Peter Liss Kevin Noone Sybil Seitzinger Thomas Rosswall Chris Rapley Will Steffen James Syvitski

REFLECTIONS ON EARTH-SYSTEM SCIENCE

The development of Earth-system science has been inseparable in many ways from IGBP's scientific and institutional evolution. We asked IGBP's past and present leaders to reflect on the programme's contributions to this discipline and the way ahead.

During the 1980s, based on decades of disciplinary research, scientists and policymakers grew to realise that the Earth was in fact an integrated system. As a seminal NASA report from 1986 put it, "This insight has set the stage for a more complete and unified approach to its study, Earth System Science". The time was ripe for an international programme that would unify not only disciplines but also the global community of scientists to understand the Earth as a whole. This programme, IGBP, will close at the end of 2015 after three decades of coordinating and facilitating research on global change. In this context, we posed a series of questions to IGBP's past and present chairs and executive directors about the programme's contributions to Earth-system science and the future of this discipline. Below we present their edited responses:
Thomas Rosswall (Director, 1987–1994);
Peter Liss (Chair, 1993–1997);
Chris Rapley (Director, 1994–1997);
Will Steffen (Director, 1998–2004);
Kevin Noone (Director, 2004–2008);
Sybil Seitzinger (Director, 2008–2015);
James Syvitski (Chair, 2012–2015).

Q: How do you conceptualise Earth as a system?

ROSSWALL: IGBP was established around the time of the Gaia hypothesis and Jim Lovelock's attempts to view the Earth as a self-regulating system. IGBP's initial thinking was very much guided by the Bretherton diagram (see page 10), where the sun and humans were external factors and the World Climate Research Programme (WCRP) plus IGBP constituted the research needed to understand the Earth system. With the 2001 Amsterdam declaration and the establishment of the Earth System Science Partnership (ESSP), the human component became an integral part of the Earth system. At least that was the vision, even if reality did not move very quickly.

LISS: I sometimes liken the Earth as a system, and how our ideas about it have evolved, to a grand building. The bricks are equivalent to single disciplines, which then become linked together into pillars of the edifice – for example, biogeochemistry in IGBP and physics and maths in WCRP. Then the pillars are linked and roofed to complete the building, which I liken to Earth-system science. There's a limited amount of social science, as represented by the International Human Dimensions Programme on Global Environmental Change (IHDP), but it is not until Future Earth appears that the social sciences start to play their full and vital role.

RAPLEY: As the most complex object (that we know of) in the universe. The well-known Bretherton diagram from the 1980s gives you an idea: this diagram shows key interactions and feedbacks within the Earth system that bear on climate. When I was IGBP Director I added colour-coded domains to illustrate the relationship between WCRP, IGBP and IHDP. You will notice that human activities are condensed into a single element. There was in fact a social process diagram developed in the early 1990s that sought to expand on this.

STEFFEN: We put a lot of thought into just this question while working on IGBP's first synthesis from 1999 to 2002. The definition we came up with for the synthesis volume (see Chapter 1 by Frank Oldfield and myself) is still a very good definition: "In the context of global change, the Earth System has come to mean the interacting physical, chemical and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes which provide the conditions necessary for life on the planet".

Then we went on to list a number of important features of the Earth system, including that "human beings, their societies and their activities are an integral component of the Earth System, and are not an outside force perturbing an otherwise natural system".

NOONE: My own concept of the Earth system is very nicely captured in the illustration we commissioned for IGBP from the artist Glynn Gorick when I was working at the Secretariat. [See page 11.] The Earth in its entirety is at the centre of my conceptualisation. It is whole; the Earth system itself does not distinguish between any of the "spheres" around which we tend to organise ourselves – the atmosphere, oceans, land, biosphere or geosphere. There is no dichotomy between humans and nature. Life is the heart of the Earth system and, while the system is amazingly resilient, change is a constant. Above all, the Earth system is something of majestic beauty.

