Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

Virtual Workshop on Computing, Data, and Cyberinfrastructure for a Systems Approach to Studying the Earth, Part 2

February 12, 2021; 12:00 pm – 3:00 pm ET

The National Academies of
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Advancing a Systems Approach to Studying the Earth:
A Strategy for the National Science Foundation

Workshop on Computing, Data, and Cyberinfrastructure for a Systems Approach to Studying the Earth, Part 2
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C. Links to Additional Resources & Upcoming Events
1. **Project Website**: https://www.nationalacademies.org/our-work/advancing-a-systems-approach-to-studying-the-earth-a-strategy-for-the-national-science-foundation
2. Upcoming Session: **Workshop on Understanding Education and Workforce in the Context of the Workshop Series** – Date TBD (additional details available soon)
3. Past Workshop Sessions:
    a. **Workshop on Education and Workforce for Earth Systems Science: Framing Session** (Nov. 13, 2020). Details here: https://www.nationalacademies.org/event/11-13-2020/advancing-asystems-approach-to-studying-the-earth-a-strategy-for-the-national-science-foundationworkshop-on-education-and-workforce-for-earth-systems-science-framing-session
    b. **Integrating Earth Systems Science and Engineering: A Virtual Workshop** (Nov. 20, 2020). Details here: https://www.nationalacademies.org/event/11-20-2020/advancing-a-systemsapproach-to-studying-the-earth-a-strategy-for-the-national-science-foundation-integratingearth-systems-science-and-engineering-a-virtual-workshop
    c. **Accelerating Integration of the Social Sciences in the Study of Earth System Interactions: A Two-Part Virtual Workshop** (Jan. 12 & Jan. 19, 2021). Details here: https://www.nationalacademies.org/event/01-12-2021/accelerating-integration-of-the-social-sciences-in-the-study-of-earth-system-interactions-workshop-part-1
    d. **Workshop on Computing, Data, and Cyberinfrastructure for a Systems Approach to Studying the Earth, Part 1** (Feb. 4, 2021). Details here: https://www.nationalacademies.org/event/02-04-2021/computing-data-and-cyberinfrastructure-for-a-systems-approach-to-studying-the-earth-part-1

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Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

Computing, Data, and Cyberinfrastructure for a Systems Approach to Studying the Earth

A Two-Part Virtual Workshop
Part 2: Friday, February 12, 2021, 12:00 - 3:00pm ET

Public Agenda

The National Academies of Sciences, Engineering, and Medicine committee on "*Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation*" has been tasked to develop a compelling vision for a systems approach to studying the Earth in order to inform approaches to integrated research at NSF and to provide guidance as to how NSF can support the research community. The final report will also identify the facilities, infrastructure, coordinating mechanisms, computing, and workforce development needed to support a more integrated approach for studying components of the earth system. This two-part workshop seeks feedback on computational, data, and analytic support for Earth systems research, including guidance on harnessing existing, planned, and future NSF-supported cyberinfrastructure.

Recording of Part 1 can be found here: https://www.nationalacademies.org/event/02-04-2021/computing-data-and-cyberinfrastructure-for-a-systems-approach-to-studying-the-earth-part-1.

Part 2
Friday, February 12, 2021
12:00 - 3:00pm ET

12:00 PM **Welcome and Purpose of Workshop**
Bill Gropp, Committee Member and Workshop Organizer

12:05 PM **AI for Earth**
Bruno Sánchez-Andrade Nuño, Microsoft

Advancing a Systems Approach to Studying the Earth:
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12:25 PM **Climate Modeling**
- *William Collins, Lawrence Berkeley National Laboratory*
- *Tapio Schneider, California Institute of Technology*

12:55 PM **Lessons Learned from Developing a Comprehensive Cyberinfrastructure for Natural Hazards**
Ellen Rathje, University of Texas at Austin

1:10 PM **Workforce Needs**
Susan Winter, University of Maryland

1:25 PM **Break**

1:40 PM **Discussant**
Inez Fung, Committee Member and Workshop Organizer

1:50 PM **Discussion and Audience Q&A**
Moderated by: Jerry Mitrovica, Committee Member and Workshop Organizer

2:50 PM **Wrap-up**
Bill Gropp, Committee Member and Workshop Organizer

3:00 PM **Adjourn**

Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

Speaker Biographies

William Collins is an internationally recognized expert in climate modeling and climate change science. He is the Director of the Climate and Ecosystem Sciences Division (CESD) for the Earth and Environmental Sciences Area (EESA) at the Lawrence Berkeley National Laboratory (LBNL), a Professor in Residence in the Department of Earth and Planetary Science at the University of California and the founding Director of Environmental Resilience Accelerator (Era), a joint initiative between UC Berkeley and Lawrence Berkeley National Laboratory to solve the critical challenges posed by environmental change. Dr. Collins is a Fellow of the American Geophysical Union, American Association for the Advancement of Science (AAAS) and the American Physical Society (APS). Dr. Collins was awarded the DOE Secretarial Honor Award for launching DOE's Accelerated Climate Model for Energy in 2015. Before joining UC Berkeley and Berkeley Lab, Dr. Collins was a Senior Scientist and Chair of the Scientific Steering Committee for the DOE/NSF Community Climate System Model project at the National Center for Atmospheric Research (NCAR). Dr. Collins is a Coordinating Lead Author of the Sixth Assessment of the Intergovernmental Panel on Climate Change (IPCC), a Lead Author of the Fifth IPCC Assessment, and a Lead and Collaborating Author of the Fourth IPCC Assessment, for which the IPCC was awarded the 2007 Nobel Peace Prize.

Ellen M. Rathje is the Janet S. Cockrell Centennial Chair in the Department of Civil, Architectural, and Environmental Engineering and a Senior Research Scientist at the Bureau of Economic Geology (BEG) at the University of Texas at Austin, USA. Her research interests include seismic site response analysis, seismic slope stability, field reconnaissance after earthquakes, and remote sensing of geotechnical phenomena. She has published over 100 papers on these topics and has supervised the research of over 30 graduate students. Her research has been funded by the U.S. Geological Survey, the U.S. Nuclear Regulatory Commission, the U.S. National Science Foundation, the State of Texas, and the United Nations Development Programme. Dr. Rathje is the Principal Investigator for the development of the DesignSafe cyberinfrastructure for the NSF-funded Natural Hazards Engineering Research Infrastructure (NHERI). She is part of the Leadership Team for the TexNet Seismic Monitoring Program, housed at the Bureau of Economic Geology of UT. She also is a founding member and previous Co-Chair of the Geotechnical Extreme Events Reconnaissance (GEER) Association, the pre-eminent organization in the world coordinating geotechnical investigations after extreme events, such as earthquakes and floods. Much of her consulting work is associated with site response and seismic hazard studies for nuclear facilities around the globe, including the Thyspunt Nuclear Site in South Africa, four existing nuclear power plants in Taiwan operated by Taipower, and multiple nuclear facilities at the Idaho National Laboratory. She has been a member of the Board of Directors of the International Association for Earthquake Engineering (IAEE) since 2017 and a member of the NSF Advisory Committee for Cyberinfrastructure (ACCI) since 2019. Dr. Rathje has been honored with various research awards, including 2018 William B. Joyner Lecture Award from the Seismological Society of America and EERI, the Huber Research Prize from the American Society of Civil Engineers (ASCE) in 2010, the Hogentogler Award for outstanding paper from ASTM Committee D18 in 2010, the Shamsher Prakash Research Award in 2007, the Shah Innovation Prize from EERI in 2006, and the Casagrande Award from ASCE in 2002. She was elected Fellow of the American Society of Civil Engineers in 2016.

Bruno Sánchez-Andrade Nuño is a principal scientist at Microsoft's AI for Earth program, building the "Planetary Computer". He has a Ph.D. in Astrophysics from the Max Planck Society. He has led Big Data innovation at the World Bank Innovation Labs, served as VP Social Impact at the satellite company Satellogic and Chief Scientist at Mapbox. Bruno has published the book "Impact Science" on the role of science and research for social and environmental Impact. He was a Mirzayan Science Policy Fellow at the U.S. National Academies of Sciences, engineering, and Medicine and a Young Global Leader of the World Economic Forum.

