Bridging the gap between resource use and Planetary Boundaries

Joint European Master in Management and Engineering of Environment and Energy

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### Index note

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Abstract

Impacts of human agency have become a major driver in the Earth System, with magnitude comparable to that of natural occurring global processes. Several earth system processes are under substantial pressure. These human induced pressures are likely to increase, potentially leading to undesirable changes at planetary scale. In that context, the Planetary Boundaries concept has been put forward aiming at defining a “safe operating space” for future endurance of humanity: relevant processes were identified with associated boundaries that, if respected, would avoid large-scale or irreversible change. The present study explores how human driven resource use relates to the Planetary Boundaries concept, through a water-food-energy-climate nexus perspective. It aims at identifying alternatives for the consideration of biophysical constraints in ways resources are modelled, and it presents an account of the current elements that hinder the integration of new constraints. The study found that existing Integrated Assessment Models and conceptual models for exploring Climate-Land-Energy-Water Strategies present important contributions, but further integration is necessary. Furthermore, decision-making support tools in these models were designed to assess mitigation options for climate, but cannot yet be used for multi-goal or multi-constraints studies. Scenario studies were found to be an important and yet underappreciated tool for such integration. The study identified novel techniques for scenario construction that could be applied in this context – they can allow the construction of sets of scenarios to bridge across scales or to connect separate modelling communities. The study suggests that for bridging the current gaps that exist between concepts it is necessary to develop an active interface across research communities involved in global change research, integrated assessment and resource modelling communities. These interfaces need to allow the co-development of concepts, the sharing of data and the confrontation of different perspectives on the shared challenge of exploring potential pathways for sustainability.
“Many plans, programs, and agreements, particularly complex international ones, are based upon assumptions about the world that are either mutually inconsistent or inconsistent with physical reality. Much time is spent designing and debating policies that are, in fact, simply impossible.”

(Donella Meadows et al. 1982, p.xix)
Presentation of the Stockholm Resilience Centre

The current master thesis was hosted at the Stockholm Resilience Centre (SRC). The centre is a transdisciplinary research centre that focuses on advancing research on the governance of social-ecological systems with a special emphasis on resilience - the ability to deal with change and continue to develop (SRC 2013a).

The centre was created in 2007, as a joint initiative between Stockholm University, the Stockholm Environment Institute (SEI) and the Beijer International Institute of Ecological Economics at The Royal Swedish Academy of Sciences. Since then, it has become a leading institution in its field, with high impact academic publications and important science-policy work. SRC’s researchers have published more than 525 publications, in a 150 journals, with about 30% of the centre’s publications among the top 10% most cited in their fields (SRC 2012).

The centre’s ethos is marked by a strong collaborative environment, an international and diverse group of researchers, and by a network of collaborators that spans across the globe (Figure 1). The SRC often hosts international events, and visitors are a common sight around its corridors. The centre contributes directly to a large number of international research programs, including the recently created Future Earth, ‘a 10-year international research initiative that will develop the knowledge for responding effectively to the risks and opportunities of global environmental change and for supporting transformation towards global sustainability in the coming decades’ (ICSU 2012).

![Stockholm Resilience Centre’s key collaborators](image)

Figure 1 International collaborators of the SRC. The SRC has a global network of collaborators, including 18 MoUs (Memorandums of Understanding), 38 agreements and 45 other collaborators (SRC 2012).
The centre hosted a workshop in 2008 - together with the SEI and the Tällberg Foundation - a workshop that united 28 renowned scientists and that culminated in the development of the Planetary Boundaries concept (Rockström et al. 2009b). Since then, this concept has been gaining prominence in both the science and policy arenas. It has also spurred an intense debate in the global change research community.

The present study was undertaken in the Planetary Boundaries research initiative, a joint activity with the Australian National University and the University of Copenhagen, which is hosted at the SRC. The project was conducted amid the formation of the Planetary Boundaries research network that counts with the collaboration of SRC, SEI, University of Copenhagen, Netherlands Environmental Assessment Agency (PBL) and the Potsdam Institute of Climate Impact research (PIK). Together, these two programs are at the core of the research surrounding Planetary Boundaries, and cover aspects related to modelling, governance and conceptual developments.

The present study also counted with a close cooperation from the Division of Energy Systems Analysis at the Royal Institute of Technology, which is at the forefront of the development of Climate-Land-Energy-Water-Strategies (CLEWs), a novel modelling framework for addressing the planning and management of integrated resources (Bazilian et al. 2011). This cooperation has in this study its first concrete outcome, and will hopefully continue to develop into a robust and fruitful relationship.
Acknowledgements

I would like to thank Sarah Cornell, my supervisor, for the great opportunity I’ve been given, for her support and inspiration, and for proving that an insatiable curiosity is a precious asset. And for making these though times easy and enjoyable.