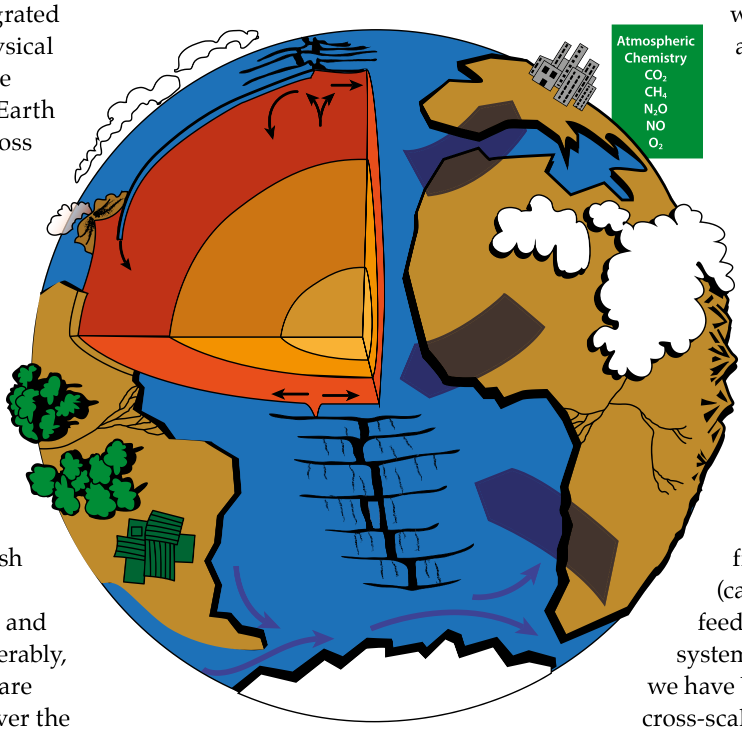
SEITZINGER: I conceptualise the Earth system through the lens of the Anthropocene: a complex, integrated socio-eco-bio-geo-chemical-physical system in which humans are the dominant force of change. The Earth system operates within and across all temporal and spatial scales.

SYVITSKI: This is an interesting question that begs to know the question's audience and its interest. At any given moment, the Earth system includes all the interconnections and teleconnections between the Earth's interior, the biosphere, cryosphere, hydrosphere and atmosphere, and oceans that slosh around at the Earth's surface.

In the world of IGBP the time and space of interest narrow considerably, as the focus is on how humans are impacting the Earth's surface over the past few thousand years – that is, the time it takes for ocean surface water to sink and deeper water to well up – and even just the past few hundred years when human population rose from a few hundred million to over seven billion. This historical period of human industrialisation is less than 0.0001% of the Earth's history. IGBP captures the Earth as a system by coordinating international projects that cover the appropriate Earth-system domains – the atmosphere, our continents and oceans, and the interactions between these domains.

Q: How has Earth-system science evolved during the past three decades?

ROSSWALL: Interdisciplinary collaboration has changed fundamentally during the past several decades. For example, during the International Biological Programme (1969-1974) it was very difficult to get communication going among the zoologists, botanists, hydrologists and others in order to shape ecosystem science. IGBP's early years were marked by difficulty in getting academics involved in studying biogeochemical cycles to talk to each other in the same language. Cooperation with WCRP wasn't easy at the time either, even on topics such as water that one would have thought were integrative. But IGBP was persistent and the horizon expanded slowly.



An early conceptualisation of the Earth system included the deeper Earth, but this fell out of favour later. Redrawn from *Earth System Science Overview*, NASA.

The ESSP took us further along this path by bringing together the four global-change programmes and diverse natural- and social-science disciplines. Future Earth, the latest initiative to emerge from the global-change community, represents a step change. Its approach of transdisciplinarity and co-design opens up an exciting new possibility to engage stakeholders in formulating problems as well as developing solutions.

RAPLEY: There has been a slow, painful and only partly successful move towards coordinating the research projects both within and between the major global-change programmes, as well as the projects carried out by other major groups. This is also the case with integrating and synthesising the results to understand the working of planet Earth as a system and provide insights and information of value to society. The problems are manifold but relate mainly to limitations of the academic rewards system, scientific training and cultural norms. At least now the global-change programmes talk to each other and treat each other with a degree of respect, which was not the case in the late 1980s and early 1990s. However, the ESSP was a disappointment, and I have grave doubts about Future Earth!

STEFFEN: It is really hard to describe the enormous progress in Earth-system science over the past three decades comprehensively but briefly. Here I'd like to highlight three strands of development that I think are important.

1) The past three decades have seen a remarkable shift from disciplinary thinking (cause-effect) to systems thinking – feedbacks, thresholds, abrupt shifts, system-level phenomena. I also think we have become wiser in dealing with cross-scale interactions, and particularly in a more cautious approach to scaling up from local to global levels.

