# AMERICA'S FUTURE

*ENVIRONMENTAL RESEARCH AND EDUCATION FOR A THRIVING CENTURY*

A 10 YEAR OUTLOOK

A REPORT BY THE
NSF ADVISORY COMMITTEE FOR
ENVIRONMENTAL RESEARCH & EDUCATION

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## ABOUT THE ADVISORY COMMITTEE FOR ENVIRONMENTAL RESEARCH AND EDUCATION

In 2000, the National Science Foundation (NSF) established the Advisory Committee for Environmental Research and Education (AC-ERE) under the Federal Advisory Committee Act (FACA) to:

- *Provide advice, recommendations, and oversight concerning support for NSF's environmental research and education portfolio.*
- *Be a base of contact with the scientific community to inform NSF of the impact of its research support and NSF-wide policies on the scientific community.*
- *Serve as a forum for consideration of interdisciplinary environmental topics as well as environmental activities in a wide range of disciplines.*
- *Provide broad input into long-range plans and partnership opportunities.*
- *Perform oversight of program management, overall program balance, and other aspects of program performance for environmental research and education activities.*

The AC-ERE has particular interest in those aspects of environmental science, engineering, and education that affects multiple disciplines. Each of the directorates and major offices of NSF has an advisory committee that provides guidance on the disciplinary activities within that directorate. The AC-ERE includes scientists from many disciplines, including a member from each of the other NSF advisory committees, and focuses on coordination, integration, and management of environmental programs across the Foundation. AC-ERE interests include environmental education, digital libraries, and cyberinfrastructure, as well as interdisciplinary programs, centers, and major instrumentation.

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# A NEW VISION

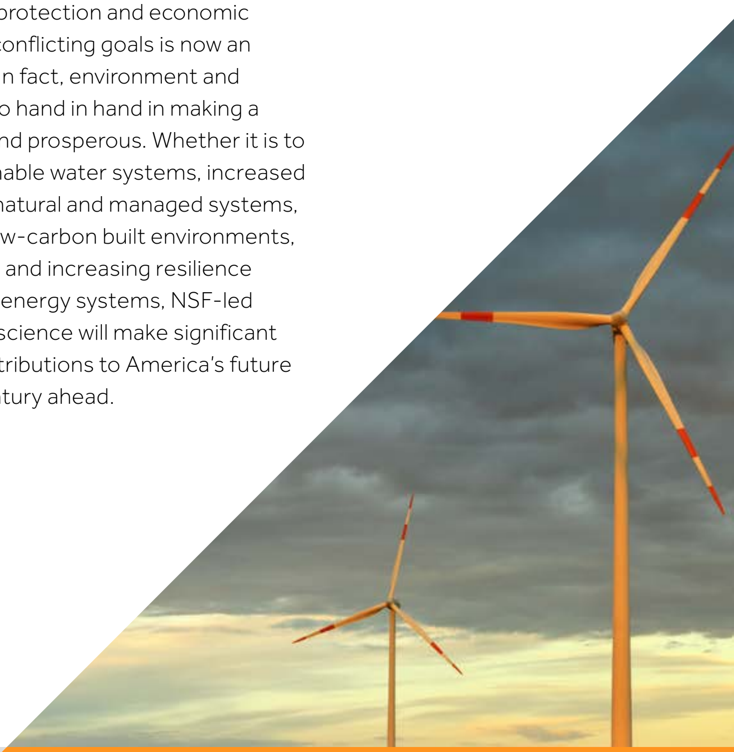
In 2003 the Advisory Committee for Environmental Research and Education (AC-ERE) published a 10-year outlook report that framed new priorities in interdisciplinary programs across the entire National Science Foundation. Under the ERE portfolio, NSF has implemented many important programs related to environmental research and education across the agency, including Coupled Natural and Human Systems, Biocomplexity in the Environment, Environmental Cyberinfrastructure, Science Engineering and Education for Sustainability, and others. One key characteristic of this programming has been the cross-cutting contributions from several or all of the directorates. This has created new pathways for interdisciplinary science that push back against the proclivity to align investments by individual disciplines and directorates, and it has been widely successful. One attribute of this cross-directorate approach has been stronger integration of social and biophysical sciences.

The other key characteristic of ERE programs has been its emphasis on making investments in interdisciplinary science that have had transformative impacts on the science community at large. For instance, the number of interdisciplinary environmental and sustainability education programs, as well as centers and institutes on the nation's campuses has grown significantly in the past decade.

Now, the AC-ERE has taken on the challenge of crafting a new vision, or 10-year outlook, for ERE programing, that takes into consideration new developments and priorities, while emphasizing the realization that what has been accomplished so far has to be continuously supported and vitalized. In addition to maintaining a strong social-biophysical science integration, there needs to be more attention to integration of data, observatories, and engineering with the goal of supporting science that informs environmental decision-making and design. Continued emphasis on building a diverse and interdisciplinary workforce is also needed, as is attention to increasing the broader impact of science on society.

Further, the AC-ERE sees this outlook as an opportunity to begin to value environmental science as part of the nation's economic engine that improves the welfare of its citizens and creates economic opportunities and prosperity for all Americans. The notion that environmental protection and economic prosperity are conflicting goals is now an outdated idea. In fact, environment and development go hand in hand in making a nation strong and prosperous. Whether it is to support sustainable water systems, increased productivity in natural and managed systems, the design of low-carbon built environments, or reducing risk and increasing resilience in our food and energy systems, NSF-led environmental science will make significant and lasting contributions to America's future in a thriving century ahead.

**David Skole**
Committee Chair





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# ENVIRONMENTAL CROSSROADS

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# A CALL FOR ACTION

The nation is at an environmental crossroads where the confluence of unprecedented global environmental change and transformative new capabilities create both an imperative and an opportunity. We need to invest in changing the trajectory of current trends away from warming, stress, conflict, and vulnerability, and toward resilience, well-being, stewardship and prosperity. Understanding the role of humans as drivers of environmental change, the effect of these changes on environmental and human well-being, and opportunities for changing the environmental trajectory to achieve desired outcomes will prepare the nation for a secure, prosperous, and thriving century.

Society is increasingly looking to science for answers to help solve and prevent current and future challenges. And scientists are increasingly recognizing the need to work together with decision-makers, educators, community leaders, and other stakeholders to enable research and education that fosters well-being on our dynamic and rapidly changing planet. Of the U.S. federal agencies that fund science, NSF is uniquely poised to establish the broad, systems-level approaches needed to understand complex socio-environmental systems at multiple scales and across multiple disciplines.

Since its establishment in 2000, the AC-ERE has provided guidance to the Foundation on new and emerging fronts in environmental research and education, as well as on program development and implementation, as represented in a series of reports:

**Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century**
January 2003

**Complex Environmental Systems: Pathways to the Future**
March 2005

**Transitions and Tipping Points in Complex Environmental Systems**
September 2009

Following NSF's Science, Engineering and Education for Sustainability (SEES) portfolio, the scientific community and the Foundation are now poised for new approaches to research and education that reach across scales and disciplines to provide the basic understanding needed to solve fundamental environmental and societal challenges. To this end, the AC-ERE recommends that NSF build and sustain long-term cross-directorate activities to enhance the capacity of diverse environmental researchers grounded in systems science and motivated by societal issues. Addressing complex socio-environmental problems requires understanding the interconnected nature of multiple environmental problems and challenges, fostering the cross-disciplinary research teams necessary to design and test solutions to complex, interdisciplinary environmental challenges, enabling scientists to better connect and communicate with stakeholders and communities, and coordinating sharing of information among investigators from diverse disciplines that do not commonly interact. Education programs focusing on these issues can also have a positive impact on broadening participation in science. Environmental issues have great societal relevance and many environmental problems have disproportionate impacts on under-represented and disadvantaged groups.

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*We stand now where two roads diverge. But unlike the roads in Robert Frost s familiar poem, they are not equally fair. The road we have long been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lies disaster. The other fork of the road — the one less traveled by — offers our last, our only chance to reach a destination that assures the preservation of the earth.*

*RACHEL CARSON, SILENT SPRING*

# THE WESTERN DROUGHT

An American exodus, it s been called, the largest "migration" of people in modern U.S. history.

It happened during the 1930s Dust Bowl, when severe drought conditions coupled with erosion brought about an environmental catastrophe. Choking dust storms caused major economic, ecological and agricultural damage in Texas, Oklahoma and parts of New Mexico, Kansas and Colorado.

Ill winds blew across fields, plucking deep-rooted grasses and carrying them hundreds of miles. Farmlands disappeared and homes were destroyed. These "black blizzards" swirled all the way to East Coast cities such as New York and Washington.

On April 14, 1935 — "Black Sunday" — 20 of the worst of the storms turned day into night. More than 500,000 people were left homeless. Most headed due west in search of work. Some, victims of dust pneumonia or malnutrition, never made it.

For today's residents of states such as Colorado and now California, that scene is long ago and far away. Or is it? With much of the U.S. West in an extreme drought, people are wondering.