“In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual.”

Galileo Galilei

I would also like to thank Ángel Uruburu Colsa for his supervision and Mark Howells and his team at the Division of Energy System Analysis at KTH, for the support and the welcoming workshops.

Johannes Friedrich and Manuel Weirich, I need to thank you for all the brainstorms that somehow helped with channelling ideas into the paper, and for the friendship that made Stockholm much nicer, even during the winter.

“Friendship is born at that moment when one person says to another: "What! You too? I thought I was the only one.”

C.S. Lewis

To my senior colleagues at the Stockholm Resilience Centre, Will Steffen and Ingo Fetzer, thank you for the interesting discussions and the help through this intense and interesting period.

Finally, I would like to thank Rafaëla Flach, my partner and best friend, for all the support in these two years of master, for all the patience, and for withstanding this absurd distance that will be over soon.

“If I know what love is, it is because of you.”

Hermann Hesse
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List of Abbreviations and Acronyms

DIVERSITAS – International Programme for Biodiversity Science
CGCMs - Coupled General Circulation Models
CLEWs – Climate, Land-use, Energy and Water strategies
ES – Earth System
ESM – Earth System Models
ESMIC – Earth System Models of Intermediate Complexity
ESs – Earth System science
ESSP – Earth System Science Partnership
GC – Global Change
GCs – Global Change science
IA – Integrate Assessment
IAMs – Integrate Assessment Models
IGBP – International Geosphere-Biosphere Programme
IHDP - International Human-Dimensions Programme on Global environmental Change
MDGs – Millennium Development Goals
PB – Planetary Boundaries
PBRI – Planetary Boundaries Research Initiative
PBL – Netherlands Environmental Assessment Agency
SDGs – Sustainable Development Goals
SEI – Stockholm Environment Institute
SRC – Stockholm Resilience Centre
1 Introduction

In recent years, a growing recognition of the effects of human enterprise can be seen in the reports of international research projects but also throughout society: in media, environmental activism, political campaigns and so on. Climate change, loss of biodiversity, air pollution, and extreme climatic events are examples of symptoms that are nowadays reported frequently in scientific conferences and in the environmental section of most newspapers, and figure constantly in the international policy arena. These topics are often accompanied by equally alarming headlines that discuss rising energy and food prices, the immanent risks of water scarcity that affect many regions, and problems of access to basic services, with dismal impact on the wellbeing of large portion of the world population. These issues are often divided in different sections of newspapers and studied by different research communities, but have inter-linkages that create a complex, daunting challenge.

The transformation of the Earth’s environment that have allowed the development of human societies is now so profound that it led scientists to propose the ‘Anthropocene’, a new geological era in which mankind is driver of change at global scale, comparable to ‘forces of nature’ (Crutzen 2002; Steffen et al. 2007). Moreover, the Anthropocene implies that the environmental pressures driven by human activities might force the Earth System out of the state of relative stability that has dominated the past 10000 years (Steffen et al. 2005a), denominated Holocene.

Growing evidence points to the risk of crossing thresholds and ‘tipping points’ (Lenton et al. 2008; Barnosky et al. 2012): situations in which small change in the drivers can lead to drastically different states. These new states can have severe consequences to human wellbeing and to the functioning of the Earth System.

Aiming at defining a ‘safe operating space’ for humanity, in which the thresholds are acknowledged and avoided, Rockström et al. (2009b) introduced the concept of Planetary Boundaries (PBs): for key earth system processes, control variables can be identified, for which boundaries are set aiming at avoiding global to continental thresholds, or ‘a large number of undesired threshold effects at the local to regional scale, which in aggregate add up to a serious global concern for humanity’ (see section 2.3 p. 9).

Rockström et al. (2009b) also utilized the PB concept to identify an initial set of process for which boundaries can be estimated. The authors proposed a preliminary set of 9 boundaries (7 of which quantified). This set, which will be referred herby as the Planetary Boundaries framework1, is depicted in Figure 2.

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1 The distinction between PB concept and PB framework is not particularly clear in the original publication (Rockström et al. 2009a; Rockström et al. 2009b). It will be used here to clarify the difference between the notion that it is possible to define boundaries and the initial set of boundaries proposed by the authors.
The purpose of the Planetary Boundaries framework is not to ensure, with a single boundary at global scale, that every single ‘tipping element’ at lower scales is also preserved, but rather aims at laying ‘the groundwork for shifting our approach to governance and management, away from the essentially sectoral analyses of limits to growth aimed at minimizing negative externalities, toward the estimation of the safe space for human development’ (Rockström et al. 2009b). Considering that this framework is rapidly being adopted as an overarching ensemble of metrics for global sustainability, it is increasingly pertinent to understand how it contributes or hinders the other efforts on sustainable development.