2) Two or three decades ago it wasn't clear whether the social sciences would learn to think globally. The dilemma, as emerged from my discussion with IHDP's Larry Kohler, was whether existing high-profile social scientists could adapt to thinking globally or whether a new generation of social scientists needed to be developed in a bottom-up fashion. Looking back on this challenge, I think it has been ably met by the social sciences with a bit of both approaches. In my view, one of the spectacular successes has been the rapid development of the field of Earth-system governance. I suspect the field of urban studies, in all its complexity, is also entering a rapid development phase. These two fields will likely be pillars in the Future Earth portfolio of activities.

3) The humanities have much to offer to Earth-system science. The best example of the potential of the humanities, in my view, is the Integrated History and Future of People on Earth (IHOPE) project. It takes a truly integrated view of the past (leading into the future) and asks some really fundamental questions. For example, why are some societies more resilient to external shocks and others less so? Research like this is not often considered to be Earth-system science, yet it should be front and centre in terms of informing the future evolution of the Earth system.

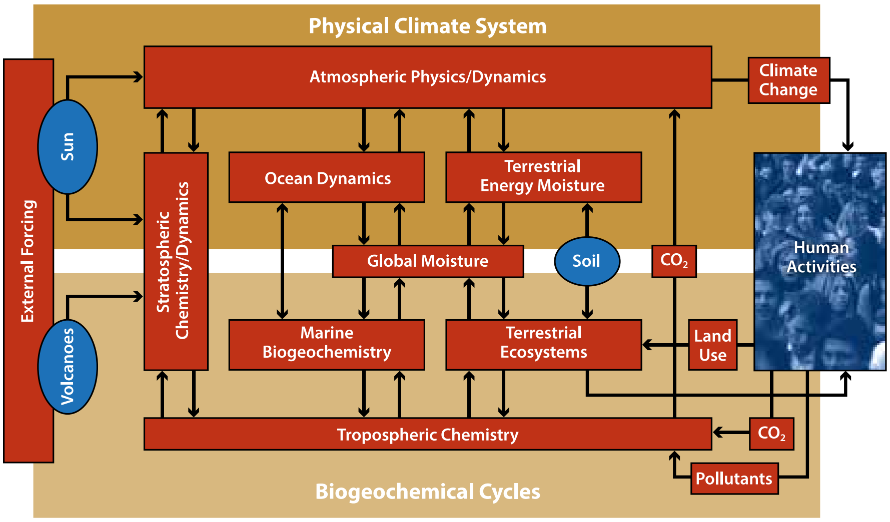
NOONE: I don't really think there was an "Earth-system science" about 30 years ago when I published my first paper. Even today, I'm not sure that we have a common definition of what Earth-system science is.

That is not to say that there has been no evolution in this area – quite the contrary. Earth-system science has gone from being an oddball notion to becoming recognised as a paradigm necessary for us to make progress on the "wicked" problems society faces today. We still haven't managed to properly integrate natural and social sciences in conceptualising the Earth system, though I do believe we have made significant progress. We are definitely behind the eight ball, though, in terms of figuring out how truly transdisciplinary research can be conceived and implemented. We need a proper infrastructure and reward system to support and encourage folks to work in this manner.

SEITZINGER: Within IGBP, Earth-system science has evolved from the development of some of the first global databases to studies primarily of individual components of the Earth system to more integrated Earth-system analysis. Throughout the past three decades there has been a steadily increasing focus on explicitly incorporating the human dimensions.

SYVITSKI: Three decades ago we could have drawn a cartoon or flow-chart of how the Earth operates as a system. And three decades ago we were making measurements on most aspects of the Earth system. But this science with a global reference was qualitative and primitive. Our observations (on the ground as well as from space) and data were far more limited. Our understanding of the carbon and nutrient cycles was so limited that we could not put together basic global budgets.

Most importantly, we had no computer model that could be used to test hypotheses. In the early 1980s we operated energy-climate models. A decade later we were coupling models that also contained climate, the ocean carbon cycle and atmospheric chemistry. Now our integrated assessment models also include sulphur and non-sulphur aerosol dynamics, the terrestrial carbon cycle, agriculture and other forms of land use, energy technology and significant upgrades to the other model components. Today, the models allow for predicting the influence of atmospheric greenhouse gases on a whole host of variables and can include such regional phenomena as changes in land-use practice.



The iconic Bretherton diagram. Redrawn from *Earth System Science Overview*, NASA.