Cherokee Marsh, it s called, this sunken enclave surrounded by cattails and bulrushes. The marsh is a mere dot on a map of the state of Wisconsin, but its importance reaches far beyond the wetland's edge.

The Yahara River flows through Cherokee Marsh, swirling through coontail, sago pondweed, glade mallow and other plants. Its next stop is the twins of Madison: Lakes Mendota and Monona.

The river and its watershed provide Madison with critical "ecosystem services" such as water quality and flood protection. But the marsh, the twin lakes that lie downstream and the river that runs through them may be threatened by the effects of climate and land-use change.

How is the Yahara faring? Lakes Mendota and Monona may be the eyes that are the windows to its soul. In summer, the lakes are often fouled by algae blooms. The blooms are a result of excess fertilizer that washes into the river and is carried downstream to Mendota and Monona.

We have the opportunity, however, to change practices while the Yahara watershed is still relatively healthy, scientists say, and before its mainstem river is but a trickle. Or until the reeds of Cherokee Marsh have dried up, scattering the watershed's heart to the four winds.

# NEW CHALLENGES, NEW VISION

We are experiencing a time in which human society and technology are increasing the pace and rate of environmental change in ways for which no precedent exists, and which have significant potential consequences. Human systems are becoming dominant forces in ecosystems and the environment resulting in novel landscapes, altered hydrologic and biogeochemical regimes, and new disease pathways. The implications for societal well-being are critical: although science has often used historical trends and records to understand the present and project the future, we are entering a world without prior analogue.

In this emerging world, both basic research and long-term observations will be the keys to understanding what changes may be in store. Sophisticated models are needed to develop scenarios and consider potential alternative futures given different choices. These challenges will require not only a prognostic understanding of changes and trends, but also building the capacity to implement strategies that change their trajectories, and manage of our planet in ways that enhance well-being. Supporting science that informs efforts to actively change the environmental trajectory in beneficial ways will require new, interdisciplinary programs. Through investments in building capacity and engaging public understanding, the Foundation can foster a workforce capable of solving complex problems. This means investing in individual as well as collaborative endeavors. From a human resources standpoint, a diversity of perspectives increases the pool of ideas and possible solutions to environmental and societal challenges. Growing evidence suggests that groups that are currently under-represented in STEM are attracted to the purpose-oriented or applied science that links science to societal needs. Hence, a robust program focused on environmental problem-solving can meet other goals in broadening participation.

In addition, beyond training scientists, we also need to enlist decision-makers, problem-solvers, and designers in environmental research and education. Preparing for and responding to future rapid environmental change, including extreme events, requires a different perspective and skillset than planning and designing for common or average conditions. An emerging suite of new resources, approaches, tools, and data streams are available that have the potential for a transformative reach, laying the foundation for the scientists, decision-makers, and life-long learners of the future.

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# IMPLEMENTING THE NEXT DECADE OF ENVIRONMENTAL RESEARCH



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# UNDERSTANDING THE CHALLENGES

There has been significant progress over the past decades in improving understanding of a wide variety of environmental problems. The most challenging of all — those with global scale, long-term changes, and severe potential consequences — represent changing states and dynamics of complex environmental systems, a program area that NSF has promoted successfully for several years. In this report, we re-emphasize that these systems are fundamentally complex socio-environmental systems, and the need to integrate our understanding of biophysical processes, social processes, and engineered systems is more pressing than ever. We must improve our understanding of how the components of complex socio-environmental systems interact if we are to move from responding to change to anticipating change, averting harm to creating opportunity. The interrelationship between human cultures, economics, biological systems, physical climate, spatial and temporal scaling, and feedbacks in response to environmental perturbations is a critical scientific challenge that demands the attention of mathematicians, biogeochemists, economists, social scientists, physical scientists, ecologists, engineers, computer scientists and more. An improved and more integrative understanding of complex socio-environmental systems makes it possible to forecast and predict future states and provides the ability to foresee problems before they become irreversible adverse conditions.

## Sustaining a Program of Understanding Complex Socio-Environmental Systems

At the core of the environmental research and education challenge of the next decade is the need to build a stronger scientific foundation for understanding complex socio-environmental systems. The scientific community that the Foundation has already enabled to study these systems requires sustained investments in experimental work, observations, and modeling. As the Science, Engineering and Education for Sustainability (SEES) portfolio transitions into new programs, it is crucial that strong collaborations between the natural sciences, social sciences, and engineering domains continue and expand in order to provide the scientific basis for sustainability. In addition, sustained support is necessary for the research community to share its knowledge through new modalities of education and capacity building and communication with society.

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## SEES

Several recent programs directly relate to the AC  ERE recommendations, and provide opportunities to continue similar investments in follow-on activities after they conclude. NSF s Science, Engineering, and Education for Sustainability (SEES) is one of these. A sustainable world is one in which human needs are met equitably without harm to the environment, and without sacrificing the ability of future generations to meet their needs. Meeting the formidable challenge of living sustainably requires a substantial increase in our understanding of the integrated system of society, the natural world, and the alterations humans bring to Earth. SEES activities aimed to address this need through support for interdisciplinary research and education.

Fundamental to all sustainability research is the simultaneous consideration of social, economic, and environmental systems and the long-term viability of those systems. Concepts that underlie the science of sustainability include complex adaptive systems theory, emergent behavior, multi-scale processes, as well as the vulnerability, adaptive capacity, and resilience of coupled human-environment systems. An important research goal is to understand how patterns and processes at the local and regional scales are shaped by-and feed into-processes and patterns that manifest at the global scale over the long term. These topics guide research to explore alternate ways of managing the environment, migrating from finite resources to renewable or inexhaustible resources, and applying technology to improve human well-being. Conceptual frameworks for sustainability, including general theories and models, are critically needed for such informed decision-making.

SEES activities at NSF spanned the range of scientific domains at NSF and aimed to: 1) support interdisciplinary research and education that can facilitate the move towards global sustainability; 2) build linkages among existing projects and partners and add new participants in the sustainability research enterprise; and 3) develop a workforce trained in the interdisciplinary scholarship needed to understand and address the complex issues of sustainability. Although the formal SEES portfolio is coming to an end, there is a great need to continue to support this research and outreach community through the activities recommended in this report.

## Multi-scale Science and the Human Context

There is still much work to be done to understand the scales at which humans interact with different aspects of the environment. Many complex socio-environmental problems can only be understood by integrating observations and processes across multiple spatial and temporal scales and placing them in a societal and historical context. To this end, research and tools are needed at the multiplicity of scales at which the world works. It is important to note that biophysical and human domains operate at many different temporal and spatial scales. Some of these scales may not overlap with the scales in which society operates: they may be too large or associated with very gradual or non-linear variability. Hence, science provides the analytical and prognostic tools to observe and evaluate what may not otherwise be obvious, and it is critical that this information is conveyed to decision-makers. The Foundation should support work on how to integrate large-scale patterns with small-scale, non-linear processes. For example, global scale changes result from the aggregation of individual actions, but purposeful actions on a large scale can change the trajectory of the climate system in a way that can create significant benefits for individuals and communities.

Although the general issue of scale is a common theme in environmental research, explicitly bridging biophysical and social scales in the study of complex socio-environmental systems is an important research frontier. The AC-ERE identified two conceptual challenges to developing an inter-scalar perspective of complex socio-environmental systems: (1) synthesizing and modeling across scales to understand their interactions and (2) studying human social systems to examine and interpret the relevant cross-scale environmental processes.

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## Improved data and observation-driven forecasting

The past decade of environmental research and education has invested heavily in the development of integrated modeling. Much of this work has been aimed at improving our understanding of how systems function from a diagnostic perspective. There is now a need to invest more in prognostic understanding, or research that improves forecasting and forecasts of environmental change into the future. Improving forecast capacity will require coupling characteristics and dynamics of both human and biophysical systems, while explicitly addressing the questions of scale noted above. These investments should facilitate new research on improving the forecast and deliberately designing the future of the local and global environment as described in the next section.

There is no doubt that continued investments in process-based models that are essential for diagnostic analysis are still necessary. However, improved prognostics will enable science to support a larger range of solution-sets, especially for those problems that require lead-time to develop adequate solutions. This will require novel methods of testing and validating forecast models without waiting to observe the actual outcome. It will also require a vastly improved understanding of the drivers of environmental change. Because of the increasing availability of data and observations, new methods can and should be robust and data-driven, integrating and adapting improvements in data assimilation, similar to advances in weather forecasting. Large computational facilities will enable more complicated projections, and environmental cyber infrastructure will be needed to support access to these facilities, with an added emphasis on using existing and emerging environmental observatories to support prognostic analysis. Careful uncertainty estimations and risk analysis will also be critical for decision-makers.

