Grand Challenges in Global Sustainability Research: A Systems Approach to Research Priorities for the Decade

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We propose a focused global initiative addressing five Grand Challenges in Global Sustainability Research. These challenges must be addressed over the next decade if society is to manage the global environmental change that is now underway and cope with the change that we cannot manage. Given the pace and magnitude of human-induced global change, immediate action is needed to avoid the most dangerous outcomes for people and for the planet. In this context, science has to focus on delivering to society information that will directly and effectively inform and support the responses and actions of decision-makers and citizens in all regions of the world. The International Council for Science (ICSU) and its partners are leading an international consultative process to: (a) define today's grand challenges in global sustainability; (b) identify high priority research that must be carried out; and (c) mobilize social scientists, natural scientists and the humanities around an unprecedented 10-yr initiative to address these challenges.

The study of the Earth System has reached a point of transition. For the past two decades, our priority has been to understand the functioning of the Earth System and, in particular, the impact of human actions on that system. While many critical research questions remain in this area, science has advanced to the point that we now have a good understanding of how the Earth System is changing and a growing understanding of how those changes will affect society and human well-being. Earth System science has provided invaluable new insights over the past decade regarding the biophysical processes that determine the functioning and resilience of planet Earth, the sensitivities of the components of the Earth System, evidence of the accelerated pace of global environmental change caused by the human enterprise, the possible consequences of those changes, and the human dimensions of how to address these challenges.

This science also tells us that the rate of global environmental change is, so far, vastly outpacing our response. Even though many questions remain to be answered, we know enough to state with a high degree of scientific confidence that humanity has reached a point in history at which a prerequisite for development – the continued functioning of the Earth system as we know it – is at risk. Without fundamental changes in the human drivers affecting the Earth System and without actions designed to enhance the resilience and decrease the vulnerability of human communities, it is now clear that changes in climate, hydrological cycles, food systems, sea level, biodiversity, ecosystem services and other factors will cause massive human suffering. If unchecked or unmitigated, these changes will retard or reverse progress towards broadly shared economic, social and environmental goals.

Building on the scientific advances that have been made over the past two decades, the research frontier is now shifting from a primary focus on understanding human impacts on the Earth System to a broader agenda that also includes a strong focus on understanding and forecasting the consequences of global environmental changes and how to respond to those changes. New, strategic, inter-disciplinary research is needed to improve our understanding of the social-environmental risks facing humanity and to provide science-based support for actions to address the growing challenge of global environmental change. **Over the next 10 years the global scientific community must take on the challenge of delivering to society the knowledge and supporting information necessary to assess the risks humanity is facing from global environmental change, and to understand how society can effectively mitigate dangerous changes and cope with the change that we cannot manage.** We refer to this field as "global sustainability research."[1] Global sustainability research builds upon expertise within the basic natural and social sciences and applies it to pressing coupled social-environmental research questions.

Just as we are at a point of transition in the focus of global social-environmental research, we are also at a point of transition in the disciplines that must be involved and the processes by which that research is undertaken. Social sciences have long been a component of Earth System research, but tackling the grand challenges described here requires a stronger involvement and greater integration of the social sciences and humanities, along with the natural sciences. It is increasingly clear that pathways to address rapid global environmental change can only be found through inquiries that integrate the social sciences, humanities and the natural sciences in ways that may lead to significant transformations in these disciplines as they are currently understood. It also requires the inclusion of local, traditional and indigenous knowledge. And, it requires the co-creation of new knowledge with a broad range of stakeholders. Research will be most useful if priorities are shaped with the active involvement of potential users of research results and if the research is carried out in the context of a bi-directional flow of information between scientists and users. These changes in the disciplines involved and research processes are needed because they will bring greater expertise to bear in addressing the research priorities, because they help to ensure that the research priorities are relevant to key stakeholders, and because the answers to the research questions can more readily inform decision making.

In light of the urgent needs, ICSU and its partners are seeking to mobilize social and natural scientists and researchers in the humanities around an unprecedented, 10-year scientific effort to address the grand challenges in global sustainability. The process to reach consensus on the grand challenges and research priorities began with an Internet consultation in July and August 2009.[2] The Internet consultation yielded more than 300 proposed Earth System research priorities contributed by scientists from 85 countries. These proposed research priorities formed the background for a

[1] We consider the field of "global sustainability research" to be largely equivalent to "Earth System research," but with a more explicit recognition of the human dimension. The Earth System is defined as the unified set of physical, chemical, biological, and social components, processes and interactions that together determine the state and dynamics of the Earth, including its biota and its human occupants. Although Earth System science includes humans as an integral component of the Earth System, this term is seen by many to focus primarily on the natural system. The term "global sustainability research," helps to give greater emphasis to the central importance of the social sciences in this research agenda.

