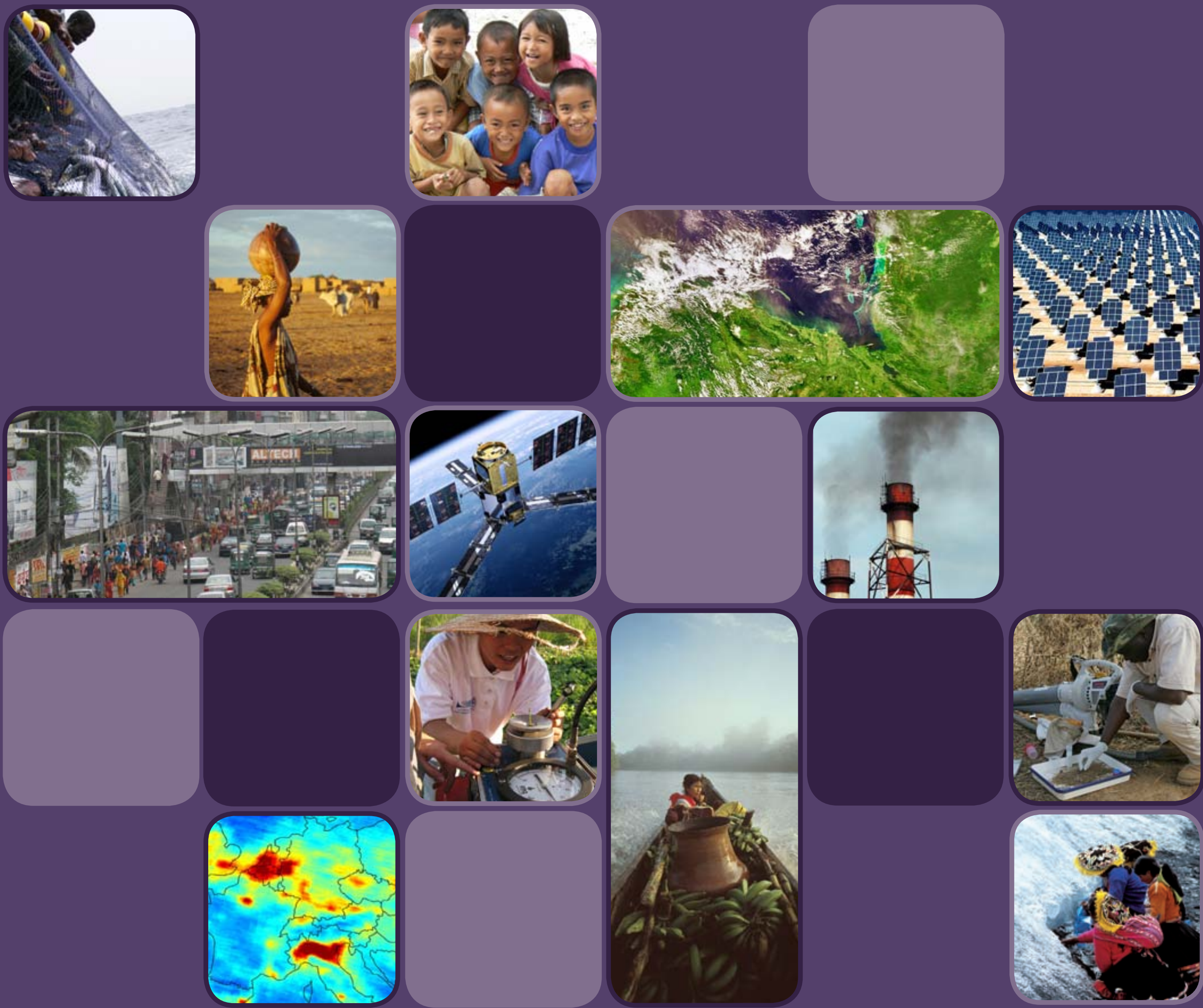

Earth System Science for Global Sustainability

The Grand Challenges

ISSC
international social science council

ICSU
International Council for Science

ICSU – International Council for Science

Founded in 1931, the International Council for Science (ICSU) is a non-governmental organization representing a global membership that includes both national scientific bodies (121 National Members representing 141 countries) and International Scientific Unions (30 Members). The ICSU 'family' also includes more than 20 Interdisciplinary Bodies (IBs)—international scientific networks established to address specific areas of investigation. These IBs are either co-sponsored or uniquely sponsored by ICSU and include the four global environmental change programmes: World Climate Research Programme, International Geosphere-Biosphere Programme, International Human Dimensions of Global Environmental Change Programme, and DIVERSITAS. Through this international network, ICSU coordinates interdisciplinary research to address major issues of relevance to both science and society. In addition, ICSU actively advocates for freedom in the conduct of science, promotes equitable access to scientific data and information, and facilitates science education and capacity building.