Continued progress in understanding the challenges requires the creation and support of NSF programs that address:

- *Science and theory-building to transcend fundamental understanding of stability and complexity to characterize and model emergent properties of complex socio-environmental systems.*
- *Human responses and feedbacks within studies of the dynamics of biophysical systems, since more and "better" information about the biophysical environment doesn't necessarily lead to better decision-making without explicit consideration of social processes.*
- *Methods of scaling spatially and temporally, recognizing that biophysical and social scales vary, and that mitigation and adaptation are often local or based at the community level.*
- *Emergent properties at different scales, since scaling is not simply a problem of aggregation/disaggregation.*
- *Improvements in the capacity to forecast that integrate and leverage the increasing availability of data and observations.*

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# EDNA

*NEW TOOLS IN ENVIRONMENTAL MONITORING*

Organisms continuously shed DNA into the environment through excreted tissues, cells, and wastes. These "environmental DNA" (eDNA) molecules are everywhere and can persist in the environment for thousands of years. EDNA can be found in sediments, soil, air and water. Technologies for the detection of trace amounts of eDNA have improved dramatically over the past decade and new, mass DNA sequencing techniques make it possible for DNA from multiple genomes and taxonomic groups, such as plants, animals, fungi and bacteria, to be identified and analyzed simultaneously. Known as "metagenomics, research on multiple genomes has a wide array of applications including: ecological monitoring and bioremediation, agriculture, biofuels, biotechnology and bioengineering.

EDNA is increasingly used to monitor aquatic animals, particularly to screen for invasive species, as it allows for detection without direct observation. In one Coastal SEES funded project for example, researchers are analyzing the global shipping network to discover where the risk of invasion has been high and to identify where the risk may increase as a result of ongoing changes in shipping routes. Predictions about past and future invasions will be tested by sequencing DNA extracted from water samples taken in or near ports to detect the presence of potentially invasive species. Opportunities to apply advances in basic biology to environmental problem-solving continue to expand as new tools for detecting and understanding environmental change become available.

# DESIGNING THE FUTURE AND CHANGING THE FORECAST

The pace and scale of environmental change is so extensive that it is not sufficient to use science only to improve our basic understanding of these changes. As we have pointed out in Section 1 of this report, there is a growing realization that the environmental and scientific challenges we now face are of sufficient rapidity and scale that simply studying these challenges is no longer a viable strategy. Instead, we have entered a world in which we must begin not only to observe, but also to define ways in which society can alter unwelcome environmental trends purposefully, before irreversible harm has occurred, and to create new opportunities.

We must anticipate and shape, not merely adapt. This will require integrating an improved understanding of environmental changes with translation of this knowledge into new ideas and designs for the type of environment in which we want to live. Society is continually designing and redesigning the built and natural environment. Science and engineering can be marshaled to improve these designs and enable evidence-based decision-making through investments in scientific research.

The concept of design requires not only sufficient understanding of complex socio-environmental systems, but also tools and methodologies to support planning, decision-making, and evaluation. Developing these tools is a major undertaking for the next decade. New tools that integrate STEM and design may be observationally or experimentally based and grounded in basic science questions. For example: What are the critical observations and experiments necessary to develop and test urban designs that reduce or mitigate urban pollution? How can we bring ecosystem service value chains into markets as rising commodity prices drive incentives for de-forestation and land conversion? How does STEM interface with fields such as communications, arts, and other humanities to communicate science to stakeholders? New research is needed to develop and evaluate models that provide insight into how these coupled systems respond to perturbations and how they can be designed or managed to achieve desired outcomes.

The use of new tools and their utility for design and decision-making related to changing the trajectories of undesired environmental trends also depends on social acceptance and familiarity with the underlying science. An informed citizenry is necessary to change the forecast. In this context, understanding how scientific advances are (or are not) utilized in various societal contexts is a significant research challenge in its own right.

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## Designing for Resilience

Human uses of the environment for food, water, energy, and materials are causing global-scale changes in air, water, land, and climate. Yet connections among these social, biophysical, and built systems are poorly understood. A next step in advancing science for improved environmental system design is transitioning from sustainability science to a "science of integration." This will involve the development of a distinct set of vocabularies, theories, and methods (versus borrowing language and approaches from other disciplines). The science of integration is focused on testing hypotheses about complex systems in order to translate knowledge of complex socio-environmental systems into practice in the design of resilient systems. These are systems that can maintain their essential functions in the face of rapid or significant changes and pressures. From the perspective of environmental design, these systems may be defined at a variety of scales and are actively designed and managed such that the biophysical environment, the built environment, and human uses act in concert to optimize resource use and benefit a wide range of end users, including non-human biodiversity. To this end, basic knowledge about biophysical, social, and built environments must be applied in an integrated manner through development and testing of new theory — a critical way in which basic science can guide environmental design. The Risk and Resilience program at NSF is an excellent first step in this direction. To have the required impacts, this program must be scaled up and sustained, with participation from, and integration across, all of the Directorates to address all of the key components of complex socio-environmental systems.

Resilience is essential to living in a world that is changing on multiple scales and at unprecedented rates. However, in the face of climate variability, globalized economies, and growing populations, resilience needs to be re-framed in the context of how we will build the capacity to actively respond to the risks and opportunities we can expect to face in the future. With the goal of a thriving future for the nation, we must understand the risks we will face and prepare for those risks through planned, science-based adaptation and mitigation measures. Resilience-focused research is crucial in this endeavor, as it provides capacity to cope with both expected events and surprises.

Since resilient systems are inherently and tightly coupled to societal needs, such programs should be co-developed with the participation and input of a diverse range of end-users through partnerships between scientists, practitioners, and managers. Many scientists do not know how to co-develop science with stakeholders, so capacity-building in the research community is essential to achieving this goal. Furthermore, many resilient designed and built systems are people-centered, such that the public must be involved in the development and management of indicators of resilience. This involvement is essential so that responses to environmental changes across social scales can be made in time to ameliorate real or perceived environmental threats. Through the co-production of knowledge by scientists and stakeholders, we can reduce the possibility of personal harm, erosion of well-being, damage to valued ecosystems, and loss of livelihood. Public participation provides communities, practitioners, and decision-makers with advanced information of perceived risks that can be readily translated into prevention, mitigation, preparedness, and response actions. In other words, stakeholder partnerships facilitate resilient systems.

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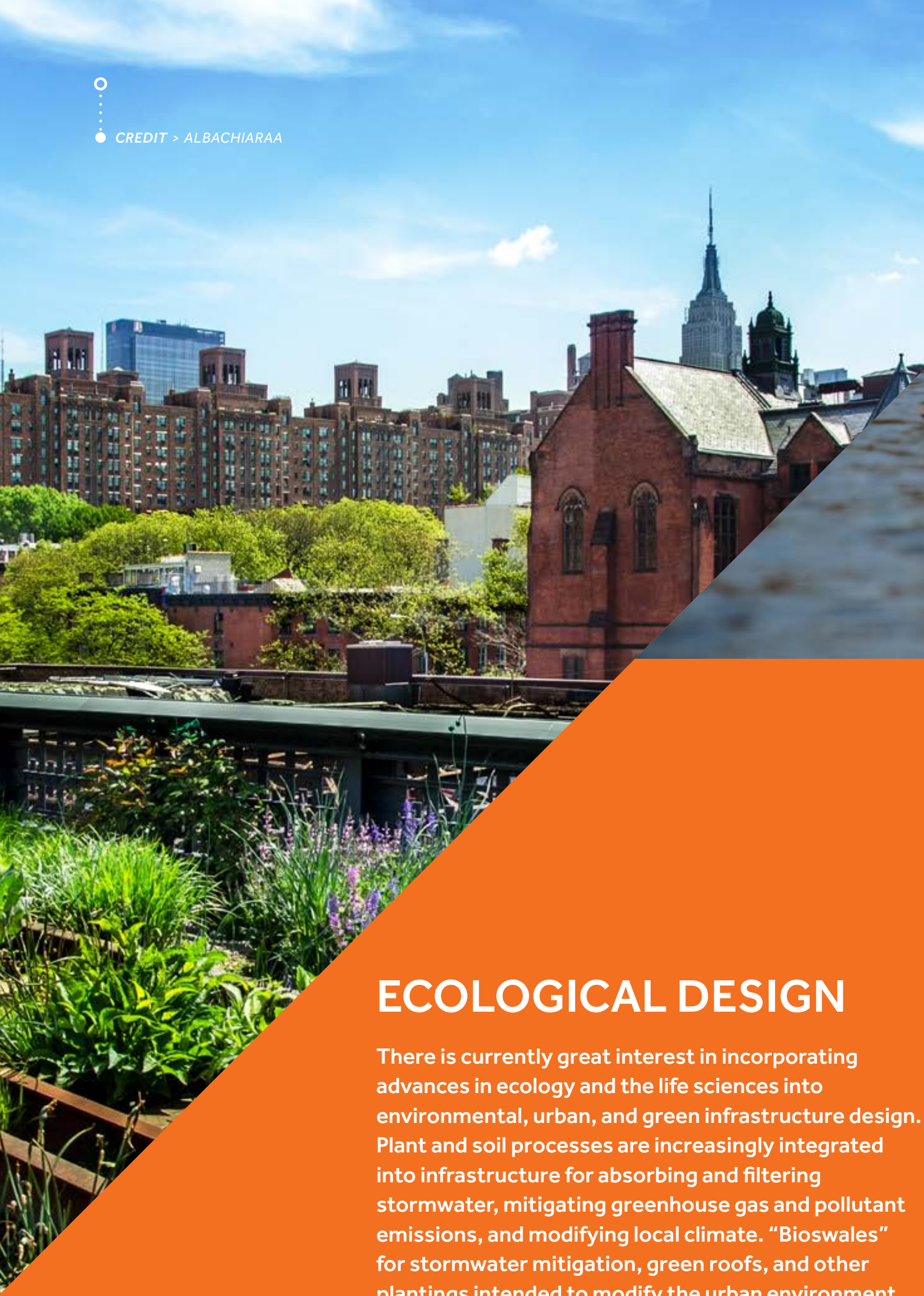