Tapio Schneider is the Theodore Y. Wu Professor of Environmental Science and Engineering at Caltech and a Senior Research Scientist at JPL. His research focuses on how the climate of Earth and other planets comes about and may change, for example, by changes in atmospheric circulation or cloud cover. To improve climate predictions, he is currently developing next-generation climate models that fuse observations with process models of the Earth system. He was named one of the "Top 20 Scientists under 40" by Discover Magazine, was a David and Lucile Packard Fellow and Alfred P. Sloan Research Fellow, and is recipient of the James R. Holton Award of the American Geophysical Union. He has a Ph.D. in Atmospheric and Oceanic Sciences from Princeton University.

Susan Winter is Associate Dean for Research in the College of Information Studies (iSchool) at the University of Maryland. Dr. Winter joined the iSchool in 2014, after serving as a Science Advisor in the Directorate for Social Behavioral and Economic Sciences, a Program Director, and Acting Deputy Director of the Office of Cyberinfrastructure at the National Science Foundation supporting distributed, interdisciplinary scientific collaboration for complex data-driven and computational science. Dr. Winter has published over 70 refereed articles in journals, conference proceedings, and edited books. She has received 11 competitive grants and serves as an adviser to government agencies. Dr. Winter also serves on the editorial boards of the Journal of Information Technology, Communications of the ACM Viewpoints (Ethics), Information and Organization, and the Online Ethics Center for Engineering and Science (Associate Editor for Computer, Mathematics, and Physical Sciences). She is frequently a program committee member for CSCW, Group, and ICIS. Dr. Winter is the co-director of Center for the Advanced Study of Communities and Information. She has a Ph.D. in Business Administration/Information Systems from the University of Arizona.

PREVENTING DISCRIMINATION, HARASSMENT, AND BULLYING: EXPECTATIONS FOR PARTICIPANTS IN NASEM ACTIVITIES

The National Academies of Sciences, Engineering, and Medicine (NASEM) are committed to the principles of diversity, integrity, civility, and respect in all of our activities. We look to you to be a partner in this commitment by helping us to maintain a professional and cordial environment. All forms of discrimination, harassment, and bullying are prohibited in any NASEM activity. This commitment applies to all participants in all settings and locations in which NASEM work and activities are conducted, including committee meetings, workshops, conferences, and other work and social functions where employees, volunteers, sponsors, vendors, or guests are present.

Discrimination is prejudicial treatment of individuals or groups of people based on their race, ethnicity, color, national origin, sex, sexual orientation, gender identity, age, religion, disability, veteran status, or any other characteristic protected by applicable laws.

Sexual harassment is unwelcome sexual advances, requests for sexual favors, and other verbal or physical conduct of a sexual nature that creates an intimidating, hostile, or offensive environment.

Other types of harassment include any verbal or physical conduct directed at individuals or groups of people because of their race, ethnicity, color, national origin, sex, sexual orientation, gender identity, age, religion, disability, veteran status, or any other characteristic protected by applicable laws, that creates an intimidating, hostile, or offensive environment.

Bullying is unwelcome, aggressive behavior involving the use of influence, threat, intimidation, or coercion to dominate others in the professional environment.

REPORTING AND RESOLUTION

Any violation of this policy should be reported. If you experience or witness discrimination, harassment, or bullying, you are encouraged to make your unease or disapproval known to the individual, if you are comfortable doing so. You are also urged to report any incident by:

- Filing a complaint with the Office of Human Resources at 202-334-3400, or
- Reporting the incident to an employee involved in the activity in which the member or volunteer is participating, who will then file a complaint with the Office of Human Resources.

Complaints should be filed as soon as possible after an incident. To ensure the prompt and thorough investigation of the complaint, the complainant should provide as much information as is possible, such as names, dates, locations, and steps taken. The Office of Human Resources will investigate the alleged violation in consultation with the Office of the General Counsel.

If an investigation results in a finding that an individual has committed a violation, NASEM will take the actions necessary to protect those involved in its activities from any future discrimination, harassment, or bullying, including in appropriate circumstances the removal of an individual from current NASEM activities and a ban on participation in future activities.

CONFIDENTIALITY

Information contained in a complaint is kept confidential, and information is revealed only on a need-to-know basis. NASEM will not retaliate or tolerate retaliation against anyone who makes a good faith report of discrimination, harassment, or bullying.

Updated June 7, 2018

Committee on Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

Ruth S. DeFries (NAS), *Co-Chair*
Columbia University

George M. Hornberger (NAE), *Co-Chair*
Vanderbilt University

Claudia Benitez-Nelson,
University of South Carolina

Asmeret Asefaw Berhe
University of California Merced

Melissa A. Burt
Colorado State University

James J. Elser (NAS)
University of Montana

Courtney G. Flint
Utah State University

Royce A. Francis
George Washington University

Inez Y. Fung (NAS)
University of California Berkeley

William D. Gropp (NAE)
University of Illinois at Urbana-Champaign

Melissa A. Kenney
University of Minnesota

Jerry X. Mitrovica
Harvard University

Constantine Samaras
Carnegie Mellon University

Kristen St. John
James Madison University

Fiamma Straneo
Scripps Institution of Oceanography, UCSD

Duane E. Waliser
Jet Propulsion Laboratory

NASEM "Hub & Spokes" Staff Team

Kerry Brenner, Board on Science Education; Education spoke
Maria Dahlberg, Board on Higher Education and Workforce; Workforce spoke
Tamara Dawson, Board on Environmental Studies and Toxicology; Hub
Lauren Everett, Board on Atmospheric Sciences and Climate & Polar Research Board; Hub, atmosphere and polar spoke
Deb Glickson, Board on Earth Sciences and Resources & Water Science and Technology Board; Hub
Rob Greenway, Board on Atmospheric Sciences and Climate & Polar Research Board; Hub
Brent Heard, Board on Energy and Environmental Systems; Engineering spoke
Anne Linn, Board on Earth Sciences and Resources; Hub, solid earth and water cycle spoke
Lynette Millett, Computer Science and Telecommunications Board; Computation and data spoke
Keegan Sawyer, Board on Life Sciences; Biology, ecology, and natural resources spoke
Emily Twigg, Ocean Studies Board; Ocean spoke
Jenell Walsh-Thomas, Board on Environmental Change and Society; Hub, social and behavioral sciences spoke

Ruth S. DeFries is a professor of ecology and sustainable development at Columbia University in New York. She uses images from satellites and field surveys to examine how the world's demands for food and other resources are changing land use throughout the tropics. Her research quantifies how these land use changes affect climate, biodiversity and other ecosystem services, as well as human development. She has also developed innovate education programs in sustainable development. Dr. DeFries was elected as a member of the U.S. National Academy of Sciences, received a MacArthur "genius" award, and is the recipient of many other honors for her scientific research. In addition to over 100 scientific papers, she is committed to communicating the nuances and complexities of sustainable development to popular audiences through her books "The Big Ratchet: How Humanity Thrives in the Face of Natural Crisis" and "What Would Nature Do?: A Guide for Our Complex World". Dr. DeFries is committed to linking science with policy, for example through her involvement with the Environmental Defense Fund, Science for Nature and People, World Wildlife Fund, and reconciling conservation and development in central India. Dr. DeFries received her Ph.D. in 1980 from the Department of Geography and Environmental Engineering at Johns Hopkins University. She currently serves on the NAS council.