Source: Rockström et al. (2009a)

Figure 2 Planetary Boundaries framework
This image is a representation of the framework of nine boundaries. The green area in the centre represents the safe operating space’, delimited by PB. The three red wedges indicate processes for which the current levels of the control variables (presented in detail in Table 1, p. 12) have transgressed the boundaries according to the analysis of Rockström et al. (2009b).

In this context, in a critique of the initial PB framework, Kate Raworth from Oxfam propose that defining a ‘safe operating space’ based on biophysical boundaries is not enough: a set of social foundations is also necessary (Raworth 2012). As shown in Figure 3, this space can be depicted as a combination of an environmental ceiling defined by PB and social foundations that are based on critical human deprivations (Raworth 2012). This proposition tries to define ‘safe and just space for humanity’. Similarly to the original PB framework, the author of Oxfam Doughnut identifies 11
priority areas that define a social foundation for just societies (Raworth 2012), based on consultations with governments in the Rio+20 conference.

Source: Raworth (2012)

Figure 3 A safe and just space for humanity
The 11 dimensions of the social foundation, represented in the inner circle, are illustrative and are based on governments’ priorities for Rio+20 (Raworth 2012)

The Anthropocene, the PB concept, and the ‘safe and just space for humanity’ concepts address complementary aspects of sustainable development. However, the recognition of the influence of human enterprise on the state of the Earth System - which permeates the proposal of the Anthropocene and the Planetary Boundaries concept – goes beyond the risk of jeopardizing ‘the ability of future generations to meet their own needs’ that is at the core of the classic definition of sustainable development expressed by the Bruntland Commission (WCED 1987). This has led to the proposition of an alternative definition of Sustainable Development:

2 Raworth (2012) also quantified the deprivations for eight of these of these proprietary areas.
“Development that meets the needs of the present while safeguarding Earth’s life-support system, on which the welfare of current and future generations depends.”

(Griggs et al. 2013)

This definition highlights the dependence of human welfare on the Earth system functioning. In this context, the provision for human needs is not separable from the state of the environment. Three resources are at the forefront of this, figuring among the ‘social foundations’ (Raworth 2012) and among the main drivers of environmental change (Foley et al. 2005; Vörösmarty et al. 2010; GEA 2012): water, food and energy.

The sectors responsible for the provision of water, food and energy ‘(...) are dynamically linked to one another in a complex interdependent system that supports and interacts with human socio-economic activities, infrastructure, and ecosystems’ (PNNL 2012). The conjunction of the prospects of climate change and the growing population with rapidly changing consumption patterns results in an immense challenge that has been identified as one of the most important risks societies face nowadays (WEF 2011a). Until recently, most planning and policy making has occurred with little interaction across sector. Aiming at reverting this and promoting the development of systems capable of securing the provision of these vital resources, even in face of the impacts of climate change, the water-food-energy Nexus approach is being developed (Hoff 2011; Bazilian et al. 2011; WEF 2011b).

By addressing in an integrated way three of the main drivers of environmental change, the Nexus approach has the potential to identify and promote the mitigation strategies in order to reduce the environmental pressures generated by these resource systems (Bazilian et al. 2011). It may also help defining adaptation strategies for coping with the impacts global environmental change, as it is evidenced by current efforts to include climate change into the Nexus (WEF 2011b).

The complexity of the systems involved, and the necessity of envisioning future patterns of resource use in order to inform planning and policy decisions makes the use of models and scenarios increasingly important (Tol 2005; Bazilian et al. 2011). These models and scenarios are necessary to explore alternative pathways for the development, to inform policy making, and to try to depict future impacts of change for which adaptation is necessary. This has spurred the development of sophisticated tools such as Integrated Assessment Models (IAMs) and scenario approaches that allow the interconnection of different modelling communities (e.g. Zurek & Henrichs 2007; Moss et al. 2010; Arnell et al. 2011). Most of the current scenarios studies available nowadays, however, assess future constraints on the emissions of green

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3 Several denominations of the Nexus have been proposed. Often they list land-use instead of food (e.g. Energy-Land-Water Nexus in PNNL 2012). Other authors include the climate as part of the nexus (e.g. WEF 2011b). The denomination used here is the same as in Hoff (2011), which was used in the Bonn2011 Nexus Conference.
house gases, but fail to capture other potential limitations that arise from other PB (Söderholm et al. 2011; van Vuuren, M. T. J. Kok, Girod, et al. 2012).