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## ECOLOGICAL DESIGN

There is currently great interest in incorporating advances in ecology and the life sciences into environmental, urban, and green infrastructure design. Plant and soil processes are increasingly integrated into infrastructure for absorbing and filtering stormwater, mitigating greenhouse gas and pollutant emissions, and modifying local climate. “Bioswales” for stormwater mitigation, green roofs, and other plantings intended to modify the urban environment are examples of designing ecological systems to serve as infrastructure in the built environment. An advantage of utilizing ecological design in this context is that these features can also provide a number of co-benefits such as recreation, habitat for native and endangered species, and food provision. Successful ecological design requires collaborations between scientists and designers to incorporate sound scientific principles into feasible and cost-effective site designs, with opportunities for monitoring and experimentation to incorporate new advances in our understanding of ecological dynamics, biogeochemistry, and microbial processes into the built environment.

Green walls,” or vertical planting systems intended for use in or on built structures, are a newer application of ecological design. In practice, green walls are not yet widely used in urban environments as they are not generally cost effective for mitigating building energy use and other possible functions. However, researchers at Yale University are studying the strategic use of green walls as an alternative to heat rejection technology. Currently, heat rejection (dissipation of excess heat) often relies on wet cooling towers that are associated with high energy and water costs. Work by student teams at Yale has resulted in designs for constructed wetlands that serve the same function as cooling towers, but without the need for water disposal, annual shutdowns for cleaning, or application of toxic chemicals as biocides and corrosion inhibiters. Instead, water can be recirculated though the wetlands which mitigates climate and water quality while also providing parkland and recreational benefits. Through an NSF CBET funded project, the team at Yale is expanding this work to transform current green wall designs into active heat rejection technology that can provide a sustainable alternative to wet cooling towers. This collaboration of ecologists and engineers is working to determine the plant species and substrates, models, and water treatment systems that will make this technology cost effective for implementation. If utilized on a large-scale, this ecological design has the potential to provide many simultaneous benefits for urban environments including stormwater mitigation, habitat provision, aesthetic functions, and mitigation of the urban heat island effect.

## Supporting the Critical Role of Science Coupled to Engineering

The AC-ERE's strong recommendation to increase support for science for design will require a strong coupling of science with engineering. We are not recommending simply more investment in engineering, but rather investments in activities that integrate the other disciplines and directorates with engineering. There is enormous opportunity and value in support for activities that explicitly couple natural and social science with engineering to foster ingenuity in environmental problem-solving. There are already a number of areas in which this is taking place: innovative materials for capturing solar energy, restoring and redesigning urban infrastructure, adaptive management of hydrologic systems, and developing and leveraging new tools (e.g., new sensors, distributed computing for smart buildings, new models, etc.). However, there is a great deal of untapped potential.

The Foundation is supporting exciting new developments in this area through support for re-engineered water treatment and delivery systems, such as Innovations at the Nexus of Food, Water, and Energy Systems (INFEWS), and Risk and Resilience. The NSF sponsored ReNUWIt project is an excellent example of an engineering effort that is enhanced through social and physical science elements. This effort is based in California, which is experiencing an historic drought. Issues related to water and agriculture are of paramount concern now and will only grow in importance in the coming decades. Coupled biological, social, and engineered systems frame these concerns. Support for integrated and interdisciplinary research on these topics can directly support environmental planning that is based on sound science. Another example of a coupled systems focus with stakeholder involvement is the America's Water initiative, a consortium of academic, industry, think tank and policy experts that aims to inform water sustainability improvements in the United States through innovative management solutions, new technologies, new infrastructure designs and new policies. The initiative was funded by NSF's Water Sustainability and Climate (WSC) program to analyze how climate, agricultural practices, energy supply, and pricing interact to impact water availability and supply risk across the country. As recognized by the forthcoming INFEWS program, increased demand for food and other materials is coupled to demands for water and an abundant supply of affordable energy. Meeting this demand will require the development of new technologies for production of renewable energy, such as photovoltaics, fuel cells, geothermal, wind, and thermoelectrics, as well as efficient electrical energy storage systems. At the same time, fossil fuels and nuclear energy will continue to be part of our energy mix in the near- to medium-term, and developing new technologies to better manage their impacts will be critical. New sources of energy may be found in better utilization of wastes from industrial and agricultural processes. Connecting basic natural and social science with technical engineering approaches and demand management is necessary to optimize food and energy production while minimizing waste of water and other resources.

We note that not all disciplines or professions related to design are well-represented at NSF (eg. architecture, art, and communication). In addition to fostering and evaluating technical solutions, a new focus on science for environmental design will require strengthening existing collaborations within the Foundation, as well as building collaborations with new communities of professionals.

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# LOW CARBON INFRASTRUCTURE

Manufacturing, housing, and transportation systems depend primarily on the combustion of fossil fuels for energy. Power plants, vehicles, and the HVAC systems in buildings are obvious examples, but there are many other less  visible examples. For instance, data centers, which form the backbone of the nation s IT infrastructure, are enormous consumers of electricity. The production of cement, which is the most important building material in our civil infrastructure, constitutes one of the most energy intensive manufacturing sectors. The connection between our built environment, fossil fuel combustion, and climate is complex but central to adaption and mitigation options in a changing climate. The built environment both impacts and is vulnerable to climate variability. Because infrastructure generally lasts longer than technologies that exist at the time of construction, later efforts to alter outdated infrastructure to reduce carbon emissions or adapt to climate variability will take many years. This means that design decisions made today will impact emissions and our capacity for resilience many decades from now.

There is a great opportunity to reinvent infrastructure systems based on basic science. For instance, the NSF Engineering Research Center (ERC) for Re-inventing the Nation s Urban Water Infrastructure at Stanford University is exploring a suite of technologies that would enable potable water reuse and conversion of wastewater constituents into energy. Other research in water systems is providing new drip irrigation designs for drought stressed agriculture, or re-designing urban water infrastructure. These projects involve interdisciplinary research and education programs that address the intersection of people, water, and the environment, providing the foundation for new industries through innovation. Given the time it takes to incubate and disseminate new technologies, these discoveries need to be fostered today.
NSF will play a critical role in driving this innovation as private corporations and regional governments do not have the financial incentives or statutory mandates in place to drive fundamental innovation in transportation, energy, and communications infrastructure. From an international perspective, many other countries model their infrastructure systems after those in the U.S. As a result, U.S. examples of innovative, low carbon infrastructure systems can play a critical role in developing countries that are rapidly building and expanding modern infrastructure. NSF programs focused on integrating knowledge and discoveries from diverse disciplines across the Foundation can be targeted to innovation of new design alternatives for the nation s extensive, fossil-fuel based infrastructure systems.

## Data-Informed System Design

Incompatibilities between society's demand for resources and the rapidly changing environments such demand creates can threaten to erode the nation's long term resource security when its adaptive capacity is low. In a heavily human dominated world, a significant barrier to designing resilient systems is that future conditions are uncertain and do not predictably follow simple historic trajectories. Instead, economic and environmental conditions can re-organize in new stable states that make adaptation difficult. This underscores the value of having multi-variable, long-term datasets over a range of scales and conditions.

Moreover, response strategies can be designed to be adaptive in real time if observations are placed in a clear set of social contexts to better inform predictive models. There is enormous opportunity to leverage current observing networks to provide relevant data for adaptation actions at increasingly finer temporal and spatial scales, for example, through investments in community-based observing networks that harness place-based, local, and traditional knowledge. This type of knowledge can reveal historical trends and socio-environmental changes ranging from the near- to the deep-past and should reflect the diversity of cultural uses of landscapes. By developing and utilizing processes and strategies to link social needs to environmental data streams and observing networks, the era of "big data" can be harnessed to improve forecasting and inform the design of adaptive systems.

