Sustainable Development and Planetary Boundaries

Background Research Paper

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The world faces a serious challenge, indeed one that is unique to our age. Developing countries rightly yearn to catch up with the living standards enjoyed in developed countries. If incomes in middle- and low-income countries were to catch up with incomes in high-income countries (roughly $41,000 per capita), there would be a roughly 3.4-fold increase in global income from $87 trillion to $290 trillion, which would increase even further if high-income countries grow further and as the world population grows. And therein lies the problem.

If the Earth's natural resource base were infinite, catching up by developing countries, continued growth in high-income countries, and further global population growth, would all be relatively straightforward. To catch up with the rich countries, the developing countries would invest in technology, infrastructure, and human capital (especially health and education), and step by step, would narrow the income gap with today's high-income countries. That, after all, is the current trajectory of Brazil, China, and India. It is also the preceding path of Japan and Korea. It is the hoped-for path of Africa as well.

Yet the Earth's natural resource base is not infinite. There is a global "adding-up" constraint that is not evident at the country level. Until recently, there were always under-utilized primary resources on the planet: for example new lands, new fossil-fuel reserves, and newly mined groundwater. Moreover, the world's ecosystems could absorb the waste of human activity: carbon dioxide from fossil fuels, nitrogen runoff from fertilizers, and even toxic pollutants dissipated by the oceans and rivers. Humanity could improve the productivity of hunting, fishing, mining, logging, and other "harvesting" activities without fear of ultimate depletion of those resources.

Now, however, the planet is crowded with 7.2 billion of us demanding primary resources, and the Earth's seemingly vast limits are being hit and hit hard. As a result global sustainability has become a prerequisite for human development at all scales, from the local community to nations and the world economy.

Various concepts exist to describe global environmental constraints: "carrying capacity", "sustainable consumption and production", "guardrails", "tipping points", "footprints", "safe operating space" or "planetary boundaries". We will employ the concept of planetary boundaries (Rockström et al 2009a), which provides a powerful description of the global "adding-up" constraints across key dimensions.

The concept of planetary boundaries has been developed to outline a safe operating space for humanity that carries a low likelihood of harming the life support systems on Earth to such an extent that they no longer are able to support economic growth and human development. As this paper explains, planetary boundaries do not place a cap on human development. Instead they provide a safe space for innovation, growth and development in the pursuit of human prosperity in an increasingly populated and wealthy world.

The nine planetary boundaries (Annex I) come in three main forms:

1. Boundaries defining a safe global level of depleting non-renewable fossil resources, such as energy (coal, oil, gas), and fossil groundwater;
2. Boundaries defining a safe global level of using the living biosphere, including exploitation of ecosystems, protection of biodiversity and consuming renewable resources, such as land use;
3. Boundaries providing a safe global level of Earth's capacity to absorb and dissipate human waste flows, including carbon, nitrogen, phosphorus, and toxic chemicals such as pesticides.

Some question the concept of planetary boundaries, in particular whether we face risks of abrupt, irreversible changes, with potentially catastrophic implications for poverty alleviation and human development. Yet, the scientific evidence has hardened substantially, and not just in the area of climate change (State of the Planet Declaration, 2012; Stockholm Memorandum; 2011; UNEP, 2012; Science 2011). We now have robust and rising scientific evidence that we have entered a new geological epoch, the Anthropocene, where humanity has become a global force of change at the planetary scale (Crutzen 2002). For the first time we are seeing evidence of human-induced changes on how the Earth system operates – from accelerated melting of ice sheets to shifts in rainfall patterns and the undermining of ecosystems and biodiversity. These global environmental changes can undermine long-term development opportunities and trigger abrupt changes for human societies (e.g. heat waves, droughts and floods, rapid sea level rise, pandemics and ecosystem collapse).

The confluence of unmet aspirations for human progress and economic development on one side and planetary boundaries on the other requires us to define a new framework for sustainable development that will permit economic and human development within the boundaries of the life-support systems on Earth (Griggs et al. 2013). This paper outlines such a framework: Section I outlines the political and normative choices imposed by a conflict between planetary boundaries and humanity's aspiration for economic growth. Section II describes a sustainable development scenario for the world and Section III discusses its practical feasibility. Section IV concludes with implications for the post-2015 agenda and the work of the High-Level Panel. To keep this paper as succinct as possible, the Annexes provide additional information and references for the interested reader.

I. Can Economic Growth and Planetary Boundaries be Reconciled?

What are the implications of planetary boundaries for economic growth? This question is usually answered with reference to three unattractive alternatives:

1. **Kick away the ladder:** The rich world is lucky to have reached a high level of income first. Low- and middle-income countries cannot grow further, to ensure the world stays within planetary boundaries.
2. **Contract and converge:** Rich countries need to substantially reduce their standard of living, and developing countries can grow until they converge at the lower income of high-income countries. At that point economic growth would need to stop.
3. **Business as usual (BAU):** In the absence of a shared global framework individual countries fail to acknowledge planetary boundaries in national policymaking. They each scramble for scarce resources. Fossil fuel and food prices soar, and planetary boundaries

are exceeded as the middle-income countries catch up with the high-income countries. The weakest countries find themselves pushed out of the marketplace and fail to develop. This zero-sum or negative-sum struggle can easily turn nasty. Richer countries will guard their advantage with military force if necessary (Annex II describes the BAU scenario in detail).

Options 1 and 2 appear politically impossible in HICs, MICs, and LICs alike. Developing countries around the world want to achieve economic progress, end extreme poverty in all its forms, and achieve higher per capita incomes. These aspirations are right and cannot be compromised on. An agenda that posits barriers to growth will not be supported by politicians and people around the world. Likewise, it seems impossible that politicians in rich countries would ever agree to drastically lower the standard of living. And why would developing countries agree to stop economic growth at a level of income that is below the income enjoyed by rich countries today?

We therefore believe that the BAU path is the most likely scenario and that it will lead to a highly unequal world that is also unstable and often violent. We know that the rich and powerful have a high tolerance for massive inequalities in wealth, income, and physical security. Yet we also believe that humanity can and should aim much higher than an open competition for increasingly scarce global resources. Rather than knowingly crossing the planetary boundaries, the world can agree and cooperate on living within the playing field they imply, by adopting improved technologies, stabilizing the world's population, and protecting threatened species and ecosystems. Such a strategy would leave all regions of the world better off than on the BAU path. Placing the world on such a "Sustainable Development Trajectory," we believe, must be a central objective of the post-2015 framework.