Q: How has IGBP influenced this evolution in Earth-system science?

ROSSWALL: Had it not been for IGBP, the biogeochemical understanding of the Earth system would have been poorer. Also, the books IGBP published in relation to its first synthesis were, and are, seminal publications. The concept of the Anthropocene was very much stimulated by IGBP research, and the Planetary Boundaries also take a lot of IGBP research as a point of departure.

IGBP could have been considerably more important if we had engaged more strategically in essential policy processes, worked better with the private sector (e.g., through the World Business Council) and engaged with important NGOs. This has been done, but at least in the beginning it was not seen as a high priority. When I chaired a review of climate/global change in Norway in 2012, very few considered IGBP important despite so many Norwegians playing important roles in the programme's work.

STEFFEN: IGBP's implementation phase began in 1990 under the energetic directorship of Thomas Rosswall with the original six core projects, and further developed from the mid-1990s with Chris Rapley at the helm. It was a very productive decade, propelled by all of the energy of a visionary new international programme and further solidified by the development of a long-term institutional framework.

I was Executive Director of IGBP from March 1998 through June 2004: in my view this was a remarkable period for the programme in terms of the transition from its first to the second phase, the implementation of the first IGBP synthesis project, the landmark Amsterdam conference in 2001 and the prominent emergence of Earth-system science as a major feature of international global-change research. It was during this period that the ESSP emerged in response to the need for more integrated research. In many ways, the

ESSP, at least in its conceptual origins and its intent, was a forerunner of Future Earth.

NOONE: I can't think of an organisation that has been more influential in the evolution of Earth-system science than IGBP. Obviously I'm biased in this regard, but trying to be as dispassionate as I can, I still come to the conclusion that IGBP has been hugely influential.

IGBP started off as a collection of relatively independent projects that were broader in scope than many contemporary scientific endeavours, but each of which still had a rather disciplinary character. Over the years IGBP itself evolved to incorporate the notion that borders didn't belong in the Earth system, and moved to change its organisation to reflect this concept. This new conception is nicely depicted in the "onion diagram" that was published in *Eos* and in the IGBP Science Plan and Implementation Strategy. That is the organisation – IGBP Phase II – that I stepped into when I started at IGBP in 2004. I still use the onion diagram to illustrate one effective way in which Earth-system science can be organised.

SEITZINGER: H T Odum [an influential ecologist at the University of North Carolina at Chapel Hill] said that scientists should always look at their research from a one- to two-order larger scale – for example, if you're studying a lake, look at it also in the context of the entire region. This is one way that IGBP has influenced the work of individual scientists on the Earth system.

Moreover, it provided the framework and support for "social physics" to inspire new ideas in Earth-system science. This was achieved by bringing people together to collaborate across disciplinary and geographic boundaries, moving people out of their comfort zones and into direct participation in conferences and workshops. Also, very importantly, through deeper engagement in planning and co-authoring syntheses and commentaries.

SYVITSKI: Without IGBP and its core projects, there would not be Earth-system science as we know it today. IPCC would not be the same – just imagine no biogeochemistry in our understanding of the land-ocean system – nor would modern climate change be put into a historical perspective. The modern level of coordination on Earth observations beyond the space agencies would probably not exist. International science would have remained patchy, with many countries lagging behind in their contribution. The US and Europe would have dominated the world of science in unhealthy ways.