## Infrastructure To Support Design

The nature of data and observations has changed significantly since the AC-ERE began publishing its reports, and this shift can be leveraged to support the science of environmental design. Now, "everything is a sensor." Whether it's a personal electronic device, an automobile, or website, data are now collected and organized all the time and everywhere, with significant advances in sophisticated observational systems. For instance, the rise of small and micro satellites has made observations from space more economical and accessible to a wider group of scientists and stakeholders. The Cubesat community, with funding from NSF, can now put shoe-box size sensors in orbit at such low cost that they can be set up as class projects. Similarly, small satellites can be put into orbit multiple times to create constellations. These systems can be built around and operated with commercial applications software with a high degree of sophistication. Near real-time, high definition video of environmental phenomena is now possible from space at 50 cm spatial resolution. At the same time that orbital systems are becoming more ubiquitous, the deployment of drones and swarms is already facilitating new science applications.

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# FOOD/WATER/ENERGY SYSTEMS

Access to a secure, affordable supply of food is a basic human need. By the end of this century, the world's population is projected to grow by 30%. Concurrently, standards of living are increasing worldwide resulting in a dietary shift from grains to meat. This transition places stress on food production because appreciably more resources are required to produce meat than grains or vegetables. In general, increased food production results in increased fertilizer use and production of farm waste. These materials impact both coastal and inland bodies of water and have already led to severe economic losses in commercial fishing and tourism industries. Thus, there is a critical need to devise improvements in the production of food — from farm to fork — that can address the growing stress on the global food supply.

It is impossible to project strategies for meeting this demand for global food production without considering two other key factors: energy and water. Currently, 70% of global fresh water consumption is used for agriculture and this allocation is expected to grow by about 20% by 2050. In California alone, agricultural irrigation uses 10 billion kilowatts hours of electricity annually. Society is increasingly forced to choose, for example, between using land and fertilizer for food production or bio-based/renewable energy and between using limited supplies of fresh water for energy production or for irrigating food crops. Thus, food, energy, and water are inextricably linked and must be considered as a complex socio-environmental system. NSF has a critical role to play in fundamental research at the food/water/energy nexus, spanning across the biological, physical, engineering, computational, geological, social, and economic sciences. This role can complement those played by other Federal agencies, such as USDA, DOE, EPA, NOAA and NASA, providing the underpinning science needed to understand food/water/energy from a systems perspective.

At the same time, many manufactured items can be developed into smart sensors. Even when these data-gathering devices are designed for purposes other than research, they can provide great opportunities for repurposing for use by the scientific community. For instance, it is feasible to construct real-time weather reporting systems that provide locally accurate rainfall information from automobile windshield wiper sensors linked to a network. One of the more interesting aspects of the "micro-sensors everywhere" phenomenon is that new observations can be tied to databases for modeling human behavior, since many of them are embedded in personal devices. The implications for enabling data-driven social science are profound; however, these opportunities will be lost without strong theory to guide their analyses and interpretation.

There is a pressing need to bring order to the array of small and large observatories that were not necessarily designed for the scientific enterprise. Systems thinking can enable the creation of "networks of networks of sensors" that can help to manage and support information relevant to designing and testing innovative solutions to environmental problems. To this end, NSF should support existing and new observing systems and approaches to collecting and managing new environmental data streams. Once NSF enables technical and educational infrastructure to support big data, or advanced integrated data-driven process models, the next challenge is to translate this knowledge and information into decision-making that could "change the forecast."

The ubiquity of data raises issues and challenges for society, from ethical questions of privacy and freedom of access to translation of technical information to usable content for decision-makers and other members of society. NSF needs to engage with ethicists, legal experts, and stakeholders to ensure that data are not abused but serve societal needs.

In summary, to design the future and change the forecast the AC-ERE recommends that NSF and its programs:

- *Recognize that humans are continually shaping and designing the environment, and an explicit focus on science for design can lead to better environmental and societal outcomes.*
- *Focus the next phase of programs in coupled socio-environmental systems on facilitating a science of integration and partnering with stakeholders to inform and co-produce design and management of resilient systems.*
- *Continue and strengthen relationships between the natural science, social science, and engineering directorates and programs in order to advance science for environmental design.*
- *Find new ways to engage with user communities, ethicists, legal experts, and decision-makers to ensure appropriate access to data and information.*
- *Leverage new developments in sensor networks, large observatories, and "big data" to advance data-informed design.*

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# ENABLING AND SECURING THE FUTURE

We recommend that NSF work to enable and secure the future by providing stability and permanence to environmental and sustainability programs and initiatives. The National Science Board's major recommendations in its overview of environmental research and education at NSF in 2000 were for substantially increased funding and for a new organizational approach within NSF, including a focal point and budgetary authority in the Foundation. While there has been considerable progress, those recommendations have yet to be fully implemented. Funding for ERE type activities has been inconsistent and mostly tied to programs and initiatives that have come and gone. Ad hoc and episodic cross-directorate efforts can cause considerable strain on NSF program officers and may not build sufficient capacity within the scientific community. The AC-ERE recognizes the need for NSF to continuously revitalize the portfolio of activities encompassed by environmental research and education. However, to meet environmental challenges at the scale that is needed to secure environmental and human well-being and prosperity, the environmental research and education enterprise needs more permanence and stability.

The AC-ERE recommends that NSF build on its current core and special programs, for example, Dynamics of Coupled Natural and Human Systems CNH, INFEWS and Risk and Resilience, to integrate a stable, Foundation-wide environmental portfolio across its research and education directorates and programs, creating new programs when needed to address specific research questions and societal-environmental challenges, such as the environmental design challenge presented here. A robust environmental portfolio is essential to advance a new generation of diverse environmental science researchers grounded in systems science that is motivated by societal issues; catalyze cross disciplinary teams supported by the larger and longer research grants necessary to solve complex interdisciplinary environmental challenges; and enable scientists to better connect and communicate with stakeholders and communities. Such a portfolio needs a stable institutional home within the Foundation that includes core funding and a set of program officers who are charged with facilitating partnerships with their colleagues across the Foundation as their core responsibility.

Addressing societal challenges by catalyzing exciting and innovative science in next-generation environmental research will require a large and diverse community of scientists, educators, and other professionals. This community will be called upon to reinvent and sustain a thriving nation in partnership with local residents and communities. The skillset required of the scientific community in this endeavor is an unprecedented combination of multi-scale, systems-thinking skills, innovative and collaborative research and design capacity, the ability to co-create and share scientific knowledge with the citizenry, and to engage with individuals and institutions that implement solutions.

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# GREEN CHEMISTRY

Strategies to meet future societal demands for transportation, communications, and manufacturing require new processes for producing food, chemicals, and materials that are cost effective while also avoiding negative impacts on the environment. These needed advances present technical challenges and require fundamental research to identify new chemical processes and materials.

In particular, new processes are needed for production of chemicals and materials that minimize the use of toxic solvents and reduce energy costs. This is an inherently interdisciplinary problem; efficient food production, for example, requires pest and weed control. Insight into the mechanisms of bio-control of pests and weeds can lead to a new generation of agricultural chemicals that are highly specific to the target threat yet pose little risk to other species. New separation processing can have both high selectivity and efficiency to reduce waste and energy costs. New membrane materials and chelating chemistries, ion exchange processes, or selective membranes can be devised to improve the efficiency of production of scarce elements in mining processes and to recycle these elements economically from consumer products. Finally, industrial catalytic processes include conversion of nitrogen into ammonia for fertilizer, methane into hydrogen for chemical production, and higher weight oil products into liquid fuels. Improvements in catalysis represent a huge opportunity for improvements in agriculture and industry. New concepts are needed to make catalysts more selective, producing the desired product and minimizing by-products that would require removal by separation.

These advances will require new data streams as well as analytical and computational methods. Sensors can monitor the materials' structure and reaction dynamics that once understood, can lead to new chemical and physical processes. In situ and real time data on industrial and agricultural processes are essential to optimize these processes while minimizing waste and energy costs. In the case of agricultural sensors, decisions about the application of pesticides and irrigation water can be made precisely with the aid of in-field sensors and advanced data analytics. Therefore, physical science, biological science, computational science, and engineering all have roles to play in the discovery of innovations in future chemical and material processes.

Education is a key part of securing the future. Environmental education is necessary both to build the skills of future environmental professionals and to enhance public literacy. The academic community is starting to meet this challenge, with some 700 college and university presidents signing the American College and University Presidents Climate Commitment (ACUPCC), and nearly 2000 interdisciplinary degree programs in environment and sustainability (Vincent et al 2012), as well as numerous other actions to transform higher education to meet the needs of students and society in the 21st century. However, interdisciplinary and problem-focused approaches to education are still hampered by institutional structures at colleges and universities as well as at NSF that impose disciplinary barriers to collaboration and may stifle innovation. Without an overarching framework for coordinating and planning environmental programs Foundation-wide, the agency is not well structured to meet these challenges.

With the goal of building capacity in environmental problem-solving and design, in the next decade NSF should invest in projects focused on studying best practices and supporting research that will improve methods of connecting science with decision-making. In recent years there has been great progress in the integration of processes in complex socio-environmental systems through the development of a science of integrative assessment and process-based models aimed at understanding the drivers of environmental change. As we noted in the previous section, the challenge now is not so much integration, but developing of a science of integration that can understand how integrated, multifaceted systems behave and how they can be shaped to sustain and enhance well-being.