The Nexus approach represents an important advancement when comparing with classic, sectoral planning. The PB concept, if used in this context, can expose symptoms of the change that currently transcend the scope of the Nexus. For this to happen, however, it is necessary to clarify the knowledge gaps that exist between these two concepts, and to search for possible ways of bridging the gaps.

1.1 Purpose of this Study

The purpose of this study is to provide insights for further development of the PB framework, with clearer interconnections to human activities. It integrates the activities of the Planetary Boundaries research initiative, hosted by the SRC, where other aspects of the concept and its application are being studied.

The study aims at exploring the knowledge gaps that the PB concept and the Nexus approach, and to provide insights for the development PB concept on the light of water-food-energy Nexus approach. This investigation will have a particular focus on the usage of scenarios studies for promoting the integration.

Thus, the following research questions were posed:

- Q1 - What characteristics of the PB framework (in its current form) hinder the utilization of the concept in this context?
- Q2 - What characteristics of current models used in integrated resource assessment hinder its usage in this context?
- Q3 - How can scenario studies be used to assess pathways of development that respect the planetary boundaries, including insights from the Nexus?

The significance of the questions posed by this project relate to the operationalization of the PB concept, motivated by its adoption by policy and business arenas. Recently, the PB concept figured in international environmental and energy assessments (UNEP 2012; GEA 2012) being part of the input to Post-2015 agenda discussion (SDSN 2012; Schultz et al. 2013), and figuring constantly in the dialogues that will lead to the definition of the Sustainable Development Goals (SDSN 2013). The use of PB for definition of SDGs remains controversial; whenever possible, the relevant aspects of the controversy are highlighted. However, it is out of the scope of this project to assess whether or not this is desirable. The analysis focuses rather on identifying the elements that would allow improving the representation of constraints in integrated resource assessment techniques.

In order to explore these questions, this project is based on a review of the literature. Since these questions have not been posed before, most of the literature found relates to either of the concepts (a brief overview of the concepts is provided in sections 2.1 - 2.4 ) to modelling and to the use of scenarios (sections sections 2.5 and 2.6 respectively). The findings from the review were then analysed in an in depth
discussion. The discussion surrounding Q1 and Q2 are presented throughout section 3. The discussion on the role of scenarios (Q3) is then presented at section 3.4. The conclusions are presented in section 4, with section 4.3 describing the activities that will follow this study.

The explorative character of this study is justified by the necessity of characterizing the concepts involved. The extensive overview of the literature is justified by the need of establishing which of existing tools and communities have dealt with similar issues.
2 Literature Overview

2.1 The Earth as a System

The modern conceptualizations of the Earth as a complex interacting system of global-scale cycles, in which both the biosphere and human factors are integrated, have emerged from a varied array of disciplines and perspectives. These conceptualizations have been strongly influenced by the ‘Gaia Hypothesis’ formulated in late 1960s by James Lovelock - the idea that the Earth operates in an analogous way to a living organism, with self-stabilizing dynamic processes and life as indispensable for this self-regulation (Cornell et al. 2012; Steffen et al. 2005a). In these initial conceptualizations, the relevance of humans in the system was seen as relatively limited (Cornell et al. 2012). Recently, the coupled socio-ecological dynamics has become central for the research (e.g. Costanza et al. 2012).

Often, terms such as Earth System science, Earth System analysis, Global Change science and Global Change research can be found in literature, without a clear distinction among them (Cornell et al. 2012; Schellnhuber 1999; Fries et al. 2012; Steffen, Grinevald, et al. 2011).

Earth System science developed on foundations laid by physical climate science and geophysics, which still influences considerably (Cornell et al. 2012). The recognition of the importance of life in modulation the geophysical, and on the role of anthropogenic drivers in altering the Earth System have led to a continuous expansion in the scope of this science. Earth System science (ESs) may be characterised by its ‘(...particular focus on the nature of the interactions between the many components of the Earth system, the human controls of system processes, and of course the global scale of inquiry’ (Cornell et al. 2012, p.xix).

The recognition of planetary-scale changes in the Earth System, initially expressed by concerns such as ozone depletion and global warming, have stimulated the creation of four Global Change programmes4. In 2001, during first Global Change Open Science Conference in Amsterdam, the Earth System Science Partnership (ESSP) was formally established (ESSP 2012). Nowadays these constitute an intricate network of researchers from several disciplines, organized among four global change research programs that cover different aspects of global environmental and social change. These research programs are on the verge of merging into a singular programme, Future Earth, that aims at developing crosscutting integrative science to enable science and society to respond to the issues of global sustainability (ICSU 2012).