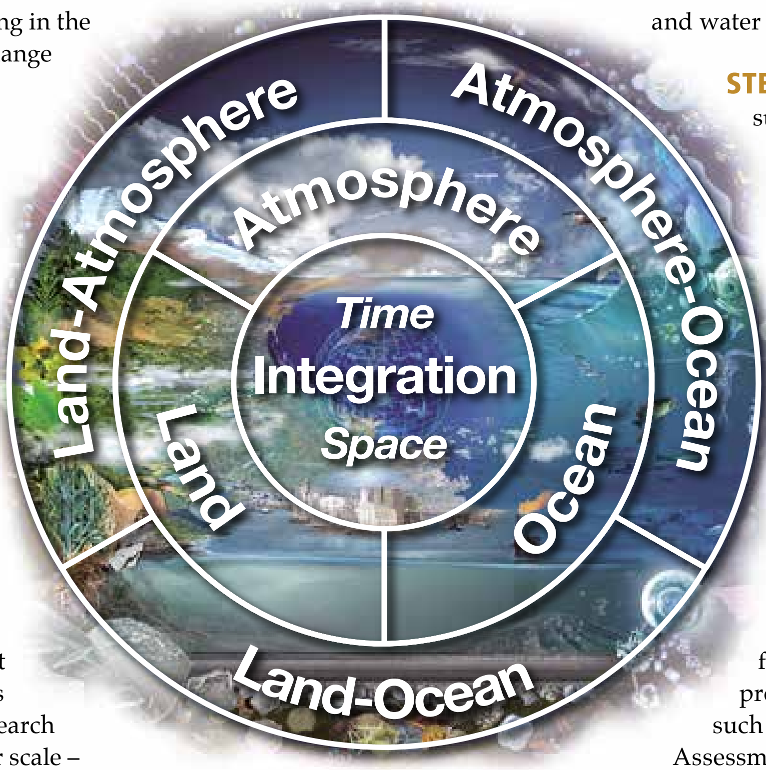


Illustration by Glynn Gorick underlying the "onion diagram".

Q: How successful has IGBP been in focusing scientific, policy and public interest on global change, not simply climate change?

ROSSWALL: Apart from the interaction of biogeochemistry with the climate system, IGBP has been successful in also looking at issues such as ocean acidification, transboundary air pollution, and so forth. Some of IGBP's syntheses have been assessments, although they might not be recognised as such, unlike the IPCC.

LISS: Because of IGBP's breadth it has embraced the science necessary for many policy aspects in addition to climate change. For example, air pollution (International Global Atmospheric Chemistry, IGAC), land degradation (Global Land Project, GLP) and biodiversity (Global Change and Terrestrial Ecosystems, GCTE, and eventually leading to the independent DIVERSITAS programme).

RAPLEY: My impression is that IGBP has been especially successful at highlighting in informative and useful ways the broader issues of land-use change, food and water security, and so on.

STEFFEN: Only partly successful, I think. There is still a huge emphasis on climate change, and this is perhaps appropriate given that it represents a rapid destabilisation of the energy balance at the Earth's surface. But I think that this situation is starting to change, especially over the past decade. This shift can trace some of its origins to a set of IGBP core projects (GCTE and Biosphere Aspects of the Hydrological Cycle, BAHC, for example), as well as other programmes and initiatives such as the Millennium Ecosystem Assessment and DIVERSITAS.

The legacy of all of these efforts can be seen, for example, in the Planetary Boundaries framework, in which climate change is one of nine boundaries.

IGBP's superb communication team played a significant role in getting global change – not just climate change – recognised beyond the research community.

NOONE: I think IGBP has been fairly successful in focusing scientific attention and interest on issues of global change. There have also been successes in the policy and public arenas too, but I personally feel that credit for many of these is more appropriately due to individuals associated with IGBP rather than the organisation itself. IGBP provided the support structure and soapbox (which was invaluable), but ultimately delivering the messages was effected by some of the talented folks associated with the organisation.

In my time at IGBP, we were going through a bit of an identity challenge (not a crisis!). The prevailing opinion was that IGBP was a science organisation that should be policy relevant but not policy prescriptive. We were moving into the domain of actively promoting new science results to wider audiences and actively seeking contacts in the policy and to some extent the private sectors.

Still, we were very much in a broadcasting mode, not really an interactive one. Nobody in the organisation wanted it to become another Greenpeace or WWF, but there was a realisation that we needed to be able to play some additional roles than the traditional one of dispassionate scientist disconnected from society. We had broken down the borders between scientific disciplines in the organisation, but still had ones between us and the rest of society.

SEITZINGER: One of the strengths of IGBP is that it does not only focus on climate change, but on the broader issues of global change. I made a back-of-the-envelope analysis of activities across IGBP and estimated that about half of our activities are primarily focused on climate change and the other half on other global changes.

From a policy perspective IGBP has always contributed to the IPCC, which has influenced policy (although IPCC has had less influence than we would have liked). In the past decade IGBP has developed many policy briefs and engaged directly with international conventions [see page 20]. IGBP has probably had the least impact on public interest in global change, although many of our communication products – visualisations, press releases, the *Global Change* magazine, etc. – have reached a broad audience.