II. The Sustainable Development Trajectory

The Sustainable Development (SD) Trajectory addresses the planetary boundaries in a new way: not by an open struggle for resources, nor by contraction of high-income levels, nor by kicking away the ladder. We propose that the world should live within the planetary boundaries through the deployment of new sustainable technologies and new global rules of the game. Our contention is that an orderly and cooperative process will lead to dramatically improved outcomes for all parts of the world.

The SDSN is developing a simplified quantitative model for the BAU and Sustainable Development Trajectory, which will be completed soon in its first generation. Preliminary results from this modeling work suggest that a Sustainable Development Trajectory would comprise six major structural transformations to ensure that the world continues to develop economically while staying within planetary boundaries. We emphasize that these transformations would only form a subset of a post-2015 agenda, since they do not fully address issues such as ending extreme poverty, gender equality, health, education, and so forth (Annex IV and SDSN 2013).

Each of the transformations outlined in this section requires detailed strategies, major ongoing R&D efforts and continuous problem solving. A lot remains unknown about how exactly these transformations might work. Yet, we do know enough to get started with confidence that remaining issues can be resolved.

II.1. The Energy Transformation

Perhaps the most important transformation for the sustainable development trajectory is the shift towards a low-carbon economy. This shift must occur for two reasons. First, under a BAU trajectory the world will likely experience a likely 3-5°C increase in temperatures by the end of this century that would expose all countries to catastrophic climate change, including sea level rise, ocean acidification, extreme storms, droughts, floods, crop failures, and the collapse of whole ecosystems (World Bank 2012). In 2011 the world emitted some 4.9tCO_2e per capita in greenhouse gases from energy use and consumption alone (EDGAR 2013). This must come down to 2tCO_2e per capita by 2050 (Stern 2009). Most of the reduction effort must occur in the energy sector, which accounts for the bulk of greenhouse gas emissions.

Second, we are depleting key fossil fuel resources, notably conventional oil and gas but also coal, which will drive up fossil fuel prices and make traditional means of power generation and transport fuels more expensive. Unconventional oil and gas will increase fossil fuel supplies (at the cost of more CO_2 emissions of course), but are unlikely to break the upward trend of fossil-fuel costs. The structural rise in fossil fuel costs and the resulting economic incentive to shift towards cleaner fuels is often under-emphasized in discussions on energy and climate policy. The SD trajectory embraces the high social returns to early development and deployment of renewable energies. The underlying analysis is described further in Annex III.

An emerging, though still incomplete, body of research outlines the key components of the transformation to low-carbon energy systems. This early research underscores the economic and technological feasibility of a massive decline in carbon emissions by 2050 in high-income countries (Williams et al. 2012, ECF 2010, Ekins et al. 2013). The key elements of an 80% reduction in greenhouse gas emissions by 2050 include: (i) electrification of vehicle transport and heating/cooling for buildings; (ii) almost CO_2-free electricity generation by 2050 using a balance of renewables (essentially wind, solar), nuclear and carbon capture storage (CCS); (iii) major energy efficiency gains; (iv) advanced biofuels for a small but significant share of transport; and (v) land-use change and emission reduction in agriculture.

Critically, the details of such transformations, including their costs, need to be worked out for each region depending on renewable energy endowments, legacy infrastructure, population distribution, etc. Much less is known about how these transformations can be achieved in Upper Middle-income Countries, but it appears likely that their de-carbonization strategies will include broadly similar elements.

II.2. The Food Security Transformation

The global demand for food will increase due to rising incomes and an additional two or three billion people to feed. At the same time, the world's food supply will be under threat because of growing ecological pressures. Climate change will threaten large growing regions susceptible to drought, floods, extreme storms, and temperature stress. Depletion of groundwater and melting of glaciers will threaten many food-growing regions with increased water stress. Loss of biodiversity may undermine crop productivity. The list of risks is long.

An important step towards meeting this challenge is to head off the worst of climate change through de-carbonizing the energy system as described above. Climate change has already begun to destabilize the world's food supply, with massive crop failures in recent years in Argentina, Australia, China, Russia, Ukraine, US, and other grain exporting regions. We have also seen severe droughts in highly vulnerable food-importing regions like the Sahel, North Africa, and the Horn of Africa. The resulting food crises are likely to worsen under the BAU scenario.

Yet, agriculture itself needs to undergo major systems changes to meet rising demand and ensure food security. Rising food production must be decoupled from unsustainable utilization of water, energy, fertilizers, chemicals and land. This will require a multi-faceted agro-ecological intensification of food production involving at least four steps (after Doberman and Nelson 2013. See also Conway 2012, IAAST 2009, WEF 2010, and World Bank 2008).

First, we must increase productivity by at least 70% on existing crop and pasture land (FAO 2009). New technologies – better seeds, micro-dosing of fertilizers, precision farming, no-till farming, drip- and other precision-irrigation, integrated pest management, etc. – offer ways to raise crop productivity while lowering the impact of farming on the climate and biodiversity. Yet, food production is a highly localized activity, dependent on ecology, soils, culture, institutions, and many other factors. There are no one-size fits all approaches to creating a sustainable food system. The changeover to "Complex Farming", as we like to call it, is a major transformation, requiring research, development, agricultural extension, and improved economic incentives for farmers. It won't happen by itself.

Second and closely related, the intensification of agriculture must occur without significant extensification (expansion of land under cultivation). The resource use efficiency of agriculture (water, fertilizer, agrochemicals) must increase dramatically to reduce the environmental impact of agriculture including its substantial contribution to global greenhouse gas emissions (CO_2 from land-use change and energy inputs; methane from animal husbandry and rice cultivation; and N_2O from fertilizer use).

Third, targeted support is needed for smallholder farmers in impoverished regions who have minimal resources but need to grapple with climate change, water depletion, biodiversity loss, and land erosion. Unless smallholder farmers can become more productive to sustain their families, the pressure on marginal land and biodiversity will only rise.

Finally, a food security transformation will require a drastic reduction in food waste. Much food is lost post-harvest due to improper storage, spoilage, problems in transportation, etc. Reducing food waste can dramatically increase the food supply without increasing yields or the amount of farmland used.

The SDSN Thematic Group on Sustainable Agriculture and Food Systems is preparing a detailed background brief for the HLP that will describe the food security transformation in detail and document its feasibility.