George M. Hornberger is Distinguished University Professor at Vanderbilt University, where he is the Director of the Vanderbilt Institute for Energy and the Environment. He has a shared appointment as the Craig E. Philip Professor of Engineering and as Professor of Earth and Environmental Sciences there. He previously was a professor at the University of Virginia for many years where he held the Ernest H. Ern Chair of Environmental Sciences. He also has been a visiting scholar at the Australian National University, Lancaster University, Stanford University, the United States Geological Survey (USGS), the University of Colorado, and the University of California at Berkeley. His current work focuses on coupled natural-human systems and aims to understand how climate, groundwater, surface water, energy production, food production, and human abstraction of water interact in complex ways. Hornberger is a fellow of the American Geophysical Union (AGU), a fellow of the Geological Society of America, and a fellow of the Association for Women in Science. Dr. Hornberger won the Robert E. Horton Award (Hydrology Section) from the AGU in 1993. In 1995, he received the John Wesley Powell Award from the USGS. In 1999, he was presented with the Excellence in Geophysical Education Award by the AGU and in 2007 he was selected Virginia Outstanding Scientist. He was elected to the American Academy of Arts and Sciences in 2020. He has served on numerous boards and committees of the National Academies, including as chair of the Commission on Geosciences, Environment, and Resources (1996-2000), chair of the Board on Earth Sciences and Resources (2003-2009), and chair of the Water Science and Technology Board (2013-2017). Dr. Hornberger is a member of the U.S. National Academy of Engineering, having been elected in 1996.

Claudia Benitez-Nelson is the Associate Dean Associate Dean for Instruction, Community Engagement, & Research and Carolina Distinguished Professor & Endowed Chair in Marine Studies in the College of Arts & Sciences at the University of South Carolina. As an Associate Dean, Dr. Benitez-Nelson has direct oversight of five departments (Biological Sciences, Mathematics, School of the Earth, Ocean & Environment, Psychology, and Statistics) that encompass over 300 faculty and staff, 300 graduate students, and over 2500 undergraduate majors. Dr. Benitez-Nelson's research focuses on the biogeochemical cycling of phosphorus and carbon and how these elements are influenced by both natural and anthropogenic processes. She is a diverse scientist, with expertise ranging from radiochemistry to harmful algal bloom toxins and is highly regarded for her cross-disciplinary research. Over the past two decades, Dr. Benitez-Nelson has authored or co-authored more than 100 articles, including lead author publications in the journals Science and Nature. She has been continuously supported by substantial, multi-year research and education grants from the National Science Foundation and the National Aeronautics and Space Administration, among others. Her many research honors include the Early Career Award in Oceanography from AGU and Fulbright and Marie Curie Fellowships. In 2015 she was named an AAAS Fellow, and in 2017, was named an ASLO Sustaining Fellow. Dr. Benitez-Nelson is also highly regarded as a teacher and mentor, having received the National Faculty of the Year Award from the National Society of Collegiate Scholars and the University of South Carolina's Distinguished Professor of the Year Award, SEC Faculty Achievement Award, and Outstanding Faculty Advisor of the Year. In 2014, she received the Sulzman Award for Excellence in Education and Mentoring from the Biogeosciences Section of AGU. Dr. Benitez-Nelson is regularly called upon by national and international scientific and policy agencies for her expertise and currently serves or has served as a member of the Advisory Committee to the Geoscience Directorate of NSF, the EPA Science Advisory Board, and the National Academy of Science's Ocean Studies Board. Dr. Benitez-Nelson earned a B.S. in chemistry and oceanography from the University of Washington and a Ph.D. in oceanography from the Woods Hole Oceanographic Institute/Massachusetts Institute of Technology Joint Program in 1999.

Asmeret Asefaw Berhe is a professor of Soil Biogeochemistry, and Falasco Chair in Earth Sciences at the Department of in the Life and Environmental Sciences at University of California, Merced. In addition, she serves as the Interim Dean of the Graduate Division at UC Merced; Associate Editor of Journal of Geophysical Research – Biogeosciences and Elementa. Her research focus lies at the intersection of soil science and global change science. In its most general sense, her research seeks to elucidate how bio-physical and socio-political changes in the environment affect different soil processes and land management. Within in this framework, she is exploring two general issues: (a) how geomorphic processes, anthropogenic disturbances, and climate change affect the dynamics of biogeochemical processes (esp. carbon, nitrogen, and phosphorus biogeochemical cycles) in the pedosphere, and its interactions with the atmosphere and hydrosphere on one hand, and (b) how the landuse choices that humans make and their relations with land are influenced by complex dynamics between socio-politico-economic factors on the other. Her research approaches range from lab- and field-intensive data collection to quantitative analyses and qualitative research methods that attempt to unravel the many facets, causal links, interactions, and feedback mechanisms among different processes in the earth system. In her work, she combines insights from various disciplines. Concepts and methods that she employs in her research are grounded in biogeochemistry, soil science, geomorphology, plant ecology, surface and isotope geochemistry, analytical and atmospheric chemistry, and political ecology. She is the Past Chair and current ex-officio member of the US National Committee on Soil Science at the National Academies; Current member of the Board of International Scientific Organizations; and she is a member of the inaugural class of the US National Academies of Science, Engineering and Medicine's New Voices in Science, Engineering, and Medicine. Asmeret holds a Ph.D. in Biogeochemistry from the University of California, Berkeley, M. Sc. in Resource Development (Political Ecology) from Michigan State University; and B. Sc. in Soil and Water Conservation from University of Asmara, Eritrea. Prior to joining the faculty at UC Merced, Asmeret was a University of California President's Postdoctoral Fellow (2006-2008) at the University of California, Berkeley and at the University of California, Davis.

Melissa A. Burt is the Assistant Dean for Diversity and Inclusion in the Walter Scott, Jr. College of Engineering at Colorado State University. In this position, Dr. Burt, oversees and leads the strategic and implementation efforts for diversity, inclusion, and equity goals across the College. The Office of the Assistant Dean for Diversity and Inclusion focuses on recruitment, retention, and engagement of faculty/staff, and supports the college-wide recruitment and retention efforts of undergraduate and graduate students from historically underrepresented groups. Dr. Burt is also a Research Scientist in the Department of Atmospheric Science at Colorado State University. Her research focuses on the interactions of Arctic clouds, radiation, and sea ice, with interests ranging from cloud-radiation feedbacks, hydrological and energy cycles in climate, and climate change feedbacks. Melissa has a B.S. degree in Meteorology from Millersville University and a M.S. and Ph.D. in Atmospheric Science from Colorado State University.

James J. Elser is Bierman Professor of Ecology of the University of Montana (UM) and since March 2016 has been Director of UM's Flathead Lake Biological Station at Yellow Bay. He also holds a part-time research faculty position in the School of Life Sciences at Arizona State University. Trained as a limnologist, Dr. Elser is best known for his role in developing and testing the theory of ecological stoichiometry, the study of the balance of energy and multiple chemical elements in ecological systems. Currently, Dr. Elser's research focuses most intensively on Flathead Lake as well as mountain lakes of western Montana and western China. Specific studies involve observational and experimental studies at various scales, including laboratory cultures, short-term field experiments and sustained whole-ecosystem manipulations. Previous field sites have included the Experimental Lakes Area in Ontario, Canada; lakes of the Arctic and of Patagonia; lakes, forests, and grasslands of the upper Midwest; and desert springs in Mexico's Chihuahuan Desert. In recognition of his research accomplishments, in 2019 Dr. Elser was elected to the National Academy of Sciences. He has also been named a Fellow of the American Association for the Advancement of Science (AAAS) as well as a foreign member of the Norwegian Academy of Arts and Sciences. In 2012, Elser received the G.E. Hutchinson Award of the Association for the Sciences of Limnology and Oceanography (ASLO), the world's largest scientific association dedicated to aquatic sciences.