SYVITSKI: One of the concepts developed by IGBP is the notion of the Anthropocene, in which humans were collectively creating a new geological epoch wherein atmosphere, ocean and land biogeochemical cycles were under the strong influence of humans and their societies. The extent and rate at which humans have modified Earth's land surface, through deforestation, mining, urbanisation and agricultural practice, is striking. Humans are now the largest force in the movement of sediment – greater than ice, wind and water.

IGBP has led efforts on understanding the impact in the growth of megacities, how deltas are sinking faster due to subsidence than sea level is rising, and how oxygen-depleted dead zones in our coastal oceans are tied to upstream agricultural practices. IGBP has reached out to involve social scientists at every level of its organisation and has help set the agenda for Future Earth with regard to environmental sustainability. The IGBP agenda as of 2014 contained about 70% Earth-system science and about 30% human dimensions science.

Q: Where does Earth-system science go from here in view of the changing landscape of science-society-policy interactions?

ROSSWALL: Well, it seems that Future Earth is the way forward. But maybe the time has come to change the way scientific collaboration is planned and executed. During the Norwegian review I mentioned earlier, almost all scientists knew about the International Polar Year (IPY). The reasons include dedicated funding and firm and published criteria for deciding on affiliated projects. This was a win-win-win for scientists, funders and sponsors.

But the way Belmont funding is developing, I see no signs of it working in support of a strong Future Earth programme. In the future the most crucial factor is how to reach out to the new generation of potential Earth-system scientists with a very compelling story. Also, it is essential to clarify how they can get involved. They have a competitive future and to attend planning meetings is probably not the most important activity to prepare them for a successful career. Especially if the IPY model of dedicated funding is absent.

LISS: What do you expect me to say, except Future Earth! We are in the first stages of completing the building of the Earth-system science edifice, with the needs of society framing the questions to be addressed.

RAPLEY: A single overarching programme is the correct approach in principle. It would contribute to both scientific understanding of the Earth system (including its future trajectory) as well as provide information of value to society – as determined by appropriate representatives of society in an adaptive and co-productive manner.

The problem is that if the estimates of remaining permissible carbon emissions are correct, there is no time for a leisurely 10- to 20-year science programme. Action is required now and this requires the global-change science community to prioritise communicating and delivering what it knows already to society in a manner that galvanises and facilitates necessary action. I don't see that recognition with Future Earth.

STEFFEN: Actually, the "changing landscape of science-society-policy interactions" is part of the Earth system itself, in fact, a very important part. As we look forward towards the trajectory of the Earth system, the trajectory that the human enterprise takes will be critical. And an important part of any scenario of the human enterprise is how societies will react to the ongoing developments in science and how this knowledge-generation process intersects with the policy and governance communities. Climate change is a classic example of this. So Earth-system science would be wise to include the changing landscape of science-society-policy interactions in any of its future scenarios, and it actually does so in some of the excellent research over the past few years in the field of Earth-system governance.

NOONE: I think the University College London report that Chris Rapley and others recently published (*Time for Change? Climate Science Reconsidered*, 2014) contains a lot of good ideas and analysis in this regard. The relevance and utility of Earth-system science will be substantially augmented if we are able to successfully develop and play roles that go beyond the linear science model of merely communicating scientific facts.

