

Earth System Science for Global Sustainability: Grand Challenges

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Tremendous progress has been made in understanding the functioning of the Earth system and, in particular, the impact of human actions (1). Although this knowledge can inform management of specific features of our world in transition, societies need knowledge that will allow them to simultaneously reduce global environmental risks while also meeting economic development goals. For example, how can we advance science and technology, change human behavior, and influence political will to enable societies to meet targets for reductions in greenhouse gas emissions to avoid dangerous climate change? At the same time, how can we meet needs for food, water, improved health and human security, and enhanced energy security? Can this be done while also meeting the United Nations Millennium Development Goals of eradicating extreme poverty and hunger and ensuring ecosystem integrity?

Answering these questions will require reorientation toward new research that better allows science and society to address the needs of decision-makers and citizens at global, regional, national, and local scales (2). We will have to meet a twofold challenge: (i) develop strategies to respond to ongoing global change while meeting development goals and (ii) deepen knowledge of the functioning of the Earth system and its critical thresholds (3). Promoting sustainable development requires research on a wide range of social, economic, cultural, institutional, and environmental issues (4). Given that sustainable development is no longer possible without addressing interactions with global change dynamics (5), we focus here on an important dimension of this larger sustainability agenda: the need to broaden and

deepen Earth system research to encompass the intersection of global environmental change and sustainable development.

Grand Challenges

A great deal of collaborative international research on global environmental change is coordinated through four Global Environmental Change Research Programmes (6) and the Earth System Science Partnership. In light of the need for an overarching set of solution-focused and integrated research priorities for these institutions, the International Council for Science (ICSU) and the International Social Science Council (ISSC) carried out a consultative process to rethink the focus and framework of Earth system research (7, 8). Efforts were made to obtain balanced input from developed and developing country experts, young and senior scientists, social and natural sciences, and both researchers and those using the findings of research. This process resulted in five “Grand Challenges” (listed below in *italics*), a consensus list of the highest priorities for Earth system science that would remove critical barriers impeding progress toward sustainable development (9). The challenges meet four criteria: (i) scientific importance, (ii) need for global coordination, (iii) relevance to decision-makers, and (iv) leverage (i.e., would help address multiple problems). For each grand challenge, several important research questions are identified as answerable within a decade.

Improve the usefulness of forecasts of future environmental conditions and their consequences for people. We need to develop what amounts to an enhanced Earth system simulator to improve our ability to anticipate impacts of a given set of human actions or conditions on global and regional climate and on biological, geochemical, and hydrological systems on seasonal to decadal time scales. Most current efforts to build state-of-the-art whole-Earth system models depart from sophisticated geophysical kernels (coupled atmosphere-ocean models based on exact dynamical equations like Navier-Stokes) that are to be complemented by equally powerful tools (once they become available) representing other parts of the planetary makeup. But,

Progress in understanding and addressing both global environmental change and sustainable development requires better integration of social science research.

for instance, there is no marine-biosphere model available that will match the standards of the fluid-dynamics-based simulators of the atmosphere within the next 5 years, and the situation seems to be even worse when it comes to simulation of economic, social, and cultural processes. Thus, alternative approaches need to be explored, such as distributed simulators, where available models for all relevant Earth system compartments are virtually assembled from institutions around the world, even if those sectoral models differ heavily in predictive power, or an ensembles approach, where a given Earth system module would be represented by an entire set of credible realizations.

Research is also needed to assess the potential impact of environmental changes on regional economic conditions, food security, water supplies, health, biodiversity, and energy security. Furthermore, research is needed to understand how people are likely to respond to such changes in different socio-geographic and cultural contexts, in particular in poor and vulnerable communities.

Develop, enhance, and integrate observation systems to manage global and regional environmental change. Although investments are being made to build and coordinate more effective observation systems (e.g., the Global Earth Observation System of Systems), current systems fall short of addressing the grand challenges and meeting decision-makers’ needs for forecasts and other research products. Economic and social science data, for example, are often gathered and reported at scales that are incompatible for analyzing interlinkages between social and natural systems. 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 address the needs of vulnerable groups. To design cost-effective systems that meet these needs, important scientific questions need to be addressed: What do we need to observe, at what scales, in coupled social environmental systems in order to respond to, adapt to, and influence global change?

Determine how to anticipate, avoid, and

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manage disruptive global environmental change. Human interference will likely trigger highly nonlinear changes in the global environment that will tend to alter the very character of the life-support system in question and be largely irreversible on human time scales. In turn, disruptive changes in social systems can result from such events, as well as from more gradual environmental changes. For example, a relatively gradual decline in annual precipitation or soil fertility could lead to an abrupt change in the social system as residents abandon unproductive lands and become environmental refugees. Social and economic policies and institutions are rarely designed for abrupt nonlinear social and environmental change. Understanding the underlying nonlinear dynamics will require integration of environmental and complexity sciences, two fields that have developed largely separately. To confine global change to tolerable ranges, having a low risk of dangerous thresholds or “tipping points,” we will have to identify and track system conditions with respect to key planetary boundaries (e.g., critical levels of ocean acidification) (10). To confine the impacts of unavoidable excursions of the system into dangerous ranges, we will have to enhance resilience to change. Such research may explore whether there are also “positive” social tipping points, that is, pioneering action that can tip economic or social dynamics into sustainable regimes.