Courtney G. Flint is a Professor of Natural Resource Sociology at Utah State University. Her work focuses on the perspectives and collective actions of people in changing landscapes and social and natural resource conditions. She strives to provide sound data to support local and regional decisions on land use, natural resource management, and wellbeing. Her research is highly interdisciplinary as she has worked closely with researchers from water science, engineering, forestry, biogeochemistry, plant phytochemistry, agricultural science and engineering, systems ecology, landscape planning, and other sciences as well as local leaders and representatives of citizen action groups to address complex social-environmental changes. Her current research and engagement efforts emphasize inquiry and assessments related to individual and community wellbeing, as well as the social ecology of rivers in the US Intermountain West. She serves on the Board of Scientific Counselors for the U.S. Environmental Protection Agency as the chair of the subcommittee on Sustainable and Healthy Communities as well as on other advisory boards in Austria and South Africa. Her bachelor's degree is in geography from Northern Arizona University, her master's degree is in geography from the University of Colorado at Boulder, and her PhD is in rural sociology from Penn State University where she also enjoyed a strong working relationship with the US Forest Service's Pacific Northwest Research Station that extended into her post-doctoral research and tenure track position at the University of Illinois at Urbana-Champaign. She moved to Utah State University in 2013 where she is now a Professor of Sociology and a Community Resource Specialist for USU Extension. She directs the Institute of Social Science Research on Natural Resources and serves on the leadership team for the NSF-funded Climate Adaptation Science Graduate Training Program at USU.

Royce A. Francis is an associate professor in the Department of Engineering Management and Systems Engineering at George Washington University. His overall research vision is to conduct research, teaching, and service that facilitates sustainable habitation of the built environment. This vision involves three thrusts: 1.) infrastructure management, including sustainability assessment and risk analysis; 2.) regulatory risk assessment and policy-focused research, especially for environmental contaminants and infrastructure systems; and, 3.) statistical/mathematical modeling approaches to decision support. He unifies these multi-disciplinary interests under the Earth Systems Engineering and Management (ESEM) paradigm for civil/environmental systems design and analysis. In the past year, Dr. Francis's research program has incorporated two new thrusts: i.) Investigating macrocognitive decision making processes for infrastructure resilience; and ii.) Characterizing engineer identity and engineering judgment situated in low-cost air quality sensor network design. Dr. Francis earned the Ph.D. from Engineering and Public Policy and Civil and Environmental Engineering at Carnegie Mellon University, M.S. in Civil and Environmental Engineering from Carnegie Mellon University, and the B.S. in Civil Engineering from Howard University.

Inez Y. Fung is a Professor of Atmospheric Science in the Department of Earth and Planetary Science and the Department of Environmental Science, Policy and Management at the University of California, Berkeley. She studies climate change and the carbon cycle using global-scale numerical models of the Earth System and its components. Fung received her S.B. in Applied Mathematics (1971) and her Sc.D. in Meteorology (1977) from MIT. Among her numerous honors are membership of the US National Academy of Sciences, the Royal Society, London, and Academia Sinica (Taiwan). She was the US lead for the 2014 joint NAS-Royal Society study "Climate Change: Evidence and Causes" and its 2020 update. Fung is a subject in a biography series for middle-school-aged readers, "Women's Adventures in Science", launched by the National Academy of Sciences. The title of her biography is "Forecast Earth". She was also featured in a short YouTube video sponsored by WIRED magazine: "What could happen in a world that's 4 degrees warmer?".

William "Bill" D. Gropp is Director of the National Center for Supercomputing Applications and holds the Thomas M. Siebel Chair in the Department of Computer Science at the University of Illinois at Urbana-Champaign. His research interests are in parallel and high performance computing, software for scientific computing, and numerical methods for partial differential equations. He has played a major role in the development of the MPI message-passing standard. He is co-author of one of the most widely used implementation of MPI, MPICH, and was involved in the MPI Forum as a chapter author for both MPI-1 and MPI-2. He has written many books and papers on MPI including "Using MPI" and "Using MPI-2." He is also one of the designers of the PETSc parallel numerical library and has developed efficient and scalable parallel algorithms for the solution of linear and nonlinear equations. Gropp is a Fellow of AAAS, ACM, IEEE, and SIAM and received the Sidney Fernbach Award from the IEEE Computer Society in 2008. In 2016, the Association for Computing Machinery (ACM) and IEEE Computer Society named Gropp, a professor of computer science at the University of Illinois at Urbana-Champaign the recipient of the 2016 ACM/IEEE Computer Society Ken Kennedy Award for highly influential contributions to the programmability of high-performance parallel and distributed computers. Gropp is a member of the National Academy of Engineering. William Gropp received his B.S. in Mathematics from Case Western Reserve University in 1977, an MS in Physics from the University of Washington in 1978, and a Ph.D. in Computer Science from Stanford in 1982. Gropp has served on several panels and a study for the National Academies, including the Panel on Digitization and Communications Science (2008--2010), the Study Committee (co-chair): Future Directions for NSF Advanced Computing Infrastructure to support US Science in 2017-2020 (2013-2015), the Panel on Computational Sciences at the Army Research Laboratory (2017), and the Panel on Review of Extramural Basic Research at the Army Research Laboratory (2018-2019).

Melissa A. Kenney is the Associate Director of Knowledge Initiatives at the University of Minnesota's Institute on the Environment (IonE) where she directs efforts to build synergy across IonE's broad scientific research portfolio. To achieve this goal, she collaborates with faculty, community partners, the University of Minnesota's systemwide campuses, and the IonE management team to sustain existing and launch new research efforts in support of the strategic plan. Dr. Kenney is an environmental decision scientist with expertise in multidisciplinary, team-based science approaches to solving sustainability and Earth system challenges. Her research program broadly addresses how to integrate both scientific knowledge and societal values into policy decision-making under uncertainty. Her research expertise includes conceptual modeling and decision structuring, indicators, systems analysis, multi-attribute methods, and evaluation of decision support to address environmental policy decisions. These decision support tool and collaborative decision-making processes methods have been applied to a range of topics including participatory global change indicators, setting environmental policy criteria, economic analyses for restoration alternatives assessment, expert elicitation, value of information of indicators, and improving ecological forecasts. Over the past decade, this work has led to more than 50 publications; over $5M in grants awarded; more than 100 invited talks; multiple invited White House events integrating her research findings; and opportunities to translate scientific findings as policy memos or decision support prototypes to federal agencies and the highest levels of government. She was an invited presenter to the National Academies of Science, Engineering, and Medicine (NASEM) Roundtable on Science and Technology for Sustainability on Measuring Progress toward Sustainability and an invited roundtable participant for the Measures of Community Resilience workshop as part of the Resilient America Program. In addition to Dr. Kenney's multidisciplinary scientific research, she has extensive experience in high-level science policy coordination and relationship building between Federal and academic institutions. In her former role as an AAAS Science and Technology Policy Fellow, she played a role in visioning a transboundary climate early warning system in the Columbia River basin, facilitated academic center collaborations via an NOAA and NSF partnership, advised several federal agencies on enhancing their social science research agendas, and recommended methods to quantify the value of Federal programs. In recognition of her public engagement leadership, she was part of the inaugural cohort of AAAS Leshner Leadership Institute Public Engagement Fellows, where she focused on enhancing stakeholder-engaged research to create climate-resilient solutions in the U.S. and Chesapeake Bay region. Previously, Dr. Kenney was an Associate Research Professor in Environmental Decision Science at the University of Maryland and research faculty in the Department of Geography and Environmental Engineering at Johns Hopkins University. She was a postdoctoral scholar with the National Center for Earth-surface Dynamics at the University of Minnesota and Johns Hopkins University. She received a B.A. with Distinction in environmental sciences from the University of Virginia in 2002, and she earned a Ph.D. from Duke University in 2007, focused on integrating water quality and decision models.

Jerry X. Mitrovica is the Frank B. Baird, Jr., Professor of Science at Harvard University. His work focuses on the Earth's response to processes that have time scales ranging from seconds to billions of years. He has written extensively on topics ranging from the connection of mantle convective flow to the geological record, the rotational stability of the Earth and other terrestrial planets, ice age dynamics, and the geodetic and geophysical signatures of ice sheet melting in our progressively warming world. Sea-level change has served as the major, unifying theme of these studies, with a particular emphasis on critical events in ice age climate and on the sea-level fingerprints of modern polar ice sheet collapse. Dr. Mitrovica is a former Director of the Earth Systems Evolution Program of the Canadian Institute for Advanced Research and J. Tuzo Wilson Professor in the Department of Physics at the University of Toronto. He is the recipient of the Arthur L. Day Medal from the Geological Society of America, the W.S Jardetsky Medal from Columbia University, the A.E.H. Love Medal from the European Geosciences Union and the Rutherford Memorial Medal from the Royal Society of Canada. He was recently named (2019) a Fellow of the MacArthur Foundation. He is also a Fellow of American Geophysical Union and the

Geological Society of America, as well as a past Fellow of the John Simon Guggenheim Memorial Foundation.