www.icsu.org

ISSC – International Social Science Council

The International Social Science Council (ISSC) was founded in 1952, following a UNESCO General Conference resolution in 1951. It is the primary global social science organization, representing major social, economic and behavioural science institutions and interests from across the world. The ISSC's mission is to advance the social sciences—their quality, novelty and utility—in all parts of the world and to ensure their effective global representation. The council works as a catalyst, facilitator and coordinator, bringing together researchers, scholars, funders and decision makers from all parts of the world in order to promote global social science's presence and authority, capacities and connectivity.

www.worldsocialscience.org

Visioning Process and Task Team

ICSU is spearheading a three-step consultation process—in cooperation with the ISSC—to engage the scientific community to explore options and propose implementation steps for a holistic strategy on Earth system research that will encourage scientific innovation and address policy needs. Step 1 focuses on identifying the urgent scientific questions, while step 2 focuses on the institutional frameworks needed to support the research strategy. The final step will examine how to make the transition from the current approach to the needed approach. The visioning process began in February 2009 and is guided by a Task Team consisting of: Johan Rockström (Chair, Nov 2009–), Walter Reid (Chair, Feb–Nov 2009), Heide Hackmann (ISSC), Khotso Mokhele (until Sept 2009), Elinor Oström (Feb 2010–), Kari Raivio (ICSU), Hans Joachim Schellnhuber and Anne Whyte.

'Earth System Science for Global Sustainability: The Grand Challenges' is the result of step 1 and represents input from many individuals and institutions.

www.icsu-visioning.org

ICSU International Council for Science

ISSC international social science council

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Earth System Science for Global Sustainability: The Grand Challenges

October 2010

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Introduction

The International Council for Science (ICSU) proposes to mobilize the international global change scientific community around an unprecedented decade of research to support sustainable development in the context of global change. In doing so it seeks to work in close collaboration with the International Social Science Council (ISSC) and other partners. The pace and magnitude of human-induced global change is currently beyond human control and is manifest in increasingly dangerous threats to human societies and human well-being. There is an urgent need for the international scientific community to develop the knowledge that can inform and shape effective responses to these threats in ways that foster global justice and facilitate progress toward sustainable development goals. The global change research community, which has played a central role in understanding the functioning of the Earth system and the human impacts on that system, holds the promise to meet this need. Realizing that promise requires a focus on new research priorities, and on new ways of doing and using research to address needs at global, regional, national, and local scales. This report is the product of an international consultative process led by ICSU and its partners that was designed to: (a) identify broadly-accepted grand challenges in Earth system science for global sustainability; (b) identify high priority research that must be carried out to address those challenges; and (c) mobilize scholars in the sciences (social, natural, health, and engineering) and humanities to pursue that research.

The study of the Earth system—the social and biophysical components, processes and interactions that determine the state and dynamics of the Earth including its biota and human occupants—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. Science has advanced to the point that we now have a basic understanding of how human actions are changing the global environment and a growing understanding of how those changes will affect society and human well-being. This research has provided invaluable insights regarding the biophysical processes that determine the functioning and resilience of planet Earth, the sensitivities of different components of the 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 and, thus, that our current path is unsustainable. We know enough to state with a high degree of scientific confidence that without action to mitigate drivers of dangerous global change and enhance societal resilience, humanity has reached a point in history at which changes in climate, hydrological cycles, food systems, sea level, biodiversity, ecosystem services and other factors will undermine development prospects and cause significant human suffering associated with hunger, disease, migration and poverty. If unchecked or unmitigated, these changes will retard or reverse progress towards broadly shared economic, social, environmental and developmental goals.

Our existing knowledge provides a useful basis for vital activities needed to manage specific parts or features of our world in transition, but it falls well short of what can be considered integrated solutions. How can we change human behaviour and shape political will so as to make it possible to meet targets for reductions in greenhouse gas emissions that will avoid dangerous climate change? How can societies most effectively and equitably respond to the global change that is already underway? How can they eradicate extreme poverty and hunger and achieve environmental sustainability?

The international scientific community holds the promise of delivering the knowledge necessary for answering these crucial questions. But realizing that promise will require a refocusing of research priorities and a reorientation towards new research frontiers. We will have to meet a twofold challenge, namely to develop response strategies to global change, on the one hand, and to deepen our knowledge of the functioning of the Earth system and its critical thresholds and the on the other hand. This will require new ways of doing research that better link science and society to address the needs of decision-makers and citizens at global, regional, national, and local scales.