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4 These groups are International Programme for Biodiversity Science (DIVERSITAS), International Biosphere-Geosphere Programme (IGBP), International Human-Dimensions Programme on Global environmental Change (IHDP) and World Climate Research Programme (WCRP).
The global change research community is passing through a reorientation, from singularly understanding the functioning of the Earth System towards research enables science and society to address the challenges posed by the social and environmental change. One example of this is the Earth System Governance Project (ESGP), which aims at respond to \textit{‘urgent need to develop strategies for Earth System management’} (ESGP 2008), identified by the ESSP.

In fact, more than a singular approach or theory, the existence of shared research challenges, a shared and rich toolkit and a rapidly growing research community are evidences of the emergence of this new science (Steffen et al. 2005a, chap.6).

### 2.2 Anthropocene

The impact of human activities on the environment are now profound and ubiquitous, to the point that nowadays Global Change and Earth System science communities point to the fact that Earth is moving to a new state – a less forested, less biologically diverse and much warmer state (Steffen et al. 2007). Extensive evidence shows not only signs of such transition\textsuperscript{5}, but that the pressures continue to increase as human societies continues what has been called the \textit{‘great acceleration’}, the period from 1950s onwards that marks the fastest change in human societies and human impacts ever experienced. Figure 4 depicts several indicators of such change.

Based on such evidence, scientists have propose that Earth might be entering a new geological era, which has been denominated as the Anthropocene (Crutzen & Stoermer 2000; Crutzen 2002). This concept is now widely accepted by the Global Chance community and was included in the final declaration of Planet Under Pressure Conference (26-29 March 2012, London), the largest gathering of this community that counted with over 3000 delegates in preparation to United Nations Conference on Sustainable Development (Rio+20). The declaration stated:

\textit{‘Humanity’s impact on the Earth system has become comparable to planetary-scale geological processes such as ice ages. Consensus is growing that we have driven the planet into a new epoch, the Anthropocene, in which many Earth-system processes and the living fabric of ecosystems are now dominated by human activities.’} (Brito & Stafford Smith 2012)

As Steffen et al. (2011) suggests, the Anthropocene also means that the Earth is leaving its current geological epoch, the Holocene. This period, which is the relatively stable inter-glacial period of the past 10000 years, is the one in which human society developed. An on-going debate exist on whether this should be considered a desirable and ‘safe state’ for the planet, and if it can be used as a benchmark (Rockström et al. 2009b; Nordhaus et al. 2012).

\textsuperscript{5} IGBP scientists compiled a large collection of such evidence, in Steffen et al. (2005b). It includes changes in climate, biogeochemical flows (e.g. nitrogen, phosphorous, silicon), marine and terrestrial ecosystems, urbanization, land use, atmospheric chemistry and others.
Several indicators of the mounting pressures due to human activity. These indicators clearly demonstrate the ‘great acceleration’, starting in the 1950s. In this period, human population has tripled, and the global economy and material consumption have grown many times faster (Steffen, Persson, et al. 2011).

2.3 Planetary Boundaries

The debate around the Anthropocene has led a group of Global Change scientists to pose the question ‘What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales?’ (Rockström et al. 2009b). In a first attempt to
answer this question, the authors proposed the definition of a set of ‘Planetary Boundaries’, each representing critical processes of the Earth system.

One fundamental concept behind planetary boundaries is the notion of non-linear behaviour, marked by thresholds, of some processes of the Earth System (Lenton et al. 2008). These thresholds, commonly denominated ‘tipping points’, mark situations on which the development of a given system can be altered qualitatively due to a small external perturbation. Lenton et al. (2008) suggest, that it is possible to identify components of the Earth system that are susceptible of passing through such transitions - the authors denominate these ‘tipping elements’.

The diverse processes of the Earth system can present a variety of behaviours: i) some processes in the Earth system are likely to present global thresholds; ii) others can cause a degradation of the overall resilience (the system’s ability to resist or buffer external perturbances without substantial change its characteristics) or can present thresholds at regional and local scale that present global concern to humanity when aggregated (Rockström et al. 2009b). Figure 5 presents a representation of these two possibilities: a) the case in which a global threshold is likely (e.g., risk of melting the Greenland and Antarctic ice sheets); b) the case in which a threshold is not identifiable at global scale (‘slow processes’). In both, a control variable and a response variable are necessary to allow the identification of the behaviour in question.

![Figure 5 conceptual representations of the planetary boundaries](image)

Source: Rockström et al. (2009b)

This figure highlights that the definition of the PB depends on the control and response variables, and of a zone of uncertainty around a threshold or around a ‘dangerous level’.

As this figure suggests, the PB suggested by Rockström et al. (2009b) are situated at the edge of the zone of uncertainty, in respect of the precautionary principle. As the authors clarify, the definition and position of the boundaries depends on a series of normative decisions that involve: i) what constitutes unacceptable change in the environment; ii) the risk acceptance of the global community; iii) the resilience and
adaptive capacity of societies to the impacts of the change; and iv) boundaries for processes which could present thresholds on a ‘ethical time horizon’.