Constantine (Costa) Samaras is an associate professor at Carnegie Mellon University in the Department of Civil and Environmental Engineering. Dr. Samaras's research spans energy, climate change, automation, and defense analysis, and he directs the Center for Engineering and Resilience for Climate Adaptation. He assesses how technology, policy, and infrastructure system designs affect energy use, system resilience to climate change impacts, economic and equity outcomes, and life cycle environmental emissions and other externalities under uncertainty. He currently serves as the Chair of the ASCE Committee on Adaptation to a Changing Climate. Dr. Samaras is also an adjunct senior researcher at the RAND Corporation. From 2009 to 2014, he was a researcher at the RAND Corporation, and from 1999-2004 was a megaprojects engineer in New York. Dr. Samaras received his Ph.D. in civil and environmental engineering and engineering and public policy from Carnegie Mellon University in 2008, and earlier received a MPA from New York University and a BS from Bucknell University. He has previously served on the National Academies Review of the U.S. DRIVE Research Program–Phase 4 Committee, and on the Committee on Enhancing Air Mobility¬¬–A National Blueprint.

Kristen St. John is a Professor of Geology at James Madison University. She earned her B.S. in Geology at Furman University (1992), and her M.S. (1995) and a Ph.D. (1998) in Geological Sciences from The Ohio State University. Her research extends across two areas: (1) undergraduate geoscience curriculum design and community development and (2) marine sedimentology/paleoceanography. She was the Editor-in-Chief of the *Journal of Geoscience Education* from 2012-2017. She delivered the presentation on the future of geoscience education research in the 2019 *AGU Centennial Plenary: Inspire the Future for the Benefit of Humanity*. She was the lead researcher and editor of the vision and planning report: A Community Framework for Geoscience Education Research. An active researcher in the International Ocean Discovery Program (IODP), she was a marine sedimentologist for several expeditions, and worked on samples from the Arctic, North Atlantic, and North Pacific to investigate the marine record of iceberg and sea ice changes through time. She is the co-chief scientist for the future Arctic Ocean Paleoceanography expedition (Arc-OP, IODP Exp. 377). Her work in scientific ocean drilling and education intersect in two books projects; she is the lead author on *Reconstructing Earth's Climate History: Inquiry Exercises for Lab and Class*, and is collaboratively preparing a new introductory textbook, *Climate Change: A Geosciences Perspective*. She served on the U.S. Steering Committee for Scientific Ocean Drilling, was a co-leader of the IODP NEXT workshop and the IODP workshop on Scientific Exploration of the Arctic and North Pacific. Currently, she is on the U.S. IODP Education and Outreach Committee and the National Academies of Science Polar Research Board. At JMU, she received the General Education Distinguished Teacher Award in 2013, the College of Science and Math Outstanding Teaching Award in 2014, the Research and Scholarship Lifetime Achievement Award in 2017, and the Roberts Endowment for Faculty Excellence Award in 2019. She was recognized as Geological Society of America (GSA) Fellow in 2016.

Fiamma Straneo is a Professor in Polar Climate and Oceans at the Scripps Institution of Oceanography of the University of California San Diego. Prior to joining Scripps, she was a Senior Scientist at the Woods Hole Oceanographic Institution until 2017. She studies the high latitude North Atlantic and Arctic Oceans and their interaction with the atmosphere, sea-ice and the Greenland Ice Sheet. Much of her research has focused on obtaining and interpreting data from the challenging regions at the glaciers' margins. Straneo has led over a dozen field expeditions to the Arctic and Greenland. She has collaborated extensively with glaciologists and ice sheet modelers, and recently chaired the Ocean Forcing Working Group for the Ice Sheet Modeling Intercomparison Project. Straneo is co-chair of the Climate and

Cryosphere Program of the World Climate Research Program, co-chair and founder of the Greenland Ice Sheet/Ocean Science Network (GRISO), a member of the Atlantic Meridional Overturning Circulation Science Team and of the ASOF (Arctic-Subarctic Ocean Fluxes). She is also a fellow of the Leopold Leadership Program and was awarded the Sverdrup Lecture by the Ocean Sciences Section of the American Geophysical Union in 2016. Straneo obtained her Ph.D. in Physical Oceanography in 1999 from the University of Washington, USA, following a Laurea cum Laude in Physics in 1993 from the University of Milan, Italy.

Duane E. Waliser is Chief Scientist of the Earth Science and Technology Directorate at the Jet Propulsion Laboratory (JPL) in Pasadena, California, which formulates, develops, and operates of a wide range of Earth science remote sensing instruments for NASA's airborne and satellite program. His principal research interests lie in Earth system processes, observations and modeling; weather-climate linkages, particularly subseasonal to seasonal (S2S) variability; prediction and predictability; and the Earth's water cycle. His recent foci at JPL involves working within NASA and across agencies to enable and enhance societal benefits from our growing understanding, observing and modeling capabilities of the Earth System. He received a B.S. in physics and a B.S. in computer science from Oregon State University in 1985, an M.S. in physics from UC San Diego in 1987, and his Ph.D. in physical oceanography from the Scripps Institution of Oceanography at UC San Diego in 1992. Past interactions with the Academies include membership in the following three studies: 2010 Assessment of Intraseasonal to Interannual Climate Prediction and Predictability, 2016 Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts, and 2018 Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, as well as current membership on the on the Board on Atmospheric Science and Climate and the Committee on Earth Science and Applications from Space.

Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

https://www.nationalacademies.org/our-work/advancing-a-systems-approach-to-studying-the-earth-a-strategy-for-the-national-science-foundation

Summary

The Earth is a complex system, with myriad interactions and feedbacks among the atmosphere, hydrosphere, geosphere, cryosphere, biosphere, and the individuals, institutions, and technologies that respond to and influence these dynamics. Earth systems research has been conducted for decades. Making further progress will require lowering institutional and cultural barriers to engagement across traditional scientific disciplines and advancing transdisciplinary efforts that foster greater understanding of the interdependencies among the Earth system components. The National Science Foundation (NSF)—including the directorates of Geosciences, Biology, Engineering, Computer and Information Science and Engineering, Education and Human Resources, and Social, Behavioral, and Economics Sciences—seeks to build bridges across these disciplines to significantly advance a systems-level, integrated understanding of the Earth.

Statement of Task

An ad hoc committee of the National Academies of Sciences, Engineering, and Medicine will undertake a study that develops a compelling vision for a systems approach to studying the Earth and identifies facilities, infrastructure, coordinating mechanisms, computing, and workforce development needed to support that vision. All major components of the Earth system will be considered including the atmosphere, hydrosphere, geosphere, cryosphere, biosphere, and the individuals, institutions, and technologies that respond to and influence these dynamics as will their interactions and feedbacks through time. With input from virtual workshops and lessons learned from previous and current approaches to integrated research at NSF, the committee also will provide advice on how NSF can support the research community in meeting the vision and identifying overarching capabilities needed to support a systems approach to studying the Earth.