Over the next decade the global scientific community must take on the challenge of delivering knowledge required to support efforts to achieve sustainable development in the context of global environmental change. Solution-focused, strategic, interdisciplinary, long-term research is needed to improve our knowledge of the social-environmental risks facing humanity and to provide science-based support for actions to achieve sustainable development. We rapidly need to deepen our understanding of how the Earth system operates in response to human pressures, improve our ability to predict future risk patterns, and explore social transformations in the world that can overcome barriers to sustainability. The necessary research builds upon and integrates expertise within the sciences (social, natural, health, and engineering) and humanities and applies it to pressing coupled social-environmental research questions of human interactions with the Earth system.

Just as we are at a point of transition in the focus and scale of global social-environmental research, we are also at points of transition in the disciplines that must be involved and the processes by which that research is undertaken. There is a need for transitions from:

- *Research dominated by the natural sciences to research involving the full range of sciences and humanities.* 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, health sciences, engineering and humanities, along with the natural sciences. It is increasingly clear that pathways to address rapid global change can only be found through inquiries that integrate the full range of sciences and humanities 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.
- *Research dominated by disciplinary studies to a more balanced mix of disciplinary research and research that draws disciplinary expertise into an integrated approach that facilitates inter- and transdisciplinarity.* The solutions to the grand challenges must be rooted in disciplinary research, but disciplinary research alone will be insufficient. Many of the priority research questions can only be solved through effective interdisciplinary research. Moreover, it is clear that both research progress and the effective use of scientific results by society and decision-makers can often be enhanced through transdisciplinary research; that is, through greater involvement of external stakeholders in the research process. Research will often be most useful, and the results most readily accepted by users, 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. An effective response to global environmental change will be aided by the co-creation of new knowledge with a broad range of stakeholders through participatory practices.

These proposed transitions in the disciplines involved, and the research processes utilized, are needed because they will bring greater expertise to bear in framing and 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 is seeking to mobilize researchers around an unprecedented, 10-year scientific effort to address the grand challenges. The process to reach consensus on the grand challenges and research priorities began with an Internet consultation in July and August 2009.[1] The Internet consultation yielded more than 300 proposed Earth system research priorities contributed by individuals from 85 countries. These proposed research priorities formed the background for a workshop held in September 2009 involving senior researchers, early career scientists, science-policy experts and representatives of research funding agencies. A draft document presenting the selection criteria, grand challenges, and research priorities generated by that workshop was circulated for review between December 2009 and March 2010. Review comments from 46 institutions and over 200 individuals have been addressed in this report.

This report aims to provide a widely shared vision of the scientific priorities for in the coming decade. It is intended to: (a) mobilize the greater engagement of the international scientific community and, particularly, of the broader social science community; (b) stimulate innovative new research and guide the prioritization of research topics by scientists, research funders and policy makers; and (c) inform potential users of the findings that might stem from this research, 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 are the audience for this document and have been involved in its development. Additional information on this consultative process is provided in Appendix 1.

[1] The full process is described in detail at: 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.

Criteria

We have used the following criteria in selecting the grand challenges and associated 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, in the context of global environmental change?
2. **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 to others (i.e. be outside the remit of this framework, despite its importance to a given field).
3. **Relevance to decision makers.** Will the answer to the question help to inform actions to meet urgent global social and ecological needs, especially promoting sustainability, reducing poverty, and assisting the most vulnerable in coping with global environmental change?
4. **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 Earth system science for global sustainability?

In addition to these four criteria used for both the selection of the grand challenges and the research priorities, the five grand challenges were also screened against a fifth criterion: did the proposed grand challenge have broad support from the research and funding community (even those not directly involved in answering the question). We believe that each of the grand challenges is widely perceived to be a fundamental question that must be addressed in the pursuit of global sustainability. In the case of the research priorities, we also added a criterion focused on the feasibility of the research: Is it plausible that the question can be answered within the next decade? We are confident that we have the scientific basis and tools available to answer the research priorities listed in this document, but success will require adequate resources and effective coordination of the international research community to ensure that the questions are addressed with focus and intensity.