According to the criterion presented above, nine processes were identified. Figure 6 summarizes the processes and the character of the boundary proposed by (Rockström et al. 2009b). For seven of the process shown above, the authors identified a control variable and proposed an initial quantification of a Boundary. Both Chemical Pollution and Atmospheric Aerosol Loading have not been quantified up to date. Table 1 presents the control variables, boundaries and current values, according to the preliminary results of Rockström et al. (2009b). The three first boundaries were identified as being crossed. Based on these values, the authors proposed the representation of the boundaries reproduced in Figure 2, (p. 2).

Source: Rockström et al. (2009b)

The processes in question are somehow interlinked. This means that transgressing one of the PBs could precipitate others processes into an undesirable state. However, current knowledge and modelling is not adequate to explore such possibility (Friedrich 2013).
Table 1 Planetary Boundaries as suggested in the initial publication
The three boundaries highlighted have been crossed, indicating that these Earth system processes are in an uncertain condition that might lead to thresholds being crossed. The state of knowledge and of each Boundary is also presented, as well as the related categories in the Driver-Pressure-State-Impact-Response framework. Only 7 of the boundaries have been quantified in the framework presented by (Rockström et al. 2009b).

<table>
<thead>
<tr>
<th>Process</th>
<th>Control variable</th>
<th>Current Value</th>
<th>Boundary Value</th>
<th>State of Knowledge</th>
<th>DPSIR¹</th>
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<tr>
<td>Climate change</td>
<td>(i) Atmospheric Carbon Dioxide Concentration (ppm)</td>
<td>387</td>
<td>350</td>
<td>1. Ample scientific evidence.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ii) Change in radiative forcing (W/m²)</td>
<td>1.5</td>
<td>1</td>
<td>2. Multiple sub-system thresholds.</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Debate on position of boundary.</td>
<td></td>
</tr>
<tr>
<td>Biodiversity Loss</td>
<td>Rate of extinction (species per million species per year)</td>
<td>&gt;100</td>
<td>10</td>
<td>1. Incomplete knowledge on the role of biodiversity for ecosystem functioning across scales.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Thresholds likely at local and regional scales.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Boundary position highly uncertain.</td>
<td></td>
</tr>
<tr>
<td>Global P and N cycles</td>
<td>(i) Amount of N₂ removed from the atmosphere for human use (million tonnes per year)</td>
<td>121</td>
<td>35</td>
<td>N: 1. Some ecosystem responses known;</td>
<td>Driver (N)</td>
</tr>
<tr>
<td></td>
<td>(ii) Inflow of phosphorous to ocean (increase compared to natural weathering)⁹</td>
<td>8.5-9.5</td>
<td>11</td>
<td>2. Acts as a slow variable, existence of global thresholds unknown;</td>
<td>Pressure and State</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Boundary position highly uncertain.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P: 1. Limited knowledge on ecosystem responses;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. High probability of threshold but timing is very uncertain;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Boundary position highly uncertain.</td>
<td></td>
</tr>
</tbody>
</table>

⁶ Values in 2009, when the Rockström et al. (2009b) was published. Since then these values have increased. CO₂ concentrations, for example, are already above 400 ppm.

⁷ In Rockström et al. (2009b, 2009c) the zone of uncertainty and the reasons for the definition of such zone are discussed in detail.

⁸ As classified by Naturvårdsverket (2013), and depicted in Figure 7.

⁹ Another proposition for this boundary was suggested by Carpenter & Bennett (2011), which concluded that the boundary for Phosphorus has also been crossed.
<table>
<thead>
<tr>
<th>Pressure</th>
<th>Action</th>
<th>State</th>
</tr>
</thead>
</table>
| Ocean Acidification | Carbonate ion concentration (average global surface saturation state of aragonite) | 2.90  2.75                                                                                         | 1. Geophysical processes well known.  
2. Threshold likely.  
3. Boundary position uncertain due to unclear ecosystem response. |
| Stratospheric Ozone Depletion | Stratospheric O₃ concentration, (Dobson unit) | 283  276                                                                                           | 1. Ample scientific evidence.  
2. Threshold well established.  
3. Boundary position implicitly agreed and respected. |
| Land use change | Percentage of global land cover converted to cropland¹⁰ | 11.7  15                                                                                           | 1. Ample scientific evidence of impacts of land-cover change on ecosystems, largely local and regional.  
2. Slow variable, global threshold unlikely but regional thresholds likely.  
3. Boundary is a global aggregate with high uncertainty; regional distribution of land-system change is critical. |
| Freshwater Use | Consumptive blue water use (km³ yr⁻¹) | 2600  4000                                                                                          | 1. Scientific evidence of ecosystem response but incomplete and fragmented.  
2. Slow variable, regional or subsystem thresholds exist.  
3. Proposed boundary value is a global aggregate, spatial distribution determines regional thresholds |
| Atmospheric Aerosol Loading | Overall particulate concentration in the atmosphere, on a regional basis | To be determined                                                                                   | 1. Ample scientific evidence.  
2. Global threshold behaviour unknown.  
3. Unable to suggest boundary yet. |
| Chemical Pollution | Could include concentrations or effects on ecosystem and Earth System functioning of persistent organic pollutants (POPs), plastics, endocrine disruptors, heavy metals, and nuclear wastes | To be determined                                                                                   | 1. Ample scientific evidence on individual chemicals but lacks an aggregate, global-level analysis.  
2. Slow variable, large-scale thresholds unknown.  
3. Unable to suggest boundary yet. |