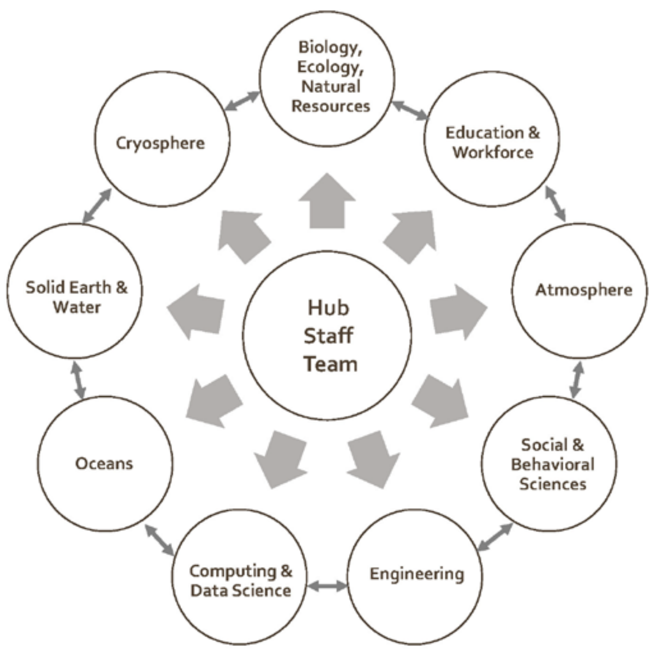
The committee's report will:

1. Describe the potential value and key characteristics of a robust, integrated approach for studying the Earth system.
2. Discuss emerging opportunities and barriers to progress for achieving this vision, including consideration of the interdependencies and synergies among all components.
3. Identify potential synergistic opportunities within current facilities, infrastructure, and coordinating mechanisms to address the overarching capabilities, and recommend ways to leverage these efforts for Earth systems research. Ideas for new approaches, facilities, infrastructure, and coordinating mechanisms may also be considered.
4. Discuss computational, data, and analytic support for Earth systems research, including guidance on harnessing existing, planned, and future NSF-supported cyberinfrastructure.
5. Discuss workforce development to support the personnel needed to advance Earth systems research. This could include undergraduate and graduate education, technical training to support facilities and infrastructure, and increasing diversity and inclusion in the future workforce. This will draw upon scholarship related to workforce development and broadening participation to consider new and existing approaches.

Work Plan

This activity will be carried out by an ad hoc committee of 16 members with expertise in atmospheric science, behavioral and social sciences, biology and ecology, climate science, computer and data science, education and workforce development, engineering, geology and geophysics, hydrology, and oceanography. Members have experience working on integrated research questions and teams, and in taking a systems approach to research. Members have expertise covering both fundamental questions and applications of science. Finally, members who have experience working with major facilities, infrastructure, and mechanisms that support integrated research were selected.

The project is supported by staff from relevant program units across the National Academies, using a hub-and-spokes team design. The "hub" will support overall coordination of the project, ensure cross-Academies engagements, and support report development. The "spokes", in partnership with committee members with relevant expertise, will be the primary conduits among designated expert communities, relevant parts of NSF, and the study.



The spokes will ensure that information and perspectives from each NSF division/directorate are considered and that their NSF points of contact are kept informed throughout the study process. Likewise, spokes will ensure that their relevant expert communities are apprised of the study, have opportunities to engage in the process (e.g., disseminating the call for nominations and requests to provide input to the committee, participating in the workshops), and to learn about the report after it is released (e.g., organizing briefing sessions at relevant conferences, board meetings). Staff serving as spokes may also have other roles during the study, as part of the hub team or as leads for specific parts of workshop planning.

The committee will convene five meetings and a series of virtual workshops. The first few committee meetings were focused primarily on developing the report vision, development of draft report text, and preparation for the workshops. The committee will continue to gather additional information and deliberate in virtual meetings as needed. The committee will also solicit community input on the statement of task through a structured online questionnaire. The questionnaire has been widely distributed to relevant Earth system communities. The questionnaire is available through December 2020: https://www.surveygizmo.com/s3/5888023/ess.

The committee will organize virtual workshops to engage scientists from a range of institutions, disciplines, and career stages. The committee's report may include syntheses of key presentations or discussions from the workshops. Presentation materials and video recordings of the workshop will be made available on the Academies' website, but workshop proceedings will not be produced.

Virtual workshop sessions will provide an opportunity for additional discussion of the draft vision as well as strategies for implementation. Workshop sessions will address crosscutting aspects of implementation, including:

- Education and Workforce Development for Earth Systems Science
- Integrating Earth Systems Science and Engineering
- Accelerating Integration of the Social Sciences in the Study of Earth System Interactions
- Computing, Data, and Cyberinfrastructure for a Systems Approach to Studying the Earth
- Facilities, Infrastructure, and Coordinating Mechanisms for Supporting Integrated Research

The committee, with support from National Academies' staff, will prepare a report addressing the vision and implementation sections of the statement of task. The full report will be subject to standard Academies' review procedures.

Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation

Draft Committee Vision

Vision. To explore interactions among natural and social systems that effect Earth's ability for sustaining life and to provide the scientific foundation for navigating our future.

A research framework to accelerate integrative understanding of Earth systems would incorporate both discovery and use-inspired research on interactions among all Earth system components across all temporal and spatial scales. It would also enable research teams to work seamlessly across NSF's natural and social science, engineering, computing, and education and workforce directorates.

* Discovery science includes prediction
* Use-inspired research includes decision making at individual to societal levels
* Earth system components include the atmosphere, hydrosphere, cryosphere, geosphere, biosphere, and human institutions and infrastructure
* Spatial scales of Earth system processes range from molecules to global, and temporal scales range from milliseconds to millennia, over periods from the geologic past to far into the future.

Exemplars for Workshops

Taming Earth's Food-driven Nutrient Cycles

For eons, Earth's ecosystems were driven by slow processes of weathering and transport of phosphorus from the Earth's crust and of abiotic and biotic fixation of atmospheric nitrogen into soils, freshwaters, and oceans. There, these critical elements were tightly recycled to sustain productivity before returning to the atmosphere (N) or re-burial in ocean sediments. During the past century these cycles have become dominated by human action, primarily to produce fertilizer to drive massive increases in food production during the Green Revolution (IGBP 2000). Thus, the flows of nitrogen and phosphorus are now largely in human hands and operate less like cycles and more like conveyor belts in which nutrients are extracted from atmospheric or geologic reservoirs and transferred to the food system where they accumulate in unavailable forms in soil, are buried in landfills, or are lost from farms, feedlots, and cities into lakes and oceans or the atmosphere (N). In aquatic systems these nutrients stimulate toxic algal blooms and drive ocean anoxia while atmospheric N losses contribute to climate change (Galloway et al. 2008, Elser and Bennett 2011). Many of these processes currently proceed unobserved, as various key pools and flows cannot be detected remotely nor even with *in situ* sensors. Furthermore, dominant fluxes of nitrogen and phosphorus are now taking place in international trade products, such as fertilizers, animal feed, and food commodities. These flows go largely unassessed and currently can only be quantified by indirect inference from sparse and potentially unreliable sources.

We need a revolution in how we study global nutrient cycling so that our use of nutrients can become sustainable, with improved efficiency of use and tight recycling flows that maintain high agricultural productivity, minimize losses to the environment, and sustain nutrient supplies by recycling nutrients in wastes (Elser 2012, Reis et al. 2016). Such a transformation will require deeply convergent research involving geoscientists, biologists, engineers, and social scientists. It will require novel technological development, for gathering better data about nitrogen and phosphorus pools and flows across scales, for improving the efficiency of nutrient use in food production, and for recycling nutrients from various waste streams. It will also require insights from economics, sociology, and political science to understand decision-making around nitrogen and phosphorus in households, regional and national economies, and global trade. In addition, a scientific workforce that has high capacity to operate across diverse disciplines and with diverse stakeholders will be required to address the nutrient challenge.

In the past, nitrogen and phosphorus flowed according to natural laws of chemical speciation, hydrological and atmospheric transport, and biological processing. 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. To grapple with understanding, predicting, and managing a system that has been so wholly transformed, only a transformed Earth system science will be sufficient.

This transformed Earth system science for nutrient sustainability will need to develop along many axes, as exemplified in the following.