The AC-ERE proposes a set of activities that would take place at a variety of scales, including the project level, the institution of the grantees (generally academic institutions), multi-institutional partnerships, and Foundation-wide.

## Facilitating Scientific Discovery

Enabling and securing intellectual advances through research and education in a changing world requires long-term investments in ways of working that deliberately connect disciplines and sectors.

**Funding and Institutional Support:** Stable and secure funding streams are necessary to both build and sustain a research community that advances fundamental understanding and informs the design and evaluation of solutions to environmental challenges. The transitory nature of environmental programs at NSF, where programs and initiatives come and go in a matter of a few years, is hampering the effectiveness of the scientific community. Among the challenges that NSF needs to tackle are development of broader programs that allow more flexibility for researchers, as well as mechanisms for sustaining cross-directorate programs, and ensuring appropriate review of highly interdisciplinary proposals. Long-term, cross-directorate programs such as CNH have been invaluable for building and sustaining an interdisciplinary research community. However, this program alone is not sufficient to support needed new directions in environmental research such as the science of integration, designing for resilience, and science to support environmental design.

Cross-disciplinary programs commonly require multiple PIs and institutions. The AC-ERE recommends that NSF establish diverse levels of support, ranging from single PIs to pairs, groups, and cross-institutional teams. Exploratory awards are appropriate both for investigators initiating new endeavors, as well as for teams to establish working relationships prior to committing to major implementation. Because the scope of environmental projects often crosses sectors as well as disciplines, long-term support is often critical to fully realizing the potential of an innovative idea.

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**Collaboration:** Collaboration is essential to environmental research. Environmental problems intrinsically cross disciplinary boundaries and few environmental problems can be understood by a single investigator acting alone. The cross-disciplinary nature of this work continues to present challenges ranging from the skillsets needed by researchers to the many institutional barriers that make cross-disciplinary collaboration more difficult. Although there are nearly 2000 interdisciplinary environmental degree programs in the U.S. (Vincent et al 2012, 2013), many scientists are still not well prepared to collaborate across disciplines or to work in multi-disciplinary teams. Programs such as postdoctoral fellowships and mid-career professional development can provide opportunities for scientists to gain additional skills and to learn about fields beyond their own core discipline. Collaboratories that transcend disciplines and public private sector boundaries can also offer promising ways for scientists to work together.

**Partnerships:** NSF should continue to build stronger partnerships with other agencies, foundations, industry, and international programs to gain synergy in areas such as observing systems, human-managed landscapes, and food, energy, and water systems. These partnerships enhance science while catalyzing the translation of science into societal needs, particularly through collaboration with mission agencies.

## Facilitating Broadening Impact

By definition, environmental research and education begins with strong connections to society and a goal of having a broad impact.

**Diversity:** Diversity is critical to enabling and securing the future. Diverse minds are needed to contribute different world views and perspectives, which leads to better understanding and problem-solving. Science needs to engage the full populace, as demographics of NSF grantees don't match national demographics. Although interdisciplinary approaches and orientation to environmental and sustainability issues such as environmental justice have been shown to attract students from underrepresented populations, the environmental field, like other STEM fields, is far from representative of the diversity of America as a whole. Broadening participation is an entry point to science and for science to connect with society. By building diverse human capital, the scientific community will advance science that is understandable and can be used by broader segments of society.

Multiple educational pathways are necessary to achieving a diverse workforce. Since its charter, the AC-ERE has emphasized the importance of empowering underrepresented minorities to participate in environmental research and education. To accomplish this, a watershed approach is needed that may need to begin at middle school or earlier, rather than a pipeline that seeks to push all students along together. A watershed approach recognizes that different people enter the STEM community at different points, with different backgrounds, skillsets, and experiences, and with different educational goals. They will move through educational systems at different rates and will need different kinds of programs and support.

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Currently, the total number of interdisciplinary environmental degree programs and students is impressive, but diversity of students in these programs is relatively poor. NSF should expand diverse research experiences for greater numbers, increased sponsorship, and funding. These efforts should link environmental and sustainability-oriented educational programs with diversity-oriented programs such as the Louis Stokes Alliance for Minority Progress (LSAMP) program. Because of the importance of community colleges in serving diverse students, NSF will need to provide increased opportunities for community colleges and universities to collaborate.

**Capacity-building:** NSF's role in capacity-building is declining at a time when increased scientific capacity and scientific literacy are critically needed for problem-solving and informed decision-making. NSF is increasingly funding research on education (the science of education), but the practice of education remains essential to making progress in capacity-building. It is important that NSF funding be sufficient to enable implementation of best practices, guided by understanding from education research. Capacity building should be based on a systems perspective that is more than simply adding programs and that begins with an assessment of needs and an evaluation of what is being done to meet those needs.

NSF must make building the nation's scientific capacity to secure the future a priority of equal weight to advancing discovery to enable and design the future. This means supporting implementation of best practices in education as well as supporting research to better understand learning and teaching. Approaches to environmental education such as those that were embodied in SEES (such as the SEES Fellows program and various coordination networks) need to be evaluated, improved, and sustained, in the long-term. NSF's portfolio of projects in innovative education e.g. the Jason Project, "flipping the classroom", Graduate Teaching Fellows in K-12 Education (G-K-12), and the National Research Traineeship (NRT) Program should be evaluated and where successful, expanded and applied to environmental education. To accomplish this, new activities must be guided by recognition that there is a need to train and develop capacity in interdisciplinary, collaborative environmental research and problem-solving. Such activities can take advantage of new opportunities to spark innovation and allow U.S. environmental industries to compete in the global marketplace.

Much of the interface between environmental research and society comes from people who do not have doctoral degrees. NSF has recently increased its attention to community colleges, which are particularly important because of their diverse student populations, practical orientation, and close ties with the communities they serve. Tribal colleges and universities are also especially important in this regard.

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Focusing support only on training the next generation overlooks the other generations in the workforce who are making decisions now. Investments are necessary to update the current workforce regarding socio-environmental changes and options for proactive decision-making. NSF should recognize the importance of professional development, including master's degree and certificate programs in producing as well as providing continuing education for professionals who are able to participate in the workforce at high levels. Nearly 25% of the programs recognized by the National Professional Science Masters Association (NPSMA) are environmental in scope.

To help the nation keep pace with the rapidity of socio-environmental change, NSF should ensure pathways of opportunity for environmentally-oriented students from pre-college through young professionals, as well those currently in the workforce. This should include fellowships and traineeships, research grants, and support for professional activities. A continuation of programs such as the SEES Fellows would be invaluable in this regard, particularly if it was expanded to support graduate students, postdocs, researchers, and faculty members who wish to cross disciplinary boundaries and connect research or educational activities to societal and design challenges. One possibility might be creation of "IV Grants" (for either "innovation ventures" or "interdisciplinary ventures") that would allow for retraining/professional development in a different area of research and education targeting those in mid/later careers (modeled on the Andrew W. Mellon Foundation New Directions Fellowships in the Humanities). NSF can build on and connect other educational approaches that have been successful within and across disciplines, such as Project Kaleidoscope, Chemistry in Context, Sustainability Improves STEM Learning (SISL), On the Cutting Edge and the InTeGrate STEP Center in the geosciences. Programs such as the STEM Talent Expansion (STEP) program take a systems approach to educational reform, including creation of standards-based curriculum, advancement of pedagogy, professional development, and departmental and institutional scale implementation activities. To build on and leverage this approach, NSF should consider support for an Interdisciplinary Environmental and Sustainability STEP Center to complement funded centers in geosciences and engineering. To be effective at securing system-scale change, STEP Centers would require investment for a period longer than 5 years. Developing partnerships with state agencies dealing with critical regional environmental issues such as California Delta Science Program can have global impact as there are many common science issues with other areas of the world.

**Environmental Literacy:** Changing the forecast in a way that will benefit a broad constituency and secure prosperity will require a scientifically informed public. Fortunately, environmental issues are excellent gateways to enhance public understanding of science. There is often wide and deep interest in these issues, including newsworthy topics such as climate change as well as newer and emerging fields such as energy education. Many successful programs of citizen science, public awareness, and lifelong learning can be built upon to reach new audiences to deepen scientific literacy. This literacy is essential to inform the personal and societal-level choices about environmental outcomes that will have to be made in the next 10 years.

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**Synthesis:** There is a need to continue and enhance support for synthesis across disciplines in science and engineering within and across academia and industry. The NSF-funded National Socio-Environmental Synthesis Center (SESYNC) is developing a field of socio-environmental synthesis, bringing together scholars and information across disciplinary boundaries with the intent of better summarizing scientific information for the public. This is a welcome development in the field. However, the emerging field of synthesis must be accompanied by a field of translation of scientific knowledge with respect to environmental design and problem-solving. In all cases, synthesis and translation will be most effective if the users/stakeholders of scientific information are engaged fully and at the earliest stages.