Adapted from: (Rockström et al. 2009a; Rockström et al. 2009b; Naturvårdsverket 2013)

¹⁰ Another proposition for this boundary was suggested by Running (2012); this proposition was since criticized by Erb et al. (2012).
2.3.1 Application and debate

In order to analyse some of the interconnections and the causal chain that connects boundaries and human drivers, Naturvårdsverket (2013) mapped the boundaries using the DPSIR (Driver-Pressure-State-Impact-Response) framework. This framework is commonly used in International Environmental Assessments to identify complex and multidimensional cause-effect relationships (e.g. EEA 2005; EEA 2010; UNEP 2012), as it categorizes the drivers of environmental change (human activities), pressures (arising from human activities of from natural process), state and trends (e.g., concentration of CO2 in the atmosphere), impacts (on the environment and on factors affecting human well being) and responses (e.g., mitigation, adaptation).

As Figure 7 suggests, some of the PBs: i) have the same driver or pressure (e.g. climate change and ocean acidification); ii) are linked in the causal chain (e.g. biodiversity can be an impact of land use change) (Naturvårdsverket 2013). The impacts of one process can affect others (as shown in the figure for the case of climate change), potentially affecting tipping elements (e.g. monsoon system and ocean anoxic events).

Source: Naturvårdsverket (2013)

Figure 7 Analysing planetary boundaries under the DPSIR framework
This classification demonstrates that the control variables from the framework are qualitatively different, corresponding to different aspects of the causality-chain of environmental change.
Since its proposition, the planetary boundary concept has generated a rich debate, which includes sectors of the Global Change research community and the policy community. Criticism has been directed to the specific boundaries proposed (Bass 2009; Molden 2009; Samper 2009), the implications for policy (P. Brewer 2009; Schlesinger 2009; Fries et al. 2012) and the concept as a whole (Nordhaus et al. 2012; Brook et al. 2013). Even with the criticisms, the planetary boundary framework has received significant attention in International Environmental Assessments, and in policy processes. One such example is the declaration from Planet Under Pressure Conference:

‘That the Earth has experienced large-scale, abrupt changes in the past indicates that it could experience similar changes in the future. This recognition has led researchers to take the first step to identify planetary and regional thresholds and boundaries that, if crossed, could generate unacceptable environmental and social change.’

(Brito & Stafford Smith 2012)

The planetary boundaries framework figured in the latest Global Environmental Outlook (UNEP 2012), and in the Global Energy Assessment (GEA 2012). In the latter, the concept was evaluated in terms of it adaptation for analysis of the energy systems (Table 2). The report pointed PB concept as useful for identifying indicators for global sustainability. However, it is clear that the indicators proposed in the initial publication might not be adequate for addressing the impacts and pressures across other scales, especially in the case of slow variables.

The usage of planetary boundaries for exploring and comparing national performance is been currently assessed by different institutions, including the SEI (Naturvårdsverket 2013), the SRC and by researchers from Oxford University (Megan Cole and Prof. Mark New, working on the downscaling of the boundaries for South Africa).

Another important policy process in which the planetary boundaries concept is been considered is the process of definition Sustainable Development Goals (SDGs), which will substitute the Millennium Development Goals (MDGs). The Goal ‘achieve development within planetary boundaries’ has been proposed by the Sustainable Development Solutions Network (SDSN 2013) which is supposed to inform the High-Level Panel of Eminent Persons on the Post-2015 Development Agenda. The same report proposes the following target ‘Countries report on their contribution to planetary boundaries and incorporate them, together with other environmental and social indicators, into expanded GDP measures and national accounts.’ Such declarations reinforce the prospect of planetary boundaries becoming an important metric for global sustainability but also spur the debate around issues of Earth System governance (Nilsson & Persson 2012) and the notion of ‘planetary stewardship’ (Steffen, Persson, et al. 2011; Seitzinger et al. 2012). Although the PB framework has been gaining prominence in the international policy arena, it is only recently that its
implications have started to be analysed (Galaz, Frank Biermann, et al. 2012; F Biermann 2012).