- **Computation**. Data-intensive, process-based models are now capable of tracking nutrients as they move at the catchment scale. To understand and predict flows and impacts of nutrients at appropriate scales as more sustainable nutrient strategies are envisioned and implemented, these models must begin to operate at continental scales and interface with climate models that drive critical processes of precipitation and runoff.
- **Observing and experimental facilities**. Currently it is quite difficult to measure key flows of N and P in the environment because of a lack of instrumentation capable of reliable detection of key pools at relevant concentrations in soil, water, and air. Thus, sensor development for deployment from satellites, autonomous rovers, and fixed stations is needed. We also need to reimagine agricultural extension facilities to advance their ability to execute the necessary experiments to evaluate effectiveness and practicality of emerging innovations in improved crops, advanced fertilizers, and soil management. New experimental facilities involving the urban food system are also needed that can test emerging approaches in areas such as urine diversion, resource recovery from wastewater, food waste management, and
- **Natural science**. Sustainable nutrient use in food production will a better understanding of how the genomes of plants drive physiological acquisition and allocation of nutrients so that we can develop "smarter" plants better able to extract N and P from soils and convert that uptake into useful product, all while coping with changing climate. Improving nutrient use

efficiency of crops will likely be facilitated by better understanding and management of soil microbiota. Furthermore, crops will need to be developed to interface effectively with emerging "alternative fertilizers" generated by nutrient recycling pathways.

- **Engineering**. Much inefficiency in nutrient use in the food system arises due to loss of nutrients in rearing of livestock and poultry. Major advances in development of robust and scalable bioreactors are needed so that useful "alternative" fertilizers can be produced by recycling animal waste products. Protecting surface waters from further agricultural intensification may require development of novel materials engineered to sorb nutrients from leak points, such as agricultural drains, rural ditches and streams, and polluted lakes, and to release those nutrients for recovery and re-use.
- **Social science**. Large-scale biogeochemical flows of nitrogen and phosphorus are now driven by higher-level (macroeconomic) and lower-level (behavioral) decisions around food and waste. Major gaps exist in how we understand the macroeconomic drivers of, for example, fertilizer price and the behavioral and cultural drivers of dietary choice (e.g. spread of vegetarianism and veganism). We also need to improve our understanding of when, how, and why the water quality degradation driven by nutrient losses does, and does not, impact decision-making at various levels of governance. Many opportunities exist to advance our knowledge about the sociological, political, economic, cultural, and behavioral determinants of, and feedbacks from, food-driven cycles of nitrogen and phosphorus.
- **Education and workforce**. The nutrient sustainability challenge highlights the need for a transformative approach to education and workforce development, one that fosters systems thinking, epistemic humility, and use-inspired focus. The challenge places a special premium on development of a scientific workforce capable not only of intense disciplinary expertise but also of great facility in collaboration and communication. What new models of science and engineering education are needed to develop not only core expertise but also commitment to translation and impact on real-world needs?

Key literature

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Disaster Exemplar

As natural hazards become more frequent and extreme, disaster losses are rising. Climate change, land use patterns, environmental and infrastructure degradation, socio-economic inequities, and population growth and migration are all exacerbating the potential for loss-producing disturbances in the Earth's system that lead to disasters. Appreciation that disasters are a function of dynamic systems relationships among the Earth's biophysical systems, constructed systems, and human systems is increasingly recognized as essential to inform hazards mitigation, preparation, response, and recovery. Yet, overly technocratic approaches and linear thinking often fail to recognize the complexity of the different processes that lead to disasters and challenges related to predictability. This can lead to "issuing *technical fixes* for what are fundamentally *human problems"* (Peek et al. 2020). Therefore, an interdisciplinary systems approach is urgently needed to spur convergence-oriented research that is problem-focused and generates decision-making and action alternatives to reduce vulnerabilities and increase resilience in the face of increasing disaster risk (Peek et al. 2020; Simonovic 2015).

Because disasters, by their very definition, involve devastating loss to people, it is imperative to integrate an ethical code of conduct into how we conduct disaster research that doesn't exacerbate trauma and vulnerability (Gaillard and Peek, 2019). The needs of local people affected by disasters must be considered in research planning, regardless of whether the focus of inquiry is on predicting physical or natural hazards, infrastructure engineering, or the responses of affected individuals and communities. Disaster research focusing on the Earth's physical processes and vulnerable populations continues to be critically important, but the integration of inquiry on institutional and governance arrangements is critical for effective and equitable disaster-related decision making.

Coordination and cooperation among hazard and disaster researchers and stakeholders is critical. This requires that future disaster researcher must be trans-disciplinary, globally integrated, and evidence-based. Communication and accessibility of scientific evidence related to disasters is essential and will require new focus on training for scientific researchers as well as policy-makers and decision-makers. (Jillson et al. 2019). Convergence-oriented research frameworks are critical to overcome the siloed approaches that have dominated Earth science and disaster research (Peek et al. 2020). Appreciating the heterogeneity in contextual factors that influence disaster event occurrence as well as outcomes requires research and modeling approaches that incorporate complexity and avoid over-generalization.

More frequent and higher intensity wildfires present an example disaster realm in need of multi-dimensional research development as follows:

- **Computation.** One of the greatest challenges in modeling wildfires to inform research and wildfire disaster preparedness is the high level of uncertainty inherent in multiple interacting dimensions of fire-prone landscapes, climate, fire and human behavior, and management. More complex systems-based and agent-based models with greater capacity to handle these complex relationships and uncertainty are needed to address this complexity.
- **Observation and experimental facilities.** While wildfire risks are generally well understood, what is less well understood are ways to implement best mitigation and recovery practices in specific landscapes and social-ecological contexts over time. Thus, observational capacity and facilities that can provide longer-term, place-based research are needed as well as systematic comparison across broader networks of contexts to better understand what is context-specific about fire behavior and management and what is more generalizable.

- **Natural science.** New metrics are needed for understanding fire resilient landscapes and the practices that enhance natural resiliency under dynamic climatic and land use conditions. Improved understanding is needed of fire behavior, including smoke behavior, and how different landscapes respond to different fires over time. High intensity fires affect hydrologic systems and sediment transport as well, thus expanding the disaster nexus to include flooding, debris flows, and beyond.
- **Engineering.** Facilitating fire mitigation and landscape restoration that will reduce fire risk will be enhanced by better understanding of how to effectively engineer fire breaks as well as what can be done with the byproducts of the needed wildland restoration such as biochar and other compromised wood products. Therefore, materials and waste management engineering will play key roles in wildfire management innovation.
- **Social Science.** The human dimensions of wildfire present some of the most challenging and complex aspects of managing this growing disaster realm. From understanding transboundary wildfire governance and the metrics associated with vulnerable vs fire-adaptive communities to better understanding the behavioral economics of fire mitigation and landscape restoration, the social sciences are critically needed to be further integrated into efforts to understand the role of individuals and institutions in wildfire management in these complex social-ecological systems.
- **Education and Workforce.** Integrating systems understanding of the relationship between biophysical fire systems with socio-economic-institutional-technological systems is challenging when researchers are already tracked into disciplinary silos. Complex systems understanding of wildfire is needed much earlier in the educational system which will also help the general public to better understand the ecological reality and potential benefits of fire in certain landscapes in order to mitigate the risks of high-severity fires. The wildfire management workforce needs better understanding of the behavioral psychology of people and institutions to overcome current blind spots in implementing best wildfire and emergency management practices.

Key Literature

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Using the Geologic Record to Probe Climate Sensitivity in a Warming World

Predicting how the Earth system will respond to rising atmospheric CO_2 concentrations is one of the most urgent scientific challenges of our time. The global geologic record provides a crucial lens to 'ground truth' climate models, and paleoclimate research provides insight into key linkages, processes, feedbacks and thresholds in the dynamic and complex Earth system. This effort illuminates coupled perturbations of global temperature, ice sheet stability, ocean circulation, atmospheric dynamics, and sea level change, as well as a range of environmental conditions such as land aridity, ocean acidification, and changes in biodiversity through time. The geologic record yields a rich and diverse archive of Earth's response to, and recovery from:

extreme greenhouse states at the Permian-Triassic boundary and end-Triassic, as well as the Paleocene-Eocene Thermal Maximum (PETM), the most extreme natural warming event in the last 66 million years (but which rates of modern warming rival); longer-term warm states like the Eocene Climate Optimum, during which CO_2 concentrations reached levels that are comparable to that projected for the next century under IPCC high emission scenarios; and the more moderate greenhouse conditions of the Miocene Climate Optimum and Pliocene Warm Period, which were characterized by CO_2 concentrations of ~400ppm—the same level reached during the last decade (Figure X). These records reveal the existence and nature of climate tipping points and they provide important constraints on natural climate variability—both these contributions have pressing relevance for model projections of modern climate.