**Translation:** Much of the portfolio of environmental research and education occurs within Pasteur's Quadrant of use-inspired basic research. To operate successfully in this quadrant, scientists must develop connections with and understand the needs of the users. NSF should support efforts for translating knowledge into action, including up front involvement of stakeholders and co-creation of knowledge to enable the application of scientific findings in decision-making and design by a range of stakeholders and users, including educators and community partners. Understanding and enabling the connections between science and society to understand decision-making and the design process, and to facilitate partnerships between scientists, scientific institutions, state and local community "implementers" (physical communities, communities of practice, institutions), non-governmental organizations, and the private sector will accelerate the use of the fundamental science supported by NSF.

NSF should look at models that have been successful in translating knowledge in other fields, such as the former publishing partners program in Education and Human Resources, Centers for Translational Practice, and various approaches in informal science education (such as how science museums have used experiences to help students understand basic science concepts — e.g. "from poop to plastic"). In addition, the I-Corps program provides a useful model, which could be modified into an "E-Corps" to provide training and resources for PIs to build connections with stakeholders.

Translation cannot be unidirectional. If science is to serve society, scientists need to listen to and understand the needs of the public whose tax dollars support science. This needs to happen on the level of the project, the institution, the community, and the nation.

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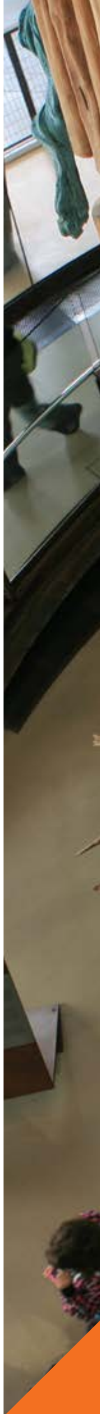
**Broader Impact Networks and Nodes:** The AC-ERE proposes the creation of a program to support Broader Impact Networks and Nodes (BINNs). BINNS would be multi-institutional collaborations that would connect education and community engagement professionals with researchers in order to more effectively accomplish broader impact objectives. They would enable PIs to embed the education and outreach activities of their projects within a larger framework that is designed to integrate current learning science and advance innovation in education and outreach with robust evaluation plans, iterative engagement with adaptive design, long-term relationships with partners, and involvement of underserved populations. This integrated approach is much more likely to have and document significant broader impacts than small-scale and uncoordinated activities of individual investigators. While individual broader impact activities may have local impact, they often require considerable resources to successfully design and implement, and are challenging to evaluate. Establishing larger broader impact frameworks can be achieved through long-term support for networks and nodes which PIs can utilize in their individual projects. Modeled on the NSF Science and Technology Centers, Centers for Ocean Science Education Excellence, Climate Change Education Partnership programs, and Research Coordination Networks (RCNs), BINNs could be thematic, regional, or institutional. Leveraging resources and best-practices among the BINNs can be achieved by establishment of a cross-cutting alliance.

A program that supports BINNS would accelerate transfer of knowledge to the public to create a scientifically literate nation, enable PIs to embed the education and outreach activities of their project within a larger framework and within an institution with professional expertise in education and communication, integrate current learning in science and advance innovation in education and outreach, have robust evaluation plans that would provide for iterative engagement with adaptive designs, establish long-term relationships with Broader Impact partners, target underserved populations, and allocate sufficient funding levels and terms to have the impact that is needed to address these challenges at scale and "move the needle."

To ***enable and secure the future***, the AC-ERE recommends NSF-wide activities that:

- *Ensure an over-arching portfolio for coordination of NSF's investments in environmental research and education, and maintain an internal structure for its management and coordination.*
- *Establish stable and long-lasting cross-directorate support that builds on core and emerging programs to catalyze and invest in cross-disciplinary teams that bridge natural science, social science, international science, engineering, education, and human resources.*
- *Integrate environmental systems-thinking and design into core programs.*
- *Provide a variety of types and levels of awards – including exploratory awards for beginning investigators as well as funding on the scale needed to support long-term, interdisciplinary teams.*
- *Accelerate diversity in research and education through systems science motivated by societal issues and multiple pathways for educating people from diverse populations.*
- *Connect scientific knowledge to societal needs by better leveraging broader impacts investments.*



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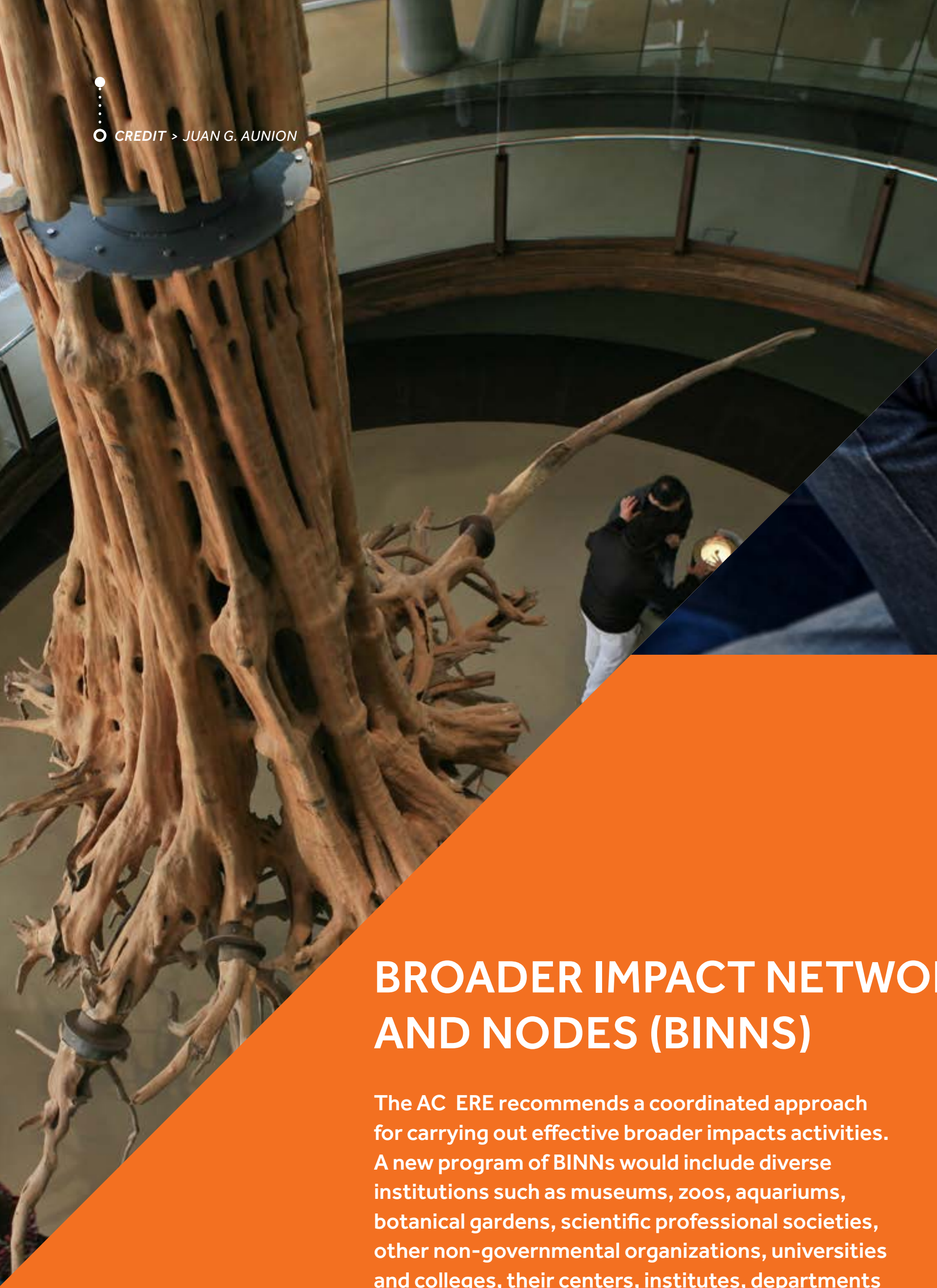

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## BROADER IMPACT NETWORKS AND NODES (BINNS)

The AC ERE recommends a coordinated approach for carrying out effective broader impacts activities. A new program of BINNs would include diverse institutions such as museums, zoos, aquariums, botanical gardens, scientific professional societies, other non-governmental organizations, universities and colleges, their centers, institutes, departments and other partners. Each BINN would have a core staff of professionals to carry out education, outreach, evaluation, and other broader impacts activities, in partnership with participating PIs and their project teams. They could organize training activities such as workshops on best practices in community-engaged research that would bring together researchers and communities. This network model can effectively reach underserved populations and provide opportunities to broaden participation in science.