The Grand Challenges

Consistent with the use of the concept of grand challenges in other areas of science, we consider the grand challenges in Earth system science for global sustainability to be a call for scientific innovation or understanding that would remove critical barriers to deciding how to achieve sustainable development. We list five grand challenges and within each, we list several top-level research priorities that must be addressed during the next decade to make significant progress in resolving the problem posed by the grand challenge. The list of research priorities is neither exhaustive nor necessarily sufficient. Nonetheless, 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 resulting challenges cover a diversity of topics but are united as elements of a systems approach that examines how the coupled social-environmental system is changing (including the dynamic responses of people and the environment) and what actions and interventions may alter the environmental and social outcomes (see Figure 1). The grand challenges adopt a systems approach from the perspective of what is being studied: the full social-environmental global system rather than independent components of that system. They also adopt a systems approach from the perspective of how research can inform actions to achieve global sustainability: none of the challenges can be fully addressed without progress in addressing the other challenges.

Consequently, the five grand challenges are an indivisible 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 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.

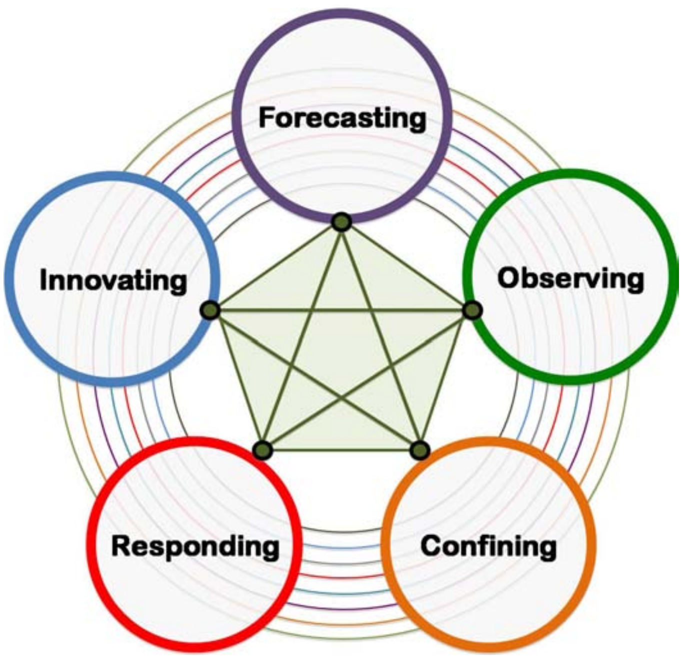

Figure 1: Grand Challenges in Earth System Science for Global Sustainability. The concentric circles represent the disciplinary research needed in the social, natural, health and engineering sciences and the humanities that must be carried out alongside interdisciplinary and transdisciplinary research in order to address the challenges. The lines linking the grand challenges show that progress in addressing any challenge will require progress in addressing each of the others.

Challenge 1: Forecasting

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 do global environmental changes pose for vulnerable communities and groups and what responses could be most effective in reducing harm to those communities?

We consider a 'useful' forecast to be one that is responsive to the needs of societies and decision-makers for information at relevant spatial and temporal scales and is timely, accurate, and reliable. Our limited ability to anticipate the outcomes resulting from the interaction of complex and diverse human societies 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 to improve our ability to use scenarios and simulations to anticipate the impacts of a given set of human actions or conditions (e.g. population size, levels of consumption, greenhouse gas emissions, deforestation, increased agricultural productivity) on global and regional climate and on biological, geochemical, and hydrological systems on seasonal to decadal time scales. Building on this work, significant advances are now also needed in our ability to assess the potential impact of those environmental changes on human well-being (e.g. impacts on economies, health, food security, energy security, etc.) and the potential human response to such changes. Such forecasts and assessments should be tailored to respond to the questions and needs of the people potentially affected, and the uncertainty should be quantified and clearly communicated.

Answering the research questions posed here will require a major new scientific endeavour to build the capacity to predict changes to the Earth system. It includes a pressing need to develop a new suite of Earth system models with the ability of predicting changes to the Earth system from anthropogenic influence at global, regional and, where possible, local scales. This will necessitate major scientific advancements in integrated analyses of the dynamics of interlinked biophysical systems on Earth and coupling these with the human dimensions of global environmental change, both in terms of drivers and impacts. This in turn will have to build on continued progress in disciplinary Earth system research, and major improvements in and intensification of Earth observation systems.