Tentative figure below. Our aim is to draft a new version that contains this information but also represented key deep-time reference points.

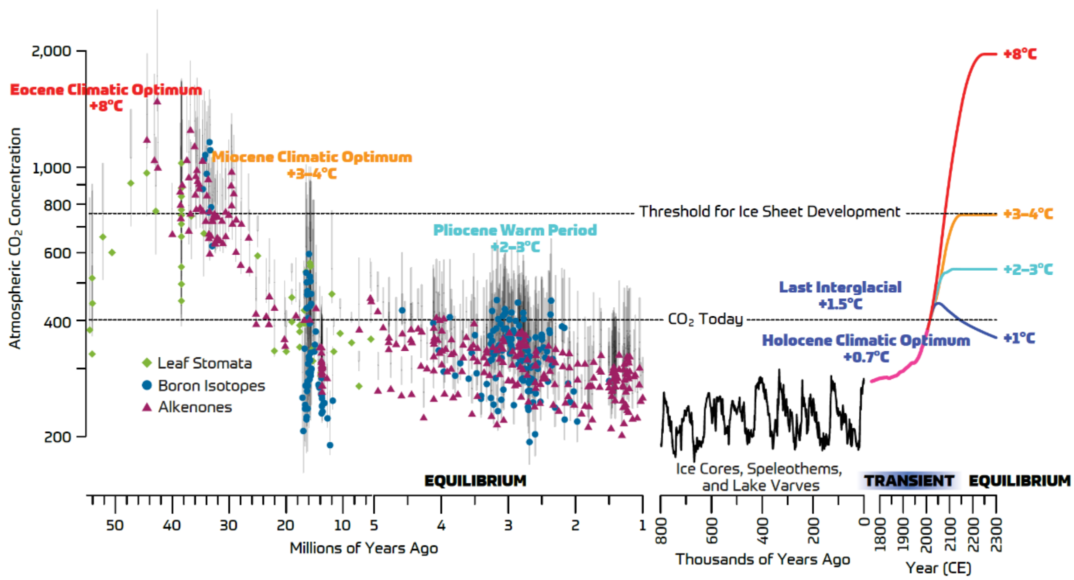

Figure X: Evolution of CO_2 over the past 55 million years, and projected to 2300. Scientific ocean drilling demonstrates the range, rates, and conditions of past climate changes, including the only opportunity to investigate the Earth system response to atmospheric CO_2 exceeding 400 ppm. Drilling provides the critical parameterization and validation of developing paleoclimate models, including paleo ice sheet and sea level reconstructions. From the 2050 Science Framework (2020) based on data from Foster et al. (2017), https://doi.org/10.1038/ncomms14845, Masson-Delmotte et al. (2013), and DeConto et al. (2008), https://doi.org/10.1038/nature07337

Accurate projections of temperature over the next century under various greenhouse gas emission scenarios require rigorous constraints on Equilibrium Climate Sensitivity (ECS), and the IPCC suggests a range of 1.5-4.5ºC warming for a two-fold increase in atmospheric CO_2 concentration. However, recent paleoclimate studies of the early Eocene hothouse provide compelling evidence for a significant state dependence of the ECS, such that warmer climates are characterized by higher climate sensitivity. Thus, there is a pressing need for a comprehensive effort to probe this state dependence using the geologic record of Earth system evolution during ancient warm periods. This initiative would require the development of improved proxies for both CO_2 and global mean temperature, as well as a deeper and more nuanced understanding of the drivers of climate change within the coupled geosphere-cryosphere-hydrosphere-atmosphere system for adoption in climate models. These insights will also be invaluable to complementary investigations of ancient episodes of abrupt climate, which provide important case studies of the response and recovery of ecosystems and global geochemical cycles to large environmental perturbations. The path forward relies on an ambitious densification of scientific ocean drilling—as described in the recent vision document *2050 Science Framework* assembled by that community—and a bold expansion of scientific continental drilling to sample critical climate events in deeper time (e.g., Permo-Triassic periods) and to improve the resolution of terrestrial records, lacustrine and fluvial, of more recent events (e.g., PETM, mid-Miocene). Progress will also come through the development of innovative engineering technologies and improvements in geochronological techniques that will together allow a broader and higher resolution sweep through geological time. Such work will be a global and strongly integrated effort that transcends disciplinary and national boundaries to refine our understanding of the evolution of the Earth system and answer fundamental questions about the future of our progressively warming world.

- **Computation needs**
  - Paleoclimate modeling community needs to establish and maintain a community paleoclimate/Earth-system model based on a state-of-the-art model being used for

modern climate studies, such as the NCAR Community Earth System Model, that evolves with this model but is suitable for paleo-studies (e.g., able to adjust to paleogeographies and be free of other modern-day tunings);

- Continued improvements in ice-sheet modeling and coupled ocean-atmosphere-ice sheet-solid Earth models that can efficiently cover time scales from centuries to multiple millennia;
- Community infrastructure for high performance computing;
- Initiative in machine learning methods as paleo data sets grow (see "education and workforce needs")

- **Observing and experimental facilities needs**
  - Renewal of the International Ocean Discovery Program (IODP) that is slated to end in 5 years. This would require a new drill ship with improved coring capability (i.e, advanced piston coring) and suitable for wide-ranging conditions (temperature, shallow water, deep water, slope coring, deep holes, sea ice). (see "engineering needs")
  - Commitment to a comprehensive continental drilling initiative. The community needs a core repository and analytical facility (perhaps through expansion of the Continental Scientific Drilling Coordination Office currently at the University of Minnesota);
  - Next generation instruments, in particular mass spectrometers, that perform very high-resolution biogeochemical measurements and geochronology (e.g., U-series, cosmogenic, K-Ar, Ar-Ar dating) – this effort will require collaboration with instrument developers.
- **Education and workforce needs**
  - Expansion of curricula in Earth system science that highlights "lessons from the past";
  - Involve scientists and educators in the design of curricula and outreach to communicate the relevance of paleoclimate studies to modern society and to be responsive to community needs;
  - Incorporation of more intensive computer science education in Earth Sciences to build broad expertise machine learning methods and "big data" analysis;
  - The geoscience workforce – including the paleoclimate community - currently does not reflect the diversity of the population we serve. This needs urgent and ongoing efforts to overcome;
- **Engineering needs**

  - Advances in ship-based ocean drilling technologies, particularly in extreme and/or hard to access sites, to improve global coverage, and improve robustness of core extractions;
  - Improvements in ice coring, including coring bedrock under ice cores, and terrestrial drilling in a wide range of environmental conditions, including permafrost.

- **Social science needs**
  - Need to integrate social science experts to effectively communicate the relevance of deep time/geologic record to modern society;
  - Establish stronger connections between Earth scientists and archaeologists to explore the complex climatic drivers of early human migration (e.g., out of Africa, Sunda to Sahul, Younger Dryas) and more recent migrations (e.g., Little Ice Age, Medieval Warm Period).
- **Natural science needs**

- Support for comprehensive data collection (tree rings, ice and sediment cores, coral records, sea level records) and archiving across the broad range of field-based paleoclimate efforts;
- Breakthroughs that will allow us to reliably resolve the continental geologic record to the millennial or sub-millennial timescale; currently many of these records cannot resolve below the precessional (~20,000 year) timescale and this challenges our ability to investigate rates of processes at the scale of societal interest;
- Support for exciting new analytical methods of great promise in paleoclimate studies (e.g., paleomagnetism) and renewed support for existing methods that are experiencing a renaissance of interest (e.g., tree ring – e.g., studies of megadroughts).