and advancing next generation Earth Systems Science. Connecting these facilities, along with cyberinfrastructure, could augment regional and continental-scale ecology studies, create new user communities, and also help users find relevant data for interdisciplinary and transdisciplinary projects that have an ecological component.

Rapid changes in computing infrastructures, technologies, and system architecture approaches also will influence the development and evolution of next generation Earth Systems Science. For example, the growing desire for more interoperable tools and data necessitates a workforce with research, data analytics, and computer skills.

NSF should promote and support collaboration, instrumentation, cyberinfrastructure, and data-sharing activities among facilities for the production of convergence research for next generation Earth Systems Science. This includes leveraging synergies between cyberinfrastructure and observing facilities, collaborating across science divisions, and working to increase adaptive flexibility as use-inspired research needs evolve.

NSF should provide leadership in the computational revolution by expanding resources (hardware, software, data analytics, and skilled workforce) and ensuring equal access to them. Earth Systems Science will need to advance with the fast pace of changes in computation and observations. Proactive planning to harness this revolution requires engaging computational and data scientists as critical members of the Earth Systems scientific community and ensuring the provision of sufficient computing resources.

Workforce and Training

NSF plays a major role in developing the research workforce for Earth Systems Science, including improving curriculum and instruction at the undergraduate and graduate levels and providing professional development opportunities for practicing natural, social, computer, and engineering scientists, and educators. It also develops programs to increase the diversity of the workforce, as discussed above.

NSF should promote and support the development of the workforce for next generation Earth Systems Science, including undergraduate and graduate students, scientists, and engineers looking to engage in convergence research. Mechanisms include sponsoring established and emerging programs that promote the development and evaluation of the necessary skills and competencies. Exposure to convergence research, transdisciplinary teams, and a diversity of perspectives in undergraduate and graduate training would foster the development of the necessary workforce. Research software engineers and system engineers also need to be considered part of the Earth Systems Science workforce.

COMMITTEE ON ADVANCING A SYSTEMS APPROACH TO STUDYING THE EARTH: A STRATEGY FOR THE NATIONAL SCIENCE FOUNDATION

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report Next Generation Earth Systems Science at the National Science Foundation (2021). The study was sponsored by The National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu.

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