Science cannot, as yet, provide adequate predictions of the Earth system response to pressures from the coupled socio-environmental complex. This is a major dilemma for humanity as a whole. We know that humanity is pushing systems on Earth towards risks that may cause abrupt, and potentially irreversible and disastrous changes. Despite major advancements in Earth system science over the past decade, the uncertainties and risks of anthropogenic change remain too high for comfort.[2] Human development continues along a dimly lit path of uncertainties and risks; in the absence of clarifying headlights policy makers and society at large inappropriately assume that the stability of the planet will prevail. Scientific evidence to date strongly suggests that it is too risky to continue along this development pathway. We urgently need improved capabilities for analyzing and understanding the global environmental change risks facing humanity. We assess that major improvements to an integrated model to predict the Earth

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[2] The uncertainty on climate sensitivity alone for a doubling of CO_2 levels in the atmosphere, range from 1.5–4°C of average global temperature, an uncertainty range that has remained stubbornly high over the past 20 years, despite major advancements in integrating the atmosphere and stratosphere, with the hydrosphere and biosphere in global climate modelling.

system response to anthropogenic pressures is within reach, but will require a major international undertaking over the coming decade, as part of the grand challenge endeavour.

Significant improvement is needed in our ability to provide forecasts that address the full range of plausible outcomes within a probabilistic framework, that incorporate the dynamic response of both the natural and social system, and that provide results at appropriate spatial and temporal scales to assess impacts on economies, ecosystem services and human well-being. Progress in this area of research will require advances in understanding and modelling the fundamentals of physical phenomena, advances in modelling capability (including development of the ultra-high performance computing infrastructure), the incorporation of information from paleo-climate change as well as historical information on social and behavioural responses and a more interdisciplinary framework of analysis. 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.

The human consequences of global environmental change will vary across regions and within societies because of geographic differences in impacts and because of differences in the vulnerability of groups of people. An important focus of efforts to improve forecasting capability must be to better understand which groups of people are most vulnerable to global change, what threats global change poses for those communities, and the potential consequences of different adaptation and mitigation actions. These communities will experience the greatest impacts associated with global change; consequently, there is an urgent need for the scientific community to provide decision-makers and society with information that can guide action to lessen those impacts.

Examples of key questions that need to be answered include: How will regional climate change over decadal time scales? What will be the environmental and health impact of changes to other biogeochemical cycles (e.g. nitrogen, phosphorus) or to increased loadings of toxic pollutants? How will the social, economic and health impacts of global environmental change vary across regions and within societies? 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 the adverse consequences of such trade-offs? What kinds and levels of biodiversity are needed to buffer the impacts of environmental change on ecosystem services?

Challenge 2: Observing

> Develop, enhance and integrate 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?

Major investments are being made to build more effective global and regional monitoring systems and to ensure their international coordination (e.g. through arrangements like the Global Earth Observation System of Systems, GEOSS). But these systems, which provide a firm foundation, still fall well short of what is needed. The current supply of information needed to manage the socio-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 coupled social-environmental 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.

To meet any of the grand challenges, a robust data and information system is needed that can combine data and knowledge gathered over centuries with new observations and modelling results to provide a range of integrated, interdisciplinary datasets, indicators, visualizations, scenarios, and other information products. Ensuring wide access to both past and future data, especially with regard to societal dimensions, is a key challenge that cannot be taken for granted.

The observation, data preservation and information 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); provide information about both direct drivers of change and indirect drivers; involve multiple stakeholders in the research process; support effective decisions at global to local scales; be formally part of adaptive decision making processes; provide full and open access to data; and be cost effective. 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 and the oceans; (2) spatial patterns and changes in freshwater quantity and quality, for both ground- and surface-water; (3) stocks, flows and economic values of ecosystem services; (4) trends in perceived and real 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; (6) patterns of human responses to these developments including changes in policies, technologies, behaviours and practices; and (7) empirical measures of the efficiency of responses. The design of such a system would need to address the question of how local and regional 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: Confining

> Determine how to anticipate, recognize, avoid and manage disruptive global environmental change.

Priority Research Questions

3.1 Which aspects of the coupled social-environmental system pose significant risks of positive feedback with harmful consequences?

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 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?

It is increasingly likely that human interference will trigger highly nonlinear changes in the global environment. Such changes may be abrupt or slow, but in all cases they tend to alter the very character of the life-support system in question and to be largely irreversible on human time-scales. Examples are major shifts in regional climate, rapid collapse of ice sheets, methane release associated with thawing permafrost and warming oceans, and discontinuous transitions in the structure and functioning of biological systems. In turn, disruptive changes in social systems can result from such events, as well as from more gradual environmental changes such when reduced precipitation or degrading soil fertility eventually leads to the creation of environmental refugees. Moreover, an increasingly interconnected world generates linked trends and shocks in seemingly disparate sectors such as energy, finance, food, health, water and security. Public policies and social and economic institutions are rarely designed with such human-induced disproportional changes and regime shifts in mind.