Determine institutional, economic, and behavioral changes to enable effective steps toward global sustainability. Global change exposes gaps in social institutions for managing emerging problems. Modern systems of governance are much more effective in addressing national and local problems over time scales of years to decades than in addressing global problems that will affect future generations more strongly than current generations. Addressing problems of global change will require a step change in research on fundamental questions of governance, economic systems, and the assumptions, beliefs, and values underlying human behavior. This must involve close integration of social and biophysical sciences. We must understand how more effective environmental governance can be established at a time of weakening confidence in traditional forms of governance. It is insufficient to identify necessary reforms in policies and institutions; research must explore how to catalyze adoption of those reforms.

Encourage innovation (and mechanisms for evaluation) in technological, policy, and social responses to achieve global sustainability. We need to improve our understand-

ing about how to strengthen incentives for technology, policy, and institutional innovation to respond to global environmental change. For example, there is need for transformative changes in the world's energy system, including efforts at an international level (e.g., establishing a global cap-and-trade system or a global tax on carbon). Insights into how best to attain such international policies can be drawn from innovations at local and regional levels, which are important laboratories for assessing how diverse carbon policies affect economic and social development at multiple scales. Just as countries seek to harmonize public sector research, economic incentives for emerging industries, and public policies to stimulate growth of new competitive industries, a mix of incentives will be needed to generate ideas and technologies to address global change in the context of sustainable development. In particular, we need focused efforts, coupled with careful assessment, on such issues as the potentials and risks of geoengineering strategies (including exploration of local to global institutional arrangements needed to oversee them) and options to meet competing demands for scarce land and water over the next half-century.

A Call to Action

These grand challenges provide an overarching research framework to mobilize the international scientific community around a focused decade of research to support sustainable development in the context of global environmental change. This will require new research capacity, including efforts to attract young scientists, particularly in developing countries. Research dominated by the natural sciences must transition toward research involving the full range of sciences and humanities. A more balanced mix of disciplinary and interdisciplinary research is needed that actively involves stakeholders and decision-makers.

These needs will be challenging to address. There is no simple mechanism to fund “global” research. And because research at the intersection of Earth system science and sustainable development has not attracted great attention from either natural or social scientists, it will take time to build this research community. The disciplinary-dominated structure of academia runs counter to the need to address interdisciplinary aspects of these grand challenges.

But, building on ongoing efforts to promote the broader field of “sustainability science,” there is a growing effort by Earth system science researchers and research funders to overcome these barriers (11–13). For

example, discussions are now under way with the Belmont Forum (13), a group of leading global-change funding agencies, to design an overarching approach that would (i) coordinate and focus international scientific research to address the grand challenges; (ii) deliver at global and regional scales the knowledge that societies need to effectively respond to global environmental change while meeting economic and social goals; and (iii) engage a new generation of researchers in the social, economic, natural, health, and engineering sciences in the necessary research. An innovative international partnership between researchers, operational agencies, research funders, and users is fundamental to this approach. Ultimately, a coordinated international funding approach is needed to ensure strategic codesign and implementation of the research.

Roughly 30 years ago, establishment of the first global environmental change research programs represented a revolutionary response by the scientific community to coordinate research across countries and continents to understand the functioning of the Earth system. In a similar spirit, we call on the scientific community to continue improving our understanding of the Earth system and human impacts, but also to deliver knowledge that will enable human development in a world facing rapid global change.

References and Notes

1. H. J. Schellnhuber, D. Sahagian, *Global Change Newsl.* **49**, 20 (2002).
2. W. C. Clark, H. J. Schellnhuber, P. J. Crutzen, in *Earth System Analysis for Sustainability*, H. J. Schellnhuber et al., Eds. (MIT Press, Cambridge, MA, 2004), pp. 1–28.
3. The Earth system is the physical, chemical, biological, and social components, processes, and interactions that together determine the state and dynamics of Earth, including its biota and human occupants.
4. R. W. Kates et al., *Science* **292**, 641 (2001).
5. B. Walker et al., *Science* **325**, 1345 (2009).
6. These are the World Climate Research Programme, International Geosphere-Biosphere Programme, International Human Dimensions Programme on Global Environmental Change, and DIVERSITAS.
7. W. V. Reid, C. Bréchinac, Y. T. Lee, *Science* **325**, 245 (2009).
8. For process details, see www.icsu-visioning.org/the-visioning-process.
9. For challenge details, see www.icsu-visioning.org.
10. J. Rockström et al., *Nature* **461**, 472 (2009).
11. B. L. Turner, 2nd et al., *Proc. Natl. Acad. Sci. U.S.A.* **100**, 8074 (2003).
12. E. Ostrom, *Science* **325**, 419 (2009).
13. ICSU analyzed global change research capacity needs on behalf of research donors; www.icsu.org/2_resourcecentre/ICSU_Belmont_report.
14. H.H., K.M., E.O., K.R., W.V.R., J.R., H.J.S., and A.W. were appointed by ICSU to guide the visioning process. We thank the more than 1000 individuals from 85 countries who contributed to the initial online consultation, participants in the September 2009 research priorities workshop, and the more than 200 individuals and 46 institutions that reviewed the draft of the grand challenges report.