II.3. The Urban Sustainability Transformation

Urbanization is proceeding at a very rapid pace in all developing countries. Between today and 2050 the share of the world population living in urban areas is expected to rise from approximately 50 percent to around 67 percent. The scale and speed of this change is unprecedented in human history. China alone is expected to add some 250 million new urban citizens from 2010 to 2025. Global investments in urban infrastructure and building are expected to rise from $10 trillion today to more than $20 trillion by 2025, with urban centers in emerging economies attracting the most of this investment (Revi and Rosenzweig 2013).

Due to their higher population densities, well-managed cities can provide high-quality social services, infrastructure as well as environmental services to their populations. They can increase per capita resource use efficiency much more easily than less densely populated areas. Yet, these opportunities can only be seized if cities have strong and effective governments that work well with their local communities to support more energy efficient building, modernized transport systems (electrified vehicles, mass transit, bicycle paths), smart power grids, and efficient use of natural resources. Urban infrastructure investments can have a lifetime of well over 50 years, so it is vital that resource-efficient investments be made soon.

At the same time, cities must become more resilient to environmental change and disasters. Most of the world's great cities are on the seacoast or river-ways, which makes them highly vulnerable to sea level rise, storm surges, and coastal pollution. In recent years, many of the world's leading cities, including New York, Beijing, Moscow, New Delhi, Paris, and others have suffered from extraordinary environmental crises, including massive storms, flooding, heat waves, droughts, and more. To increase resilience, cities must *inter alia* upgrade their infrastructure, introduce zoning and siting policies to avoid floods, and manage water resources and waste sustainably.

II.4. The Population Transformation

The world's population growth rate has slowed down significantly in recent decades, but this is now occurring off a higher base. The absolute number of people added each year will not fall substantially until mid-century (Figure 1). The figure also shows the major differences across the three fertility variants. The higher the world's population the harder it will be for the world to achieve the SD Trajectory (see Population Division (2011a)[1] for a full discussion of why population growth needs to be slowed as much as possible).

[1] Hania Zlotnik, the author of this paper, is a member of the Leadership Council of the SDSN.

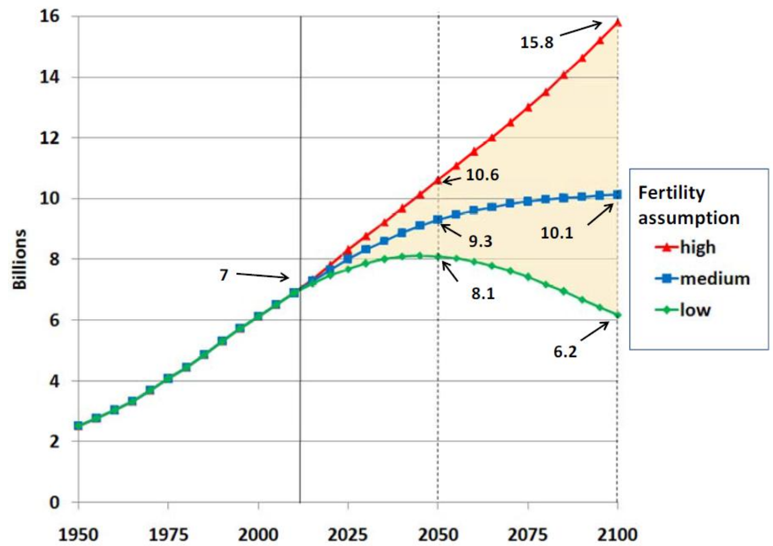

Figure 1: UN Projections of the world population according to three different assumptions about future fertility (Population Division 2011b)

Most of the high-income world and much of the middle-income world has already reached a low fertility rate, notably at or below replacement levels (roughly 2.05 children per woman on average), but fertility rates in Sub-Saharan Africa, North Africa and parts of the Middle-East, remain very high. Sub-Saharan Africa's population is projected to rise from 856 million in 2010 to more than 3.3 billion by 2100, unless the fertility rate is reduced. In a world of land scarcity, water stress, and climate change, such dramatic increases in Sub-Saharan Africa's population will likely lead to a Malthusian catastrophe. Similar conclusions apply to the BAU population trajectories in many countries across North Africa, the Middle East and Central Asia.

To head off these threats, countries need to complete the job of the demographic transition through voluntary fertility reduction. The young people of Sub-Saharan Africa will follow their counterparts in Asia and Latin America in choosing to have fewer children if they are also availed of the key reasons for fertility reduction: education at least through secondary level, an end to marriage for young girls, access to contraception, an end to taboos on family planning, women empowerment, and improvement in child survival. The introduction of social security programs in Africa (e.g. pension schemes) can also help, so that children are not the main source of parents' financial security. For more details on the elements and feasibility of the population transformation see Population Division (2011a).

II.5. The Biodiversity Management Transformation

Biodiversity protection describes the slowing of species loss[2] and the protection of habitats, ecosystems and biomes – all of which are under severe stress around the world. Since biodiversity plays a profound role in regulating Earth's system it must be maintained if humanity is to achieve the SD Trajectory.

A biodiversity management transformation at global scale would comprise strategies for managing the world's species that will operate at local and regional scales where the species live. It would also include strategies for preserving the six critical biomes that constitute key "global regulating systems" of concern for humanity as a whole, irrespective of where one lives. Rockström and Klum (2012) outline six such critical biomes:

- The Polar regions,
- The remaining tropical rainforests,
- The ocean marine system,
- The world's permafrost regions,

[2] As explained in Annex I, the planetary boundaries framework uses species loss as indicator for biodiversity loss.

- Temperate forests, and
- The world's savannahs.

Successful strategies for biodiversity management and ecosystem preservation are complex to design and require coordinated policies over a long time frame. They are also very site and context specific. Many operational questions remain unanswered and will require intense and continuous problem solving for each biodiversity management challenge.

II.6. The Private and Public Governance Transformation

One of the most difficult but important challenges will be the governance transformation. In an age of planetary boundaries public policy decisions must be made on the basis of scientific evidence. Environmental degradation is often aggravated by lack of transparency and accountability of local and national governments. When public institutions are weak or corrupt, when they do not respect the rule of law, then the public goods of sound environmental management tend to be massively underprovided. Improving governance at local, provincial and national levels is of course very complex and takes a long time.