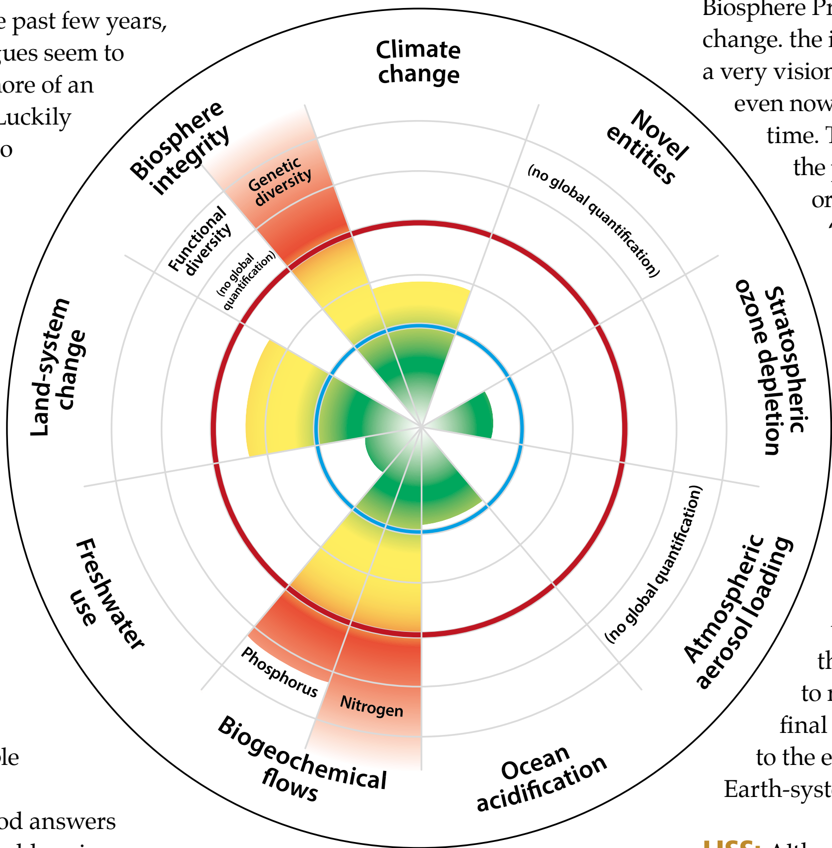
Working with a number of large private sector entities in recent years, I've often found myself playing the roles of "Issue Advocate" and "Honest Broker" proposed by Roger Pielke, Jr. Initially I found these roles to be somewhat discomforting. I struggled (as I still do) with trying to find the sweet spot at which I can express clear opinions about policy or decision options without losing my credibility as an impartial scientist (or being perceived as doing so). I've got more comfortable with this dilemma over the past few years, but now notice that colleagues seem to regard me as being even more of an oddball than I used to be. Luckily for me, I don't really have to care about this perception within the academic community. It does, however, shine a light on some conundrums we need to resolve.

For example, is it possible for any individual to occupy all of these roles without compromising his or her ability to fulfil any one of them? How do we empower stakeholders to assume the kind of influence that transdisciplinary efforts require without risking turning research into simple consultancy?

I certainly don't have good answers to these questions. Maybe addressing them should be a priority in the next evolutionary steps of Earth-system science.

SEITZINGER: We need to work with both "top down" (policy and societal questions/needs) and "bottom up" (science) approaches. Co-design is important but everything doesn't need to be co-designed. We must continue to advance the fundamental understanding of the functioning of the Earth system. This includes, of course, integration within and across spatial scales (local to regional to global) and in particular on time frames that are relevant to society – keeping in mind not only the near future, but multiple future generations. A grand challenge is integrating across the social, economic and biogeophysical domains.

SYVITSKI: Earth-system science is here to stay. It will continue through the IGBP core projects that are now part of Future Earth and through the larger academic community and their research societies. There will be a continuing role for global Earth observations and for assessments on rivers, coasts, polar regions and more. Post IGBP, there will certainly be a need for a focused international body to coordinate Earth-system science. Perhaps Future Earth will be able to play that role. And perhaps the space agencies and the larger international data efforts will also be able to provide needed coordination and focus. I remain optimistic that the internationally acclaimed achievements of IGBP will continue through the efforts of individuals and smaller teams as well as larger focused institutions, many of which have been established to mirror the organisational science structure of IGBP.



The nine planetary boundaries, as visualised by the Stockholm Resilience Centre/Globaïa. Source: Steffen *et al.* (2015) *Science*

Q: Any other thoughts or closing comments?

STEFFEN: As we reflect back on the history of IGBP and celebrate its achievements, it is very important to recognise the incredibly important foundation for the programme that was established during the planning phase in the late 1980s and the people who drove that. The best piece of evidence for the creative thinking on which the programme was founded is IGBP Report 12 ("The International Geosphere-Biosphere Programme: A study of global change. the initial core projects"). This is a very visionary and inspiring document even now, but was especially for its time. Those of us who have had the privilege to serve as chairs or directors owe much to the "founding fathers and mothers" of IGBP, and particularly to Thomas Rosswall. Without Thomas's dedication, energy and skill, the programme would never have had the excellent foundation on which it built so much over the years.

RAPLEY: What a disaster that the IGBP Secretariat is being jettisoned. The thinking behind this (was there any?) is incomprehensible to me, especially given the final points in my response to the earlier question on where Earth-system science goes from here!

LISS: Although IGBP and other such programmes often appear to be top-down organisations, some of the most successful activities have arisen spontaneously and in a bottom-up fashion. As a seminal NASA report from 1986 put it, "This insight has set the stage for a more complete and unified approach to its study, Earth System Science".

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