An urgent research challenge is to understand the underlying non-linear dynamics. This will require, in particular, the future integration of environmental and complexity science, two fields that until now have developed largely separately. In order to confine global change to tolerable domains we will have to identify and track our proximity to planetary boundaries (like critical levels of ocean acidification) and in order to confine the impacts of unavoidable excursions into dangerous systems territory we will have to find optimal ways for enhancing resilience to disruptive change. A major focus of research must also 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.[3] Such research can also inform steps that societies should take to increase their resilience to natural and human induced disasters. Research into appropriate response and adaptation strategies must extend beyond considerations of 'optimal' approaches to advance understanding of the political and social dynamics of responses. For example, despite the best efforts of analysts to identify optimal policies that might prevent a crisis, it is not uncommon for policies to be changed only when that crisis comes to pass; what does this imply for the design and promotion of response options? And a most exciting task will be to find out whether there are positive social tipping points, i.e. pioneering action that can tip economic machineries or social dynamics into sustainable regimes.

[3] These are not the only types of dangerous global changes. For example, relatively linear but small changes in the global environment can have dangerous impacts on people if they occur over long time periods. Grand Challenges 1 and 4 are well suited to addressing impacts such as these. Grand Challenge 3 addresses the risk of more discontinuous or abrupt change.

Challenge 4: Responding

> Determine what institutional, economic and behavioural changes can enable effective steps toward global sustainability.

Priority Research Questions

4.1 What institutions and organizational structures are effective in balancing the trade-offs inherent in social-environmental systems at and across 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, in the context of global environmental change, and how could they be achieved?

4.3 What changes in behaviour or lifestyle, if adopted by multiple societies, would contribute most to improving global sustainability, in the context of global environmental change, and how could they be achieved?

4.4 How can institutional arrangements prioritize and mobilize resources to alleviate poverty, address social injustice and meet development needs under rapidly changing and diverse local environmental conditions and growing pressures on the global environment?

4.5 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?

4.6 How can effective, legitimate, accountable and just, collective environmental solutions be mobilized at multiple scales? What is needed to catalyze the adoption of appropriate institutional, economic or behavioural changes?

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 short-term and private benefits, rather than long-term and collective benefits. Addressing the problems of global change, including unsustainable resource use, pollution of the global commons, growing resource demand resulting from increased population growth and per capita consumption, increased distrust by citizens of each other and their officials, and growing poverty, will require a step change in research addressing fundamental questions of governance, economic systems and behaviour.

An effective response to global 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 preventing and eradicating poverty and hunger and improving human health? How does global environmental change shift the agenda for sustainable development in the world?

Determining how to achieve changes in social organizations, institutional arrangements and human 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 actions be undertaken at unprecedented and multiple 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 within diverse settings 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 policy makers, 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: Innovating

> Encourage innovation (coupled with sound mechanisms for evaluation) in developing technological, policy, and social responses to achieve global sustainability.

Priority Research Questions

5.1 What incentives are needed to strengthen systems for technology, policy and institutional innovation to respond to global environmental change and what good models exist?

5.2 How can pressing needs for innovation and evaluation be met in the following key sectors?

- a. 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?
- b. How can competing demands for scarce land and water be met over the next half century while dramatically reducing land-use greenhouse gas emissions, protecting biodiversity, and maintaining or enhancing other ecosystem services?
- c. How can ecosystem services meet the needs for improving the lives of the world's poorest peoples and those of developing regions (such as safe drinking water and waste disposal, food security and increased energy use) within a framework of global sustainability?
- d. What changes in communication patterns are needed to increase feedback and learning processes to increase the capacity of citizens and officials, as well as to provide rapid and effective feedback to scientists regarding the applicability and reliability of broad findings and theoretical insights to what is observed in the field?
- e. What are the potentials and risks of geo-engineering strategies to address climate change, and what local to global institutional arrangements would be needed to oversee them, if implemented?

Unprecedented challenges require novel and rapid 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 at multiple levels.

A number of 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, metering and use, and to assess the impacts of these systems on the environment and society.

Second, at current rates of growth in agricultural yield and improvements in water use efficiency, it will be extremely difficult to simultaneously meet the needs over the next half century for: (a) increased food demand from growing (and wealthier) populations; (b) increased human demand for freshwater for agricultural and urban uses; (c) reduced greenhouse gas emissions associated with land use change and agricultural production; (d) potential increased production of biofuels; (e) reduced rates of biodiversity and forest loss; and (f) 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?

Third, solving the problem of poverty is integral to solving the problems of global environmental change: one is as important as the other since the two issues are tightly coupled. The poor will experience the greatest harm from global environmental change. It is imperative that solutions to the problem of global change simultaneously contribute to the needs for preventing and eradicating poverty and vice versa.