A focus on planetary boundaries requires a careful look at international governance and its compatibility with achieving the SD Trajectory. First, global problems require global institutions that are representative of the world they help govern. The voting rights and shares in many international institutions reflect the world as it was after the Second World War and not the world as it is today. This imbalance ought to be addressed so that global institutions can speak with greater legitimacy. At the same time, today's emerging economies will need to take greater responsibility in the financing of these institutions and of global public goods more generally.

Second, many international environmental negotiations (e.g. under the UNFCCC) proceed on the basis that "nothing is agreed until everything is agreed", which becomes a recipe for gridlock. Such gridlock can be exacerbated by WTO and other rules (e.g. bilateral investment treaties) that make it hard for individual countries to enact stronger environmental standards without violating these rules or without fear of competition from non-compliers. For example, a growing number of researchers and policymakers advocate border tax adjustment tariffs as a necessary means to allow individual countries to enact bigger curbs on greenhouse gas emissions without threatening their industrial base. Trade and other international rules should therefore meet the additional test of whether they are constituent with moving towards an SD Trajectory. Where this is not the case safeguards need to be put in place to allow individual countries to move forward while others are still dithering.

Third, multinational businesses are now the most powerful actors on the world stage, with financial resources, technological know-how, management capacity, scale of operations, political influence, and the power of capital mobility (shifting operations from high-tax and high-regulation regions to low-tax and low-regulation regions), that dwarfs most or all governments. Yet multinational companies must also be made accountable for their actions. They must be transparent (not able to hide in tax havens), pay their taxes, use their political influence responsibly, and clean up after their environmental damages according to the "polluter pay" principle. All of this will require fundamental changes to some business models.

Bakker and Leisinger (2013) identify four steps that business must take towards the SD Trajectory:

1. Do no harm (e.g. through environmental externalities) and adhere to the UN Global Compact standards for responsible behaviour.
2. Integrate sustainability into core business strategies.
3. Reflect sustainability challenges in long-term risk assessments for every company through investors and capital markets.
4. Institute better ways of measuring the value and true performance of companies by internalizing externalities. Examples are the E-P&L developed by Puma, Integrated Reporting (IIRC), TEEB for Business, GRI and SASB pricing of externalities.

These are some important steps that businesses everywhere need to undertake to better align private incentives with public interest. Others include responsible advertising, shifting the tax burden from "goods" to "bads," and responsible lobbying (see for example Sukhdev 2012).

III. The Feasibility of the Sustainable Development Trajectory

Our overarching point is the following. The BAU trajectory is a dark threat for the world in an age of planetary boundaries. Today's developing countries will not be able to develop simply on the basis of the same technologies and business models as the high-income world. All countries will need to converge to new sustainable technologies and new rules of the game. Fairness and efficiency will require that all countries and regions share in the process according to global goals and standards. Most importantly, we will need a rapid technological overhaul in all regions of the world to ensure that all countries can continue to benefit from 21st century technology without wrecking the planet at the same time.

The challenges to achieve the SD trajectory are ethical, political, technological, and organizational. The ethical challenge starts from the premise that the rich world cannot simply kick the ladder away from today's poor countries. They have neither the power nor the right to do so. The ethical foundation of sustainable development is convergence: that all of the world should enjoy symmetrical benefits of human knowledge and technology, meaning that all countries should live in roughly comparable conditions over time. There should be a gradual convergence of living standards, technologies, and demographic patterns in the course of this century. If the world needs a new low-carbon energy system, it is the responsibility of all countries, rich and poor. If we need to stabilize the world's population, this is also the responsibility of all countries, rich and poor. We therefore take convergence (or alternatively, "the right to development") as the starting point, ethically and practically.

The political challenge is to create a new global framework – both in the form of global goals and rules -- to avoid a scramble of all against all. This will entail not only the formulation of sustainable development goals foreseen by the Rio+20 outcome document, but also clear binding rules of action under environmental, trade, and technology treaties and agreements. And as we noted, part of those rules will involve the new accountability of multinational companies, the main drivers of the world economy today.

The technological challenge is clear: to shift our industrial-age technologies to new information-age technologies, in energy, food production, transport, finance, health, education, and other sectors. We are in the midst of an information technology revolution driven by Moore's Law (the reduction by half in the cost of processing, storing, and transmitting data every 18-24 months). The costs of processing, transmitting, and storing data has declined by a factor of roughly one billion since 1960. This is enabling the revolution of mobile phones (7 billion subscribers), smart grids, social networking, and breakthroughs in countless fields of "big data": genomics, nanotechnology, agronomics, mapping, entertainment, finance, and much more. These are the bases for the new sustainable technologies, since they in general allow us to substitute bits and bytes for physical commodities, such as converting books to e-books, malls to online shopping, ATMs to mobile banking, and a thousand other applications.

The Sustainable Development Trajectory can be achieved, but it is an unprecedented and massive technological and organizational challenge. And time is very short. The world economy is so large and dynamic – growing at 4 percent per year, and therefore doubling every two decades – that we are on a collision course with planetary boundaries that will require much more than weak market signals alone. For the first time in human history, we will have to consciously steer the direction of technological change rapidly and on a global scale. That is the essence of the SD Trajectory.

IV. Implications for the High-Level Panel and the Post-2015 Agenda

This paper identifies the transformations needed to ensure continued human progress for all in the age of planetary boundaries. As mentioned at the outset, these transformations cover only parts of a viable post-2015 agenda. The SDSN Draft Framework Document (SDSN 2013) underscores that such an agenda would need to address all dimensions of sustainable development, including ending extreme poverty in all its forms.

In summary we propose the following items for consideration by the High-Level Panel:

1. **The science of planetary boundaries makes clear that we are on an unsustainable trajectory. The world must reject the three baseline scenarios outlined in Section I (kick away the ladder, contract and converge, business-as-usual (BAU)) and strive to achieve the Sustainable Development Trajectory.**

2. **Achieving the Sustainable Development Trajectory will require an unprecedented global effort by all countries – rich and poor – that will only be possible under a shared global framework for sustainable development. Such a global framework must have the following features:**

    a. **Provide an ethical foundation based on the principle of convergence and the "right to development"[3];**

[3] Others have framed this ethical foundation as "humanity and reciprocity" (Köhler 2013)

b. **Tackle the six transformations outlined in Section II (energy, agriculture, urbanization, population, fragile states, biodiversity), which will require inter alia an unprecedented mobilization of technology;**

c. **Address the other challenges of sustainable development, including ending extreme poverty in all its forms, ensuring social cohesion, improving the governance of the public and private sectors, and developing an effective global partnership.**

See Annex IV for a preliminary draft list of the operational priorities identified by the SDSN Leadership Council for the post-2015 development agenda.