[2] The full process is described in detail at: http://www. icsu-visioning. org/the-visioning-process/. The Internet consultation (www. icsu-visioning. org) attracted over 7000 unique visitors from 133 countries and over 1000 registered users from 85 countries, who posted research questions, made comments and voted on the questions. By the end of the consultation, 323 distinct Earth system research questions had been posted on this moderated site.

workshop held in September 2009 involving senior researchers, early career scientists, science-policy experts and representatives of research funding agencies. The workshop generated the selection criteria, grand challenges, and research priorities contained in this draft. We are now seeking a broader review of this document with the aim of producing a widely shared vision of the scientific priorities for global sustainability research in the coming decade.

The final outcome of this process is intended to: a) guide the prioritization of research topics by scientists and policy makers; b) inform decisions by agencies funding research in the areas of global sustainability and Earth System research, and social and natural sciences; and, c) inform potential users of the research findings, including scientific assessments like the Intergovernmental Panel on Climate Change, and technical advisors to decision-makers in the private sector and governments. Representatives of these stakeholder groups have been involved in the development of the current draft and will continue to be involved in the ongoing consultation and revision of the draft.

The research that this process aims to catalyze, and the knowledge that will be generated, is intended to help the public and decision-makers in government, the private sector, and non-governmental organizations in their efforts to achieve economic, social and environmental goals. More specifically, progress in addressing the grand challenges of global sustainability will assist efforts to: minimize adverse global environmental change and limit further environmental degradation in socially acceptable sustainable ways; achieve food, water, energy, health and human security; address goals for economic, environmental and social sustainability and equity; and, alleviate global poverty.

Criteria

We have used the following criteria in selecting the grand challenges and research priorities.

1. **Scientific importance.** Does the question address a cutting-edge research challenge that, if answered, could significantly advance our understanding within the next decade of how to achieve global sustainability?
2. **Relevance to decision-makers.** Will the answer to the question help to inform actions to meet urgent global needs, especially promoting sustainability, reducing poverty, and assisting the most vulnerable in coping with global environmental change?
3. **Broad support.** Does the question have support from the research and funding community (even those not directly involved in answering the question)?
4. **Global coordination.** Is a coordinated international or global approach involving multiple researchers in different regions and often in different disciplines needed to answer the question? If not, then such a question would fall outside the remit of this framework, despite its importance to a given field.
5. **Leverage.** Does the answer to the question involve a scientific or technical breakthrough, or would it create a transferable theory, model, scenario, projection, simulation or narrative that would help to address multiple problems or other challenges related to global sustainability research?

The Grand Challenges in Global Sustainability

Consistent with the use of the concept of grand challenges in other areas of science, we consider a grand challenge in global sustainability research to be a call for scientific innovation or understanding that would remove a critical barrier to deciding how to manage global change and its impacts. We list five grand challenges in global sustainability. Within each, we list several top-level research priorities that must be addressed to solve the problem posed by the grand challenge during the next decade. The list of research priorities is neither exhaustive nor necessarily sufficient. However it is our judgment that these questions must be addressed to achieve the most rapid progress. In virtually all cases, a deep base of research and knowledge already exists in the areas identified by these research priorities and, building on that base, it is thus plausible that the research area can be substantially advanced in less than a decade. However, it is by no means inevitable that all the questions can be answered. These are, by definition, big and difficult problems, and will require a focused, multidisciplinary, and integrated research commitment to have a reasonable prospect of success.

The five grand challenges are a package, and the topics are not prioritized either across or within the challenges. **Progress on every one of the challenges and research questions is urgently needed.** The global sustainability research community has unique capacities to contribute to the solution of these challenges, but all of them will require working with partners outside of this research community as it currently exists.

Challenge #1: Improve the usefulness of forecasts of future environmental conditions and their consequences for people.

Priority Research Questions

1.1. What significant environmental changes are likely to result from human actions, how would those changes affect human well-being, and how are people likely to respond?

1.2. What threats does global environmental change pose for vulnerable communities and groups and what responses could be most effective in reducing harm to those communities?