We envision BINNs being supported by a core budget supplemented by project-specific funds that would be written into individual proposals. Currently, every NSF grant proposal has an individual budget for broader impact activities. A large part of the resources necessary to support more effective broader impacts could be gained by shifting those design and implementation dollars to the BINN, while retaining the salary support needed for the PI team to engage with the BINN. This would not "out source" broader impacts activities away from individual projects, but would more effectively leverage expertise to assist PIs with implementing broader impact approaches that work. For example, museum-based BINNS can involve PIs in ongoing, effective, and well-advertised lectures, demonstrations, interpreter training, and "meet the scientist," programs. Thematic BINNs can focus on engaging decision-makers, development of novel educational approaches, and connecting with specific audiences, including stakeholders. Professional society-led BINNs could provide workforce preparation through professional development programs. Because BINNs would have long-term support, stakeholder partnerships could be developed for effective collaboration, allowing for two-way communication of needs and opportunities and thus better serving national needs. A robust evaluation plan for each BINN would enable iterative improvement as part of an adaptive management approach.

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REPORT CONCLUSION

A FRAMEWORK FOR RE-ENVISIONING

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# A FRAMEWORK FOR RE-ENVISIONING

NSF's mission is "To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…." Investment in environmental science, engineering, and education carry out this mission and are essential to enable and secure a thriving century by changing the trajectory of current trends — away from warming, stress, conflict, and vulnerability, and toward resilience, well-being, stewardship and prosperity. This is the challenge, opportunity, and imperative for our time. The next decade of NSF's investments in environmental education and research will influence these trends for many more decades to come.

NSF is poised to address what is rapidly becoming the defining issue of our time, and can capitalize on the experience of more than half a century of establishing scientific research and education networks, promoting the development of new scientific disciplines, and building infrastructure to support scientific research and education. As the pace of environmental change accelerates, investment in science and engineering must keep pace to better understand the components of complex socio-environmental systems and their interactions, to design adaptive systems which increase our resilience to the coming changes and extreme events, and to build the nation's scientific capacity to secure a thriving and prosperous future.

We have outlined a framework for re-envisioning the ERE programs, with an emphasis of sustaining the past success and continuing to support strong investments in interdisciplinary, cross-directorate activities. The report promotes the notion of improving forecasting, coupled with science-based design of sustainable and resilient environmental systems. As we note above, investments in research and education can be directed to activities that anticipate and shape, not merely adapt to future states and conditions in the environment and economy. This aim requires programs that improve understanding of environmental changes with the translation of this knowledge into new ideas and designs for the type of environment in which we want to live. We argue that society is continually designing and redesigning the built and natural environment. Science and engineering can be marshaled to improve these designs and enable evidence-based decision-making through investments in scientific research.

At the same time, the Foundation should continue to invest, at increased levels, in an interdisciplinary and diverse ERE workforce. We note the increasing need for Foundation support to facilitate broadening impacts, since by definition environmental research begins with strong connections to societal needs.

We have provided an outlook for the next decade of ERE programs. The vision is rather broad, and it will be important for the Foundation to work closely with the AC-ERE to begin thinking about how the agency and its directorates might implement this agenda. We know that implementation of this vision will not be easy for NSF. The challenges are enormous and current resources pale in comparison. Our recommendation is to build on the environmental education and research programs developed over the first decade and a half of this century, but strategically increase investments through 2025. The time to begin is now.

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# LONG-TERM RESEARCH AND CHANGING THE FORECAST

Acid rain in the Northeast, urban growth in Phoenix, changing West Coast fisheries, and land-use change in New England. Scientists are peering into the future to discern long-term outcomes of these and other environmental changes. Is there any good news among these concerns?

Scientists at the Harvard Forest Long-Term Ecological Research (LTER) site are mapping what the Massachusetts landscape might look like in 2060, and what might be done to influence the outcome. With shifts in land management practices, results suggest that it s possible to preserve forest benefits — clean water, carbon storage, habitat — while supporting economic development. Other LTER sites are tackling additional environmental challenges.

At the Central Arizona Project LTER site, researchers are developing future scenarios for the city of Phoenix. At the California Current LTER site, scientists have found that marine organisms throughout the food web respond to the El Niño Southern Oscillation, with implications for managing the productivity of west coast fisheries.

At the Hubbard Brook LTER site, studies of local watersheds have been ongoing for more than 50 years. As a result, Hubbard Brook was the first place in North America where acid rain was identified, and later found to originate from the long-range transport of sulfur dioxide and nitrogen oxides from power plants. Ultimately, Hubbard Brook research influenced national and international acid rain policies that significantly reduced sulfur dioxide emissions.

Today, Hubbard Brook scientists report that decades of acid and nitrogen deposition have had persistent effects, with significant advances in understanding changes in soil chemistry caused by nitrogen pollution. The results show that these forests experienced losses in calcium — a key nutrient for tree growth. In 1999, Hubbard Brook researchers spread 40 tons of calcium over a 29-acre watershed, which significantly increased tree growth and forest productivity relative to untreated areas. New calcium addition studies continue to reveal forest responses to environmental changes, and methods for mitigation.

Scientists at LTER sites and other NSF-funded projects are working to understand our role in Earth s dynamic environment, and to discover where everything from the flow of a river to the growth of a forest to the winds of El Niño will take us in a future we can understand, predict, and mitigate in ways that will not only anticipate, but can improve the forecast.

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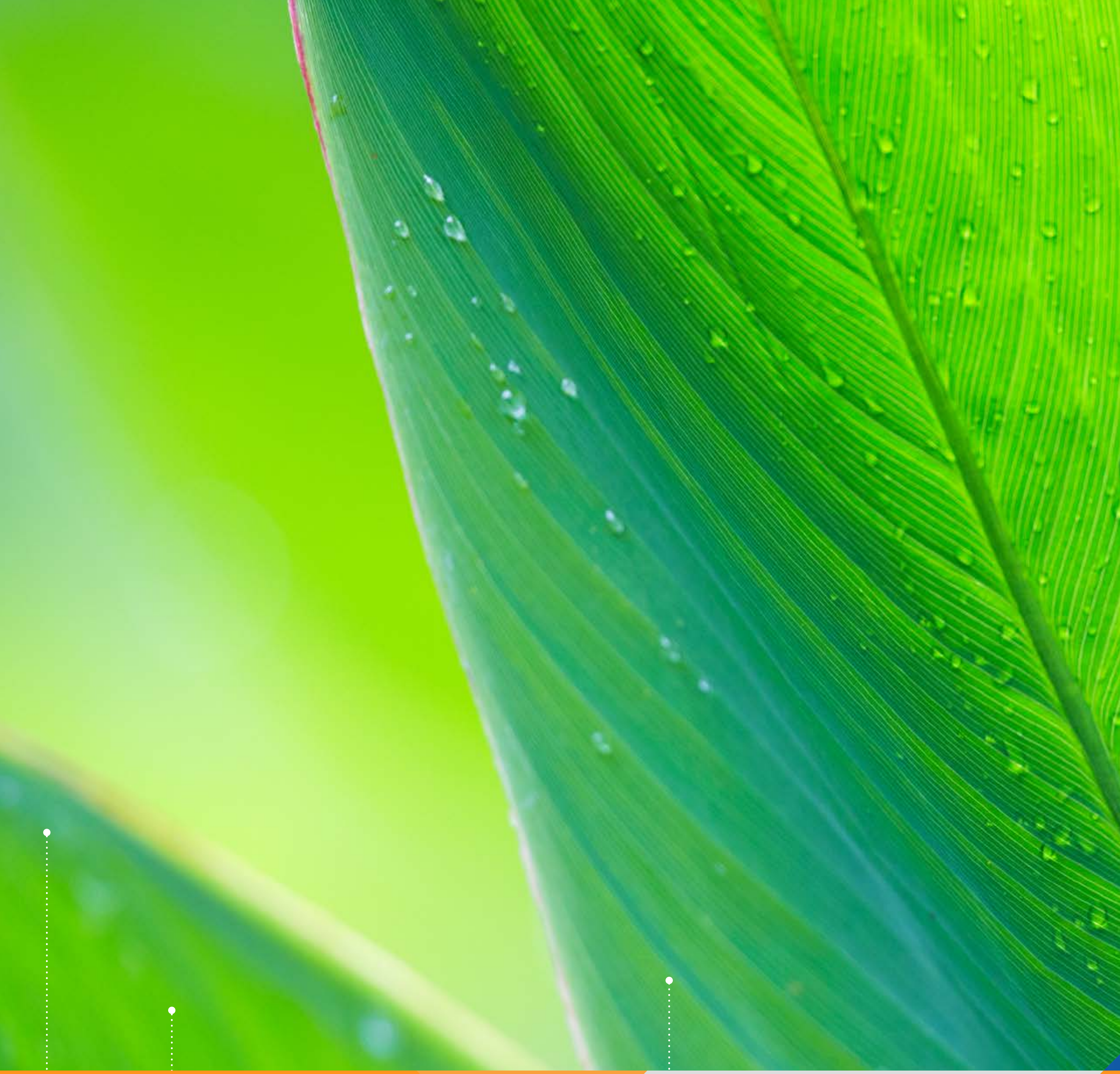

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