Fourth, in order to rapidly address the challenges of global environmental change, we must greatly enhance our capacity for learning and this in turn requires much more effective feedback loops at multiple scales. One factor that exacerbates the challenge of dealing with global environmental change is that the time scale of human impacts on the global environment (years to centuries) does not provide the immediate feedback that could inform the public and decision-makers. Mechanisms for providing feedback between the slow variables of global change and the fast variables of human response must be developed. Better communication and feedback is also needed that can enable more rapid uptake of solutions and learning across communities and societies. And the scientific community itself needs to develop better means of learning about the applicability of research findings to real-world situations.

Finally, 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? 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 geo-engineering strategies and the institutional arrangements that would be needed to oversee and assess such strategies if they were implemented.

Expected Deliverables

The primary product of the research that will be guided by these grand challenges is the knowledge base needed to support efforts to achieve sustainable development in the context of global environmental change. 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 exacerbate environmental stresses. The research will also yield a set of more tangible products:

- Improved regional and sub-regional information concerning potential consequences of global and regional environmental change and the likely impacts of different actions to mitigate or adapt to those changes. (Challenge 1 and 2)
- Improved accuracy of regional and subregional forecasts of climate, food security, health and environmental risks, and water availability. (Challenge 1 and 2)
- Improved information on the consequences, costs, benefits and risks of potential mitigation and adaptation strategies. (Challenge 1 and 2)
- Prioritized needs for Earth system observations of geophysical, 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 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, take power asymmetries into account, 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 (involving innovation in synthetic research approaches, participatory practices, and collaborations) and communicating results, in which stakeholders are empowered, informed and motivated through the research process to take effective action. (All Challenges)
- Enhanced capacity to undertake interdisciplinary and transdisciplinary research, including the development of a new generation of scholars taking a systems approach to challenges of global sustainability. (All Challenges)

Call to Action

This document is the product of an agenda-setting consultation that is intended to guide and stimulate scientific research on global change and global sustainability starting promptly and continuing 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. As the agenda-setting process goes forward, the need for input from the larger community will not be limited to responding to the specific research questions, but will also necessitate innovative approaches, including reflection upon and possible changes to the decision making process within scientific institutions in order to better facilitate the interdisciplinary and transdisciplinary research that is needed.

Major progress in addressing the grand challenges and research priorities laid out here can be achieved over the next decade, but not without changes in the existing international research structures to promote interdisciplinary research, also across scientific fields, to enable greater regionalization of that research, and to allow effective interaction with decision makers and other stakeholders to both guide the research questions and deliver the research results. And, the progress cannot be achieved without enhanced resources—the scope of research needed is far broader and the nature of research organisation far more inclusive than the work carried out over the past two decades.

A major commitment will be required by both the institutions carrying out research and the institutions supporting that research. This document is intended to help catalyze and guide an unprecedented decade of solution-oriented, focused and intensive research. Over the next year, those who have participated in this effort will seek to build a coalition of scientists, scientific institutions and funding agencies that will commit themselves to working 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.

Appendix 1: Background

ICSU and the international global environmental change research initiatives

Thirty years after the creation of the first global environmental change programme, there is a realization that the planet is in a 'no-analogue' state. While there has been much progress on understanding the complexity and vulnerability of the Earth system, there is the growing recognition science is urgently needed to address how complex social-ecological interactions play out across scales—impacting conditions for all humankind. Scientific findings have shown that the Earth's environment is changing on all scales, from local to global, in large measure due to human activities. Much of the substantiating evidence has come from scientists who are active in the global environmental change programmes: DIVERSITAS (an international programme of biodiversity science), International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme on Global Environmental Change (IHDP), and World Climate Research Programme (WCRP).[4] ICSU is the only common sponsor of these four programmes and has a long tradition in the field of global environmental change research.[5] In 2001, the four global environmental change programmes came together under the banner of the Earth System Science Partnership (ESSP), which promotes international and interdisciplinary research in focal areas—carbon, food, water and health. The four programmes and ESSP are recognized leaders in the planning and coordination of international global environmental change research (*Science*, 14 March 2008).

Recent reviews of the ESSP, IGBP, WCRP and IHDP have cited their critical contributions to international research as well as to assessments and policy initiatives, particularly in the areas of climate and biodiversity. These reviews, which were done jointly with the relevant scientific cosponsors, consistently pointed to the need to engage the scientific community to explore options and propose steps to implement a holistic strategy for global sustainability research, which would both encourage scientific innovation and address policy needs. The visioning global substantiality research process, which has produced this Earth System Science for Global Sustainability: The Grand Challenges document, emanated from these reviews.