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Annex I: The Science of Planetary Boundaries

The planetary boundary framework below is based on a decade's research suggesting a safe operating space for humanity. This was brought forward as a priority in the report from the UN Secretary-Generals High Level Panel "Resilient People Resilient Planet" (UNs Secretary-General's High-Level Panel on Global Sustainability 2012). It stated that we should "defend the science that shows we are destabilizing our climate and stretching planetary boundaries to a perilous degree".

In their report, Rockström and co-workers (Rockström et al 2009a) name nine planetary boundaries. These concern various global system issues including climate change, biodiversity loss, nitrogen and phosphorus cycles, freshwater use, land system change, ocean acidification, stratospheric ozone depletion, chemical pollution and aerosol loading (

Table 1).

Planetary boundary	Boundaries quantified
1. Climate change	CO2 concentration in the atmosphere should be limited to 350 ppm and/or a maximum change of +1 W m-2 in radiative forcing
2. Biological diversity loss	An annual rate of a maximum of 10 extinctions per million species
3. Biogeochemical cycles	Nitrogen (N) cycle - limit industrial and agricultural fixation of N2 to 35 Mt N yr-1) Phosphorus (P) cycle (annual P inflow to oceans not to exceed 10 times the natural background weathering of P
4. Global freshwater use	Limited to 4000 km3 yr-1 of consumptive use of runoff resources

5. Land system change	Not more than 15% of the ice-free land surface used as cropland
6. Ocean acidification	Mean surface seawater saturation state with respect to aragonite at not less than 80% of pre-industrial levels
7. Stratospheric ozone	Maximum 5% reduction in O3 concentration from pre-industrial level of 290 Dobson Units
8. Chemical pollution	No boundary defined
9. Atmospheric aerosol loading	No boundary defined

Table 1: Planetary Boundaries (Source: Rockström et al. 2009a)

The red areas in Figure 2 show the position of each boundary. The safe operating space for the boundaries are within the green area. Out of these nine boundaries at least three have already been passed: climate change, biodiversity loss, and the nitrogen cycle.

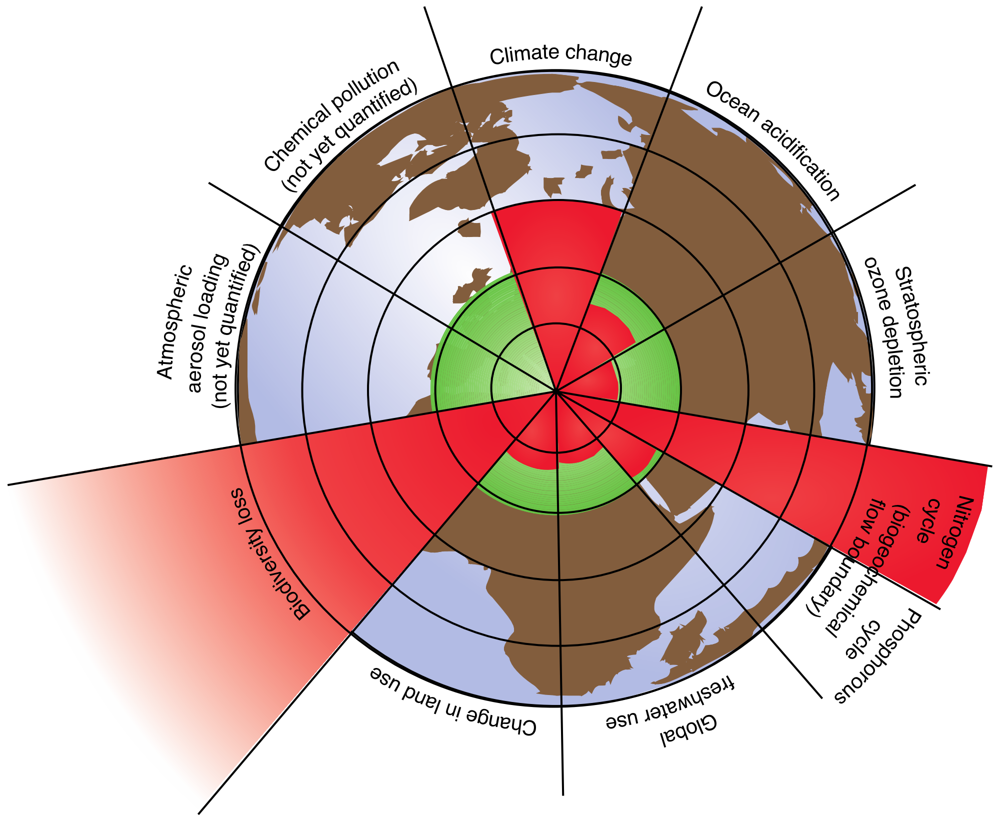

Figure 2: Planetary Boundaries (Source: Rockström et al 2009a)

Climate change is the boundary that, at a global level, has received most attention (e.g. IPCC 2007). It has been suggested that a safe temperature increase should be limited to 2°C. Within the planetary boundary framework the level of concern relates to the source, focusing on the concentration of CO_2 in the atmosphere. With a precautionary approach it has been set at 350 ppm CO_2 (which is still much higher than the pre-industrial atmospheric concentration of 270 ppm). Notably, the suggested boundary of 350 ppm CO_2 was passed some years back and today the CO_2 level is close to 400 ppm and increasing. There are data that suggest that the planet was almost ice free until concentrations of carbon dioxide fell below 450 ppm (±100 ppm) (Hansen et al 2008). According to the World Bank report "Turn down the heat" (World Bank 2012) chances are that the increase will be even larger. It should in this context be noted that climate change is not about a simple linear relationship between greenhouse gas concentrations and temperature; there is more complexity than that. For example, as glaciers melt more heat is absorbed (mostly due to changes in albedo) which will worsen the situation even further.

With big climatic changes (an increase of several degrees) devastating consequences for large proportions of society will follow. Weather patterns as we know them will change. Precipitation is expected to become more variable as well as increase in many areas. Dry areas will not necessarily benefit; on the contrary, dry areas are likely to become even dryer. Extreme weather will follow with, for example, more storms and heat waves. Food production and water availability will be reduced in many areas. Sea level rise will have a major impact on coastal areas. Notably all this will be costly to society. This is one of many examples of the costs involved in passing a planetary boundary. According to the UK Stern Review on the Economics of Climate Change, acknowledging climate change and working to prevent it is an investment; at its core it is about economic growth (Stern 2006).