Our limited ability to anticipate the outcomes that result when complex human societies interact with equally-complex natural processes is a significant barrier to timely and effective decision-making and action. Although we may never be able to accurately forecast the future of coupled social-environmental systems beyond a time horizon of several decades, there is tremendous potential for improving our ability to use scenarios and simulations to anticipate the impacts of a given set of human actions or conditions (e.g., greenhouse gas emissions, deforestation, increased agricultural productivity, etc.) on global and regional climate and on biological, geochemical, and hydrological systems on seasonal to decadal time scales. In turn, we should be able to forecast the potential impact of those changes on human well-being (e.g., impacts on economies, health, food security, energy security, etc.). Forecasts should be tailored to respond to the questions and needs of the people potentially affected, and the uncertainty of the forecast should be quantified and

communicated. By meeting this challenge, models and analyses of global and regional environmental change will be able to provide direct support to governance and management at national and regional scales, and over the typical time-frames of political and management decisions.

Significant improvement is needed in our ability to develop contingent forecasts or scenarios that address the full range of plausible outcomes within a probabilistic framework, and at appropriate spatial and temporal scales to assess impacts on economies, ecosystem services and human well-being. Importantly, such scenarios must improve representation of the dynamic response of both the natural and social system. Progress in this area of research will require advances in modelling capability (including development of the ultra-high performance computing infrastructure that will be needed for that modelling) and a more interdisciplinary framework of analysis.

Examples of key questions that need to be answered include: How will regional climate change over decadal time scales? What adaptation strategies are needed to reduce vulnerability to global environmental change? When do individual human actions aggregate to cause consequences for larger regions or the Earth system? How are changes in ecosystems and biodiversity going to affect ecosystem services and human well-being? What trade-offs occur among services and human well being, and are there strategies to minimize such trade-offs? What kinds and levels of biodiversity are needed to buffer the impacts of environmental change on ecosystem services? To respond these questions we will need scientific advances and better observation systems.

Challenge #2: Develop the observation systems needed to manage global and regional environmental change.

Priority Research Questions

2.1. What do we need to observe in coupled social-environmental systems, and at what scales, in order to respond to, adapt to, and influence global change?

2.2. What are the characteristics of an adequate system for observing and communicating this information?

The current supply of information needed to manage the social-environmental system, especially at a global scale, as well as the system for delivering that information to decision-makers, is inadequate for the task. Further advances in theories, models, scenarios, projections, simulations, or compelling narratives used to understand the Earth System and to forecast changes are constrained by limited availability of data needed to set parameters and validate predictions. Moreover, the paucity of empirical data on changes in social-environmental systems undermines the ability of decision-makers and the public to establish appropriate responses to emerging threats and to address the needs of vulnerable groups of people. Although the observation systems currently in place are insufficient to meet the needs, they do provide a firm foundation upon which the necessary systems can be built.

The observation systems required need to encompass both natural and social features, be of high enough resolution to detect systematic change, assess vulnerability and resilience, include multiple sources of information (quantitative, qualitative and narrative data and historical records), involve

multiple stakeholders in the research process, support effective decisions at global to local scales, and be formally part of adaptive decision making processes. They would include critical data needs such as: comprehensive time-series information on changes in: (1) land cover and land use, biotic systems, air quality, climate change and changes in use and ecological characteristics of the oceans; (2) spatial patterns and changes in freshwater quantity and quality, for both ground- and surface-water; (3) changes in stocks, flows and economic values of ecosystem services; (4) trends in components of human well-being (particularly those not traditionally measured, such as access to natural products that are not marketed); (5) socio-economic indicators, including population distribution, economic activities and mobility; and, (6) patterns of human responses to these developments. The design of such a system would need to address the question of how local and regional environmental changes can be scaled accurately and effectively to enhance the assessment of global changes, and vice-versa. The entire design should include a process and institutional arrangements for observation systems to be aligned with assessment and policy processes.

This grand challenge is both a research challenge and a challenge for science policy. Fundamental scientific questions need to be addressed in the design of cost-effective systems that can meet the needs of managers and decision-makers. The implementation of such systems, on the other hand, is not a research challenge but will nevertheless require an ongoing and concerted effort by the scientific community if it is to be achieved, even beyond the timescale of the work envisaged here.

Challenge #3: Determine how to anticipate, avoid and cope with dangerous global environmental change.

Priority Research Questions

3.1. Which aspects of the coupled social-environmental system pose significant risks of runaway dynamics?

3.2. How can we identify, analyze and track our proximity to thresholds and discontinuities in coupled social-environmental systems? When can thresholds not be determined?

3.3. What strategies for avoidance, adaptation and transformation are effective for coping with abrupt changes, including massive cascading environmental shocks?

3.4. How can the need to curb global environmental change be integrated with the demands of other inter-connected global policy challenges, particularly those related to poverty, conflict, justice and human security?