In cooperation with ISSC and other partners, ICSU is leading a broad consultative process to address the decision from the ICSU General Assembly (October 2008) to outline options for an overall framework for Earth system research. The visioning process will have three steps, and is founded on the principle that form should follow function:

1. a consultation primarily with, but not limited to, the scientific community to envision a research strategy and priorities for the next decade (2009);
2. a consultation on the institutional framework needed to deliver the scientific vision that results from Step 1 (June 2010). Invitees to this meeting include the co-sponsors of the global environmental change programmes and UNEP, as well as funders and key figures from within and outside of the programmes. Prior to this meeting there will be a public Open Forum; and
3. development of a plan to guide the transition from existing structures to the needed structure (2011).

ICSU has entered into this visioning process with no pre-conceived conclusions, and the ultimate goal is to strengthen, galvanize, and focus the entire sustainability research community on the most pressing societal issues.

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[4] The scope of this appendix is restricted to institutions and organizations sponsored or co-sponsored by ICSU. These are by no means the only organizations carrying out and coordinating research and monitoring relevant to global sustainability. That broader set of institutions will play critical roles in carrying out the type of research described in this document.

[5] In 1979, ICSU co-sponsored the first World Climate Conference, which led to the establishment in 1980 of WCRP with the World Meteorological Organization (WMO); in 1993 the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) also became a co-sponsor. Based on the studies of the Scientific Committee on Problems of the Environment (SCOPE) in the 1970s and early 1980s, ICSU initiated the planning of IGBP in 1986. IHDP was established with the International Social Science Council (ISSC) in 1996, and the United Nations University (UNU) became a co-sponsor in 2007. DIVERSITAS was initially established in 1991 by the International Union of Biological Sciences (IUBS), SCOPE and UNESCO. In 1996, ICSU joined as a co-sponsor.

Appendix 2: Definitions

Coupled socio-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.

Food security: the state achieved when food systems operate such that all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.

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 CO2) 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, equitable and trusting social relations, security, peace of mind and spiritual experience.

Interdisciplinary: Research that involves several unrelated academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and theory and solve a common research goal.

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.

Sustainability: A characteristic or state whereby the needs of the present and local population can be met without compromising the ability of future generations or populations in other locations to meet their needs.

Systems approach: A research approach that views individual elements as parts of an overall system and assumes that the component parts of a system can best be understood in the context of relationships with each other rather than in isolation.

Transdisciplinary: Research that both integrates academic researchers from different unrelated disciplines and non-academic participants, such as policymakers and the public, to research a common goal and create new knowledge and theory.

Vulnerability: Exposure to contingencies and stress, and the difficulty in coping with them.

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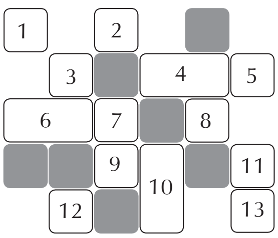
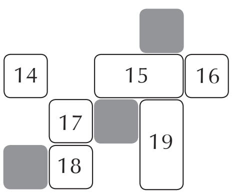
Images:

Front cover



1: IRD/Vincent Turmine. Fishing off the coast of Senegal.
2: IRD/Hubert de Foresta. Children of Tanjung village, Indonesia.
3: IRD/Olivier Barrière. Woman in Mali.
4: ESA. Envisat image of Central America.
5: USAF. Giant photovoltaic array.
6: IRD/Pierre Gazin. Dhaka, Bangladesh.
7: ESA-AOES Medialab. SMOS in orbit.
8: stock.xchng/garytamin. Smoke stacks of a power plant.
9: IRD/Marie-Noëlle Favier. Researcher in the field, Thailand.
10: IRD/Alian Laraque. On the River Curaray in the Amazon forest, Ecuador.
11: IRD/Jean-Jacques Lemasson. Researcher in the field, Senegal.
12: University of Heidelberg. NO_2 levels over Europe.
13: IRD/Bernard Francou. Women at the foot of a glacier, Peru.

Back cover



14: IRD/Bernard Moizo. Transporting rice, Laos.
15: IRD/Christophe Proisy. Aerial view of mangroves, Guyana.
16: IRD/Daina Rechner. Villagers coming together to grind grain, Burkina Faso.
17: IRD/Jean-Marie Fritsch. Constructing social housing in Johannesburg, South Africa.
18: IRD/Pascal Dumas. Mangroves of Guyana.
19: IRD/Thierry Lebel. Installing a weather station, Benin.

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