Biodiversity is another planetary boundary of major concern that has been passed. Biodiversity is a measure of variation in nature. The specific boundary chosen as a measure for biodiversity in the planetary boundary framework is the rate of extinction. Before industrialization the extinction rate was less than one species per million species each year. At present more than 100 species out of a million are going extinct each year. The proposed boundary is set at 10 species per million species per year.

Biodiversity is the control panel for those living on Earth. Big changes in biodiversity will have major effects on the Earth system. Biodiversity is the natural capital we depend on to sustain ecosystem functions. There are many benefits for humans that in a direct manner relate to biodiversity, including clean air and water, food security, and health. Biodiversity loss comes with a price. According to The Economics of Ecosystems and Biodiversity the costs of the loss of terrestrial ecosystem services is estimated to be USD 50 billion per year (TEEB 2008).

Notably biodiversity is not only about species numbers. It also concerns variability in terms of habitats, ecosystems, and biomes. Habitat and ecosystem availability is essential for species diversity; if they disappear so will species. To quote the world renowned biologist E.O. Wilson: "The one process that will take millions of years to correct is the loss of genetic and species diversity by the destruction of natural habitats. This is the folly our descendants are least likely to forgive us". This can be illustrated with the highly diversified coral reef ecosystems. On coral reefs a large number of fish species are only found in association with certain coral habitats (Öhman and Rajasuriya 1998). If the corals are degraded due to temperature rise, as a consequence of climate change, not only the corals disappear but also the fish species associated with them (Garpe et al 2006).

Biomes are ecological regions at a global scale such as tropical rainforests, boreal forests (taiga), grasslands, tundra, and deserts. Since they are formed primarily due to variation in temperature and precipitation their distribution is mainly determined by climate and hence sensitive to climate change. With increased temperatures whole biomes can start changing in character. This can interact with a range of ecological components. For example, increased temperatures boost the outbreak of the mountain pine beetle that is devastating forests in western Canada (Taylor et al 2007). Climate affects biomes but it also works the other way around, i.e. biomes affect climate and other processes within the Earth's system. If biomes are altered this may change the climate in a profound manner, passing thresholds and causing long-term changes. In this respect all biomes are important and play a role to uphold the Earth system as we know it. Some biomes may play a more critical role in influencing climate and should be given attention accordingly. Forests, for example, affect a range of factors that relate to climate such as precipitation. Their importance in carbon sequestration is well known, and again we can return to the example with the mountain pine beetle. Where the outbreak occurred, the forest went from being a carbon sink to a carbon source (Kurz et al 2008). Critical biomes should not only be characterized by the role they may play to uphold a stable climate. It is also important to consider their sensitivity to human activities and how easily humans can change their structure and content. Technically speaking, deforestation is easily done and it causes a major ecological change where it occurs.

The cycles of Nitrogen (N) and Phosphorus (P) are essential for life on Earth. The availability of N and P in the biosphere has increased massively over the last decades. More atmospheric N is now transformed into reactive forms than all the naturally occurring processes on land (Rockström et al 2009b). This has major environmental impacts. Large quantities of reactive N result in nutrient overload (eutrophication) in soils, waterways, lakes, and seas. It also affects the atmosphere. Excessive nutrients in lakes and seas cause algal blooms, which may lead to oxygen depletion.

The usage of P is still within the boundary. However, the amount of N taken out from the atmosphere is beyond what would be considered a sustainable level. The present amount of atmospheric N (N_2) that is removed is 121 million tons per year; the proposed boundary is set at 35 million tons per year. Thus, this is a boundary that has been passed by a wide margin.

There is an ongoing debate on the relevance of planetary boundaries and how they may be quantified. The discussion will continue and other boundaries may be added or existing ones may be re-defined. The key point is that living on Earth is dependent on a basic life-support system in which the nine boundaries mentioned here play a very important role. Planetary boundaries define a planetary playing field that guide humanity on how to avoid environmental changes on a global scale.

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Annex II: The Business-as-Usual Scenario

For an illustrative business-as-usual (BAU) trajectory we assume the absence of a shared global framework for sustainable development and uncoordinated economic policies. The BAU path reflects the current fundamental drivers of global change. There are eight that are of prime significance:

1. Continued population growth concentrated mostly in developing countries and being especially fast in poorer countries. With an acceleration of fertility decline in the high-fertility countries of today, the global population is projected to rise from 6.8 billion in 2010 to 8.3 billion in 2030, 9.3 billion in 2050, and 10.3 billion in 2100.
2. The tendency on average for the economies of developing countries to grow more rapidly than those of rich countries as the developing countries close the technology gap. The current global growth pattern is of 1-2 per cent annual growth in high-income countries compared with 5-6 per cent growth in developing countries (all growth is calculated in purchasing-power-parity adjusted units).
3. High variance in GDP growth rates among countries, within both the developed and developing groups. Among developed countries, for example, Southern Europe is in deep economic decline, while Northern Europe is not. Among developing countries, most in East Asia are growing rapidly, while the poorer regions of Africa and the Middle East are in turmoil.
4. Rapid but uneven development and diffusion of information technologies building on Moore's Law.

5. Intensifying environmental stresses: global warming, unstable precipitation, loss of species habitat, ocean acidification, over-harvesting of fauna and flora (fishing, poaching, deforestation, etc.)
6. Depletion of conventional oil reserves and uncertain overall reserves of other key fossil fuels (coal, natural gas) and other minerals (e.g. phosphates), leading to high natural resource prices.
7. Instability of global food supplies resulting from the imbalance of rising global food demand and a relatively static and volatile supply-side.
8. Social, economic, and political instability in major regions (Sahel, Horn of Africa, West Asia, Central Asia).

Notice that the BAU trajectory fails to achieve sustainable development in multiple ways. Some regions fail to escape extreme poverty. Most regions suffer from high inequality and lack of social inclusion. The entire world experiences unprecedented environmental degradation (climate change, loss of biodiversity, ocean acidification, loss of habitat, rising sea level) that will make every country and region worse off by 2050.