3.5. How can improved scientific knowledge of the risks of global change and options for response most effectively catalyze and support appropriate actions by citizens and decision-makers?

Linear changes in the global environment can have dangerous impacts on people if their magnitude or rate is sufficiently high. In addition, it is increasingly likely that we will encounter discontinuous ('abrupt' or 'non-linear') changes in the global environment such as abrupt changes in regional climate, rapid collapse of ice sheets, rapid methane release associated with melting permafrost, and abrupt change in the structure and functioning of biological systems. Moreover, an increasingly

interconnected world generates linked trends and shocks in seemingly disparate sectors such as energy, finance, food, health, water and security. A major focus of research must be to better determine strategies for avoidance, adaptation or transformation of social-environmental systems to accommodate changes that are dangerous because of their speed, scale, non-linear nature, cumulative impact, self-amplifying nature or irreversibility. Research into appropriate response and adaptation strategies must also extend beyond considerations of 'optimal' approaches to advance understanding of the political and social dynamics of responses. Under what conditions are policy innovations more likely to occur (e.g., many significant policy changes take place during times of crisis) and what are the implications of these patterns for the design and promotion of response options?

An effective response to global environmental change will also require much greater understanding of the inter-relations between global environmental change, global poverty and development needs, and global justice and security. For example, how will global environmental change influence progress toward the goals of reducing poverty and hunger and improving maternal and child health? What are the risks posed by global environmental change to human security? How does global environmental change shift the agenda for sustainable development in the world?

Challenge #4: Determine what institutional and behavioural changes can best ensure global sustainability.

Priority Research Questions

4.1. What institutional structures are effective in balancing the trade-offs inherent in social-environmental systems at local, regional and global scales and how can they be achieved?

4.2. What changes in economic systems would contribute most to improving global sustainability and how could they be achieved?

4.3. What changes in behaviour or lifestyle, if adopted by a particular society, would contribute most to improving global sustainability and how could they be achieved?

4.4. How can institutional arrangements prioritize and direct resources to alleviate poverty and address social injustice under rapidly changing local environmental conditions and growing pressures on the global environment?

4.5. How can effective, legitimate, accountable and just collective environmental solutions be mobilized?

Global change exposes gaps in social institutions, including governance and economic systems, for managing emerging global (and local) problems. The time and spatial scales of global change differ fundamentally from the types of problems that humanity has addressed in the past. Currently, decision-makers have incentives that favour local, short-term and private benefits, rather than long-term and collective benefits. Addressing the problems of global change, including resource use, pollution of the global commons and population growth, will require a step change in research addressing fundamental questions of governance, economic systems and behaviour.

Determining how to achieve such changes in social institutions and behaviour is just as important as establishing what changes are desirable. In many cases, successful changes in institutions will stem from steps taken to achieve collective social action in response to the challenge. How can timely action be undertaken at unprecedented geographical and geopolitical scales, where the nature and scale of the issues involved means that the actors have widely differing – and disconnected – values, ethics, emotions, spiritual beliefs, levels of trust, interests, and power? How can we better understand the role of individual decisions as the building block of societal decisions? How can we better understand the factors shaping individual behaviour, values and perceptions of threats and risks and how those values and perceptions influence both individual action in relation to global change and the potential for collective action? Recognizing individuals, not just policymakers, as a fundamental unit forces attention to a new level of detail on how information about the environment and feedback on thresholds being reached and breached can impact social changes and actions. Such information can influence individuals, who then incorporate this information along with other factors such as institutions or policies, to make decisions that then aggregate to impact society and the environment.

Challenge #5: Develop and evaluate innovative technological and social responses to achieve global sustainability.

Priority Research Questions

5.1. What incentives are needed to strengthen national systems for science and technology innovation to respond to global environmental change and what good models exist?

5.2. What incentives are needed to strengthen policy and institutional innovation to respond to global environmental change?

5.3. How can global energy security be provided entirely by sources that are renewable and that have neutral impacts on other aspects of global sustainability, and in what time frame?

5.4. How can food production be increased to meet anticipated needs over the next half century while dramatically reducing land-use greenhouse gas emissions, protecting biodiversity, and maintaining or enhancing ecosystem services?

5.5. What are the potentials and risks of technological strategies (e.g., geo-engineering) to address global environmental change, and what local to global institutional arrangements would be needed to oversee them, if implemented?