Table 2 Summary of proposed global sustainability indicators for energy systems based on planetary boundaries

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Receptor System</th>
<th>Planetary Boundary</th>
<th>Indicator target or orientation value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission of radiative forcers (e.g., CO₂, PM, aerosols), leading to changes in global and regional climate</td>
<td>Atmosphere</td>
<td>Climate change; Rate of biodiversity loss; Ocean acidification; Atmospheric aerosol loading</td>
<td>350 ppm CO₂ or climate forcing less than 1 W/m² above the pre-industrial level, or less than 1000 GtCO₂-eq released in the period 2000–2050. No more than 2°C above pre-industrial of human-induced global warming, with a probability greater than 50%. Aim for 50% GHG emission reduction by 2030 and subsequent reductions to achieve the target. Reduce by 2030 and eliminate by 2050 emissions of black carbon, organic carbon, nitrogen and sulphur, and other particulate matter that contribute to atmospheric aerosol loading, so that radiative forcing remains less than 1 W/m².</td>
</tr>
<tr>
<td>Emission of air pollutants (e.g., SO₂, NOₓ, O₃)</td>
<td>Atmosphere</td>
<td>Climate change; Rate of biodiversity loss; Nitrogen cycle; Chemical pollution; Atmospheric aerosol loading</td>
<td>Reduce by 2030 and eliminate by 2050 emissions of black carbon, organic carbon, nitrogen and sulphur species, and other particulate matter that contribute to atmospheric aerosol loading, so that radiative forcing remains less than 1 W/m². Reduce by 2030 and eliminate by 2050 emissions of air pollutants that contribute to human health and ecosystem damage – further research required to define such limits.</td>
</tr>
<tr>
<td>Land requirement and degradation</td>
<td>Terrestrial biosphere</td>
<td>Change in land-use; Rate of biodiversity loss; Chemical pollution</td>
<td>No more than 15% of global land cover should be converted to cropland.</td>
</tr>
<tr>
<td>Water resource requirement and impaired water quality</td>
<td>Freshwater and marine systems</td>
<td>Global freshwater use; Rate of biodiversity loss; Chemical pollution</td>
<td>Limit global freshwater use to no more than 4,000–6,000 km³/yr of consumptive use of accessible river flow.</td>
</tr>
</tbody>
</table>

Source: GEA (2012, p.241)

Currently, the Planetary Boundaries Research Network is being created with the objective of fostering the research around the PB concept, including efforts of conceptual development, conceptual modelling, Integrated Assessment Modelling (IAM, see section 2.5 ). The research network includes the SRC at Stockholm University, the SEI, the Potsdam Institute of Climate Impact (PIK), the Netherlands Environmental Assessment Agency (PBL) and Copenhagen University.
2.4 Water-Food-Energy Nexus

The systems used for the provision of water, food and energy are interrelated. Many of the components of each of these systems depend on common and limited resources, and interact in various ways (PNNL 2012). They are dependent on the climate, and are affected by trends such as population grow, urbanization and economic development which have been increasing the pressure on each of the systems (Hoff 2011; WEF 2011b). As the pressures of global environmental change increase (Ingram et al. 2010; E. F. Lambin & Meyfroidt 2011; Vörösmarty et al. 2010; Rockström et al. 2012), the security of provision of water\(^ {11} \), food\(^ {12} \) and energy\(^ {13} \) needs to be addressed as a nexus (Bazilian et al. 2011; WEF 2011b), ‘an approach that integrates management and governance across sectors and scales’(Hoff 2011, p.7). Figure 8 depicts a conceptualization of such nexus (climate included as a trend).

Figure 8 A conceptual depiction of the Water-Food-Energy Nexus approach
In this conceptualization, climate change is represented as a global change, as a global trend. There is a clear focus on the security of supply, and centrality of water resources.

‘An integrated view across the nexus provides more comprehensive information on relative resource scarcity and productivity, and on the potential for sustainable intensification in different regions’ (Hoff 2011). Thus, the nexus approach aims at informing policy

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\(^ {11} \) Water security was defined by the MDGs as ‘access to safe drinking water and sanitation’, both which have recently become a human right (UN 2010; Hoff 2011) 

\(^ {12} \) ‘Food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life’ (FAO 2008) 

\(^ {13} \) There are many definitions for energy security. For a review: Winzer (2011). In this document, nation’s energy security is defined as ‘protection