The diverging economic prospects and high population growth in low-income countries will increase migration flows across the world. If poorly managed these migration flows stand to increase social divisions and tensions. Without improved cooperation, multinational corporations may be free to arbitrage across countries, thus putting major pressure on public revenues in every country.

The reason for the poor results of the BAU scenario is the failure of global cooperation around a shared framework for sustainable development. A global market economy without cooperation around a shared framework is not equipped to ensure widespread use of new technologies, address environmental threats (especially climate change), support vulnerable regions, reduce inequalities between skilled and unskilled workers, and provide opportunities for all children. In short, a BAU world will not witness the broad-based economic, social, and environmental transformations needed in every country to achieve sustainable growth with equity.

In **Fehler! Verweisquelle konnte nicht gefunden werden.** we highlight the regions likely to suffer moderate (M) and high (H) costs in the BAU trajectory. Given global interdependencies, however, all regions experience significant and avoidable costs.

	North America	Latin America & Caribbean	Europe	Middle East & North Africa	Sub-Saharan Africa	South & Central Asia	Southeast Asia & Pacific	East Asia
Poverty				M	H	H		
Food Insecurity				H	H	H	M	M
Health Insecurity				M	H	H	M	

Energy Poverty					H	H		
Water Stress & Drought	M	M	M	H	H	H		M
High Fertility				H	H	H		
Temperature Stress	M	M	M	H	H	H	H	M
Extreme Storms	M				H		H	H
Sea Level Rise	M	M	H	M	H	H	H	H
Ocean Acidification	M	H	H	H	M	M	H	M
Biodiversity Loss	M	H		M	H		H	

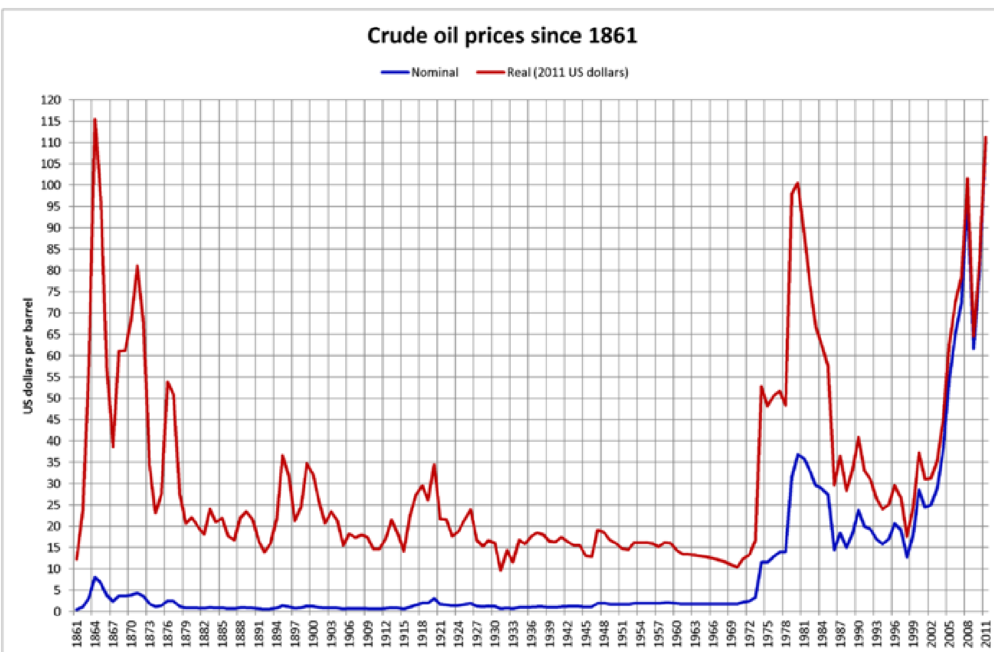
Table 2: Illustrative impacts of a BAU Scenario by region (Source: authors' estimates). Explanations see text.

Annex III: Possible Fossil Fuel Constraints on the BAU Scenario

Fossil fuels constitute the overwhelming share of energy resources in the world economy, greater than 80% of primary energy use. Their utilization continues to rise rapidly as the world economy expands. There is considerable debate about the long-run global supply curves for various fossil-fuel energy sources. This issue is of crucial significance. The long-term supply curve of fossil fuels will affect future growth prospects, optimum investments in renewable and nuclear energy sources, and prospects for CO_2 emissions in the long run.

The long-term supply conditions differ markedly, though uncertainly, across the major categories of fossil fuels: conventional oil, non-conventional oil (shale oil), natural gas (conventional and shale gas), and coal of various grades. One common view is that conventional oil is becoming more scarce ("peak oil") while the other forms of oil (e.g. shale oil, tar sands), as well as gas and coal are still generally plentiful. Yet this conventional view may be too optimistic. Global energy use is now so large, and is rising so rapidly, that all major forms of fossil fuels may face rising real production costs during the 21st century.

The long-term real price of oil is shown in Figure 1. We see that after the initial period of discovery in the 1860s and 1870s, oil prices fell to around $20 per barrel (in $US 2011 prices) for roughly a century, until the early 1970s. Oil prices spiked, fell sharply in the 1980s, and then resumed an upward trajectory in the early 2000s. They are near all-time highs at the moment. Many economists and market experts feel that the recent rise in prices reflects long-term depletion of major fields coupled with the soaring demand from China, India, and other emerging economies. Believers in peak oil argue that conventional oil production will peak very soon, perhaps this decade. According to the 2011 BP Statistical Review, the current Reserve/Production (R/P) ratio is around 54 years, but with the global demand for oil growing rapidly and with major fields in decline, that 54-year estimate might be optimistic. Yes, reserves surely understate the ultimate resource availability (since "reserves" designate discovered oil that is economically recoverable with today's technologies), yet demand is also soaring and depletion of existing fields is extensive. The International Energy Agency points out that nearly two-thirds of the current production of conventional crude oil (equal to 39.4 mbd) will need to be replaced by 2035 because of depletion of existing fields. (IEA, World Energy Outlook 2012). This will be a very tall order.