Unprecedented challenges require novel, innovative responses. While many of these grand challenges address the need for solutions-oriented research, it is increasingly clear that the scale and potential impact of global environmental change may necessitate the consideration of entirely novel technologies, institutions and policies. Considerable work is underway to explore innovative approaches such as geo-engineering and green energy technologies. How can such innovation be responsibly intensified? How can risks associated with global environmental management be adequately assessed?

Three issues demand particular research attention in this regard. First, it is clear that fundamental changes are needed in our systems of energy production and use in order to avoid dangerous climate change. Research is needed to help identify and develop new systems for energy production and use and to assess the impacts of these systems on the environment and society. Second, at current rates of growth in agricultural yield it is highly unlikely that we can simultaneously meet the needs over the next half century for: a) increased food demand from growing (and wealthier) populations; b) reduced greenhouse gas emissions associated with land use change and agricultural production; c) increased production of biofuels; d) reduced rates of loss of biodiversity; and, e) enhanced ecosystem services. What are plausible scenarios for addressing this problem? What are the costs, benefits, and risks of different policy, technological or ecosystem-based management strategies that might be applied? Finally, although research is needed to explore the entire set of policy, institutional and behavioural changes that could mitigate climate change and enhance adaptation to climate change, increased attention should now be given to research to understand the costs, benefits, and risks of various geoengineering strategies and the institutional arrangements that would be needed to oversee such strategies if they were implemented.

Expected Outcomes

The primary product of the research that will be guided by this 10-year initiative is the knowledge base needed to manage global change and to cope with the change that cannot be managed. This knowledge base, and the process of developing it, should make a major contribution to efforts to reduce global poverty and improve global justice in ways that do not unduly exacerbating environmental stresses. This research will yield a set of more tangible products:

- Validated theories, models, scenarios, projections, simulations, or compelling narratives of social-environmental systems at global to local scales. (Challenge 1 and 2)
- Prioritized needs for Earth system observations of physical, chemical, biological and social variables and the design features of a system for delivering that information. (Challenge 2)
- A framework for forecasting the likelihood, location, drivers, severity and risk of high magnitude, abrupt or non-linear changes associated with global environmental change. (Challenge 3)
- Options for practices and institutions that allow effective action (or provide sufficient resilience) in response to signals of impending dangerous changes. (Challenge 3 and 4)
- Designs for institutions, procedures and practices that will serve to align disconnected interests, rebalance power asymmetries and facilitate collective action. (Challenge 4 and 5)
- Options for policies and practices that accelerate social and technological innovation relevant to the needs of managing global environmental change. (Challenge 5)
- Methods for exploring the costs, benefits and risks of alternative strategies to achieve global sustainability. (Challenge 5)
- New methods for doing research, in which stakeholders are empowered, informed and motivated through the research process to take effective action. (All Challenges)

Next Steps

This document is part of an agenda-setting consultation that is intended to guide and stimulate scientific research on global change and global sustainability over the next decade. As such, it is a 'living document' that will be improved and revised as more stakeholders contribute to its content and confirm its basic premises. It is expected to become part of a broader process among scientists and scientific institutions to commit themselves to work together systematically – across disciplines and geographic regions – on agreed priority research questions that are critical to the sustainability of our planet for the future. The collaboration will likely be transformative for all involved, and one in which the goals are recognized as going far beyond science itself. As the process goes forward we invite contributions to this document to expand and improve it.

Definitions

Coupled social-environment system: A system in which the social and biophysical subsystems are intertwined so that the system's condition and responses to external forcing are based on the synergy of the two subsystems.

Earth system: The unified set of physical, chemical, biological, and social components, processes and interactions that together determine the state and dynamics of the Earth, including its biota and its human occupants.

Ecosystem services: The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational, and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions for life on Earth.

Global change: Changes in biophysical environment caused naturally or caused (or strongly influenced) by human activities and the associated changes in society, institutions and human well-being. These may either manifest at the global scale or be occurring on a local scale but so widespread as to be a global phenomenon.

Global environmental change: Changes in biophysical environment caused naturally or caused (or strongly influenced) by human activities. These may either manifest at the global scale (e.g. increasing atmospheric CO_2) or be occurring on a local scale but so widespread as to be a global phenomenon (e.g. soil degradation).

Human well-being: A context- and situation-dependent state, comprising basic material for a good life, freedom and choice, health and bodily well-being, good social relations, security, peace of mind, and spiritual experience.

Resilience: The level of disturbance that an ecosystem can undergo without crossing a threshold to a situation with different structure or outputs. Resilience depends on ecological dynamics as well as the organizational and institutional capacity to understand, manage, and respond to these dynamics.