The recent advent of shale gas and shale oil, made possible by two innovations – horizontal drilling and hydraulic fracturing ("hydrofracking") of shale to release the oil and gas trapped in the rock

– has given rise to considerable industry optimism that new production can meet the rapidly growing world demand for energy (putting aside considerations of CO_2 emissions for the moment). Yet it's very easy to overstate the global significance of the new shale gas and oil. Consider recent estimates of shale gas reserves in the United States (where production is most advanced) and also globally. The US Energy Information Agency puts the proved shale gas reserves at 97.4 TCF. To put this in perspective, this amounts to 17.46 billion barrels of oil equivalent. With global oil consumption of around 6.8 billion barrels per year (2011), this represents around 2.5 years of oil consumption. This is large, but not fundamentally transformative. Of course the total base of "technically recoverable resources" is still larger. The US Energy Information Agency (EIA) puts total resources at 862 TCF, or roughly 22 years of current oil use. Worldwide, according to EIA, the total recoverable shale gas resource base might be as large as 6,600 TCF, which works out to about 36 years of current global oil consumption.

Note that while worldwide shale gas resources are obviously substantial, they do not really change the fundamental reality that oil and gas resources are likely to be substantially depleted this century (or outcompeted by alternatives). First, not all of the 6,600 TCF will be economically recoverable. Second, the EIA estimate has been criticized as too large, for allegedly not taking into account observed rapid declines in productivity of hydro-fracked gas wells. Third, global demand for oil and gas is rising, so that shale gas must not only replace current production but also meet growing demand. Fourth, the costs of recovering the resource base will probably rise significantly as more marginal fields are brought on line.

Many observers have argued that coal resources are the ultimate backstop for the world's fossil fuel economy. Coal resources are very large, arguably available on a centuries-long scale. Since coal can be converted both to gas and liquids (through the Fischer-Tropsch process), coal can conceivably replace depleting oil and gas fields. There are limits to this conversion, of course. Fischer-Tropsch is expensive, capital intensive, and requires a considerable investment lead-time. More fundamentally, though, there are also significant doubts regarding the conventional estimates of plentiful coal reserves. A series of recent studies have argued that there are clear signs of "peak coal" like peak oil, albeit with the coal peak coming in the 2030s-2050s rather than in the next decade as with conventional oil. One of the surprising features of the current scene is that China, the world's largest producer and consumer of coal, became a net importer of coal in 2009. This contributed to a rise in global thermal coal prices, from around $20 per ton at the start of the 2000s to around $60 per ton today.

Figure 3 Thermal Coal CAPP Price (Source: http://www.infomine.com/investment/metal-prices/coal/all/, accessed on 15 March 2013)

Annex IV: Possible Operational Priorities for a Post-2015 Agenda

This list outlines a preliminary set of operational priorities for the post-2015 agenda identified by the members of the Leadership Council of the Sustainable Development Solutions Network. This list may change in coming months in light of comments received on the draft framework document of the SDSN (SDSN 2013) and the reports prepared by the thematic groups of the Solutions Networks. The operational priorities could form the basis for framing post-2015 goals with quantitative targets and metrics to be added.

A central challenge in defining operational priorities for the post-2015 agenda is how to tackle inequality. Most inequality is explained by (i) unequal opportunities facing children according to household incomes; and (ii) discrimination of certain groups of society. The first driver of inequality is best addressed by ensuring that every child, whether born to a rich or poor household, has the full chance to develop his or her full physical, cognitive, and economic potential. This requires public financing of human capital – health, early nutrition, early childhood development, primary and secondary school, advanced training – to ensure that children of all classes have an equal opportunity. The challenge of discrimination and exclusion is best tackled through respect for and enforcement of human rights as outlined under priority 4 (see also Castellino and Diop 2013).

1. **Ending Extreme Poverty:** Extreme poverty in all its forms should be eliminated everywhere (possibly backed by an expanded and extended set of MDG targets to 2030).

Special attention will be given to fragile regions that need international support to achieve middle-income status.

2. **Promoting Sustainable Growth and Wellbeing:** All countries have a right to development based on a global norm of convergence. By 2030, all societies should be middle-income or higher. The measure of GDP should be improved to capture environmental losses and other pertinent non-market phenomena. Broader measures of wellbeing should be deployed including direct measures of subjective wellbeing.

3. **Productive Rural Communities and Sustainable Agriculture:** To promote the rural economic transformation, create productive, healthy and resilient rural communities. Use improved technologies, farming practices and policies to ensure higher and sustainable yields, crop resilience, protection of ecosystem services, reduced post-harvest losses, and lower food waste.

4. **Quality Education, Job Skills, and Decent Work:** The world of work is changing rapidly, driven by globalization and technological changes. Youth in particular must be prepared for decent work in the new era through universal quality secondary education and school-to-work policies including vocational training. Early childhood education (ECD) will be expanded to promote equal opportunities for all children. Communication and information technologies can play a central role in expanding access to quality education in all areas.

5. **Gender Equality, Personal Security, and Human Rights:** Ensure that all people enjoy equal opportunities regardless of gender, race, religion, etc. Provide personal security and freedom from all forms of violence.

6. **Healthy Lives and Sustainable Fertility:** By 2030 children and mothers should not die of preventable and treatable causes. All families should have access to reproductive health and other services needed for voluntary reductions in fertility rates to stabilize or reduce the world's and every country's population. Every country should have a healthy life expectancy of at least 70 years by 2030, and many countries will achieve 80 years or more. This can be achieved through universal access to health services, improved lifestyles, and healthy diets.

7. **Productive, Inclusive, and Resilient Cities:** To promote the urban economic transformation, create productive, healthy, peaceful and resilient cities, well-adapted to larger populations, job creation, and environmental changes. Cities should be free of slums and debilitating living conditions.

8. **Averting Dangerous Climate Change and Industrial Pollution:** Decarbonize the energy system by mid-century to avoid a 2-degree Celsius rise of the Earth's temperature through energy efficiency and the use of renewable and low-carbon technologies. Adapt to ongoing climate changes. Re-design industrial processes for materials efficiency, recycling, and safe waste management.

9. **Protecting Biodiversity and Ecosystem Services:** Address market failures that lead to environmental destruction. Protect all key ecosystems, marine and terrestrial, by ensuring sustainable practices of land use, waste management, water use, and other practices.

10. **Good Governance, Global Partnership, and Ensuring the Benefits of Technology:** Promote transparency, accountability and good governance for public actors (local governments, municipalities, national governments, international organizations), business, civil society, academia and the research community. Ensure an effective international partnership on the basis of a graduated set of global rights and responsibilities. The rules of the international system are made consistent with the trajectory for convergence and sustainable development. Key sustainable technologies should be promoted for early-stage development and for broad global diffusion, especially to ensure the interests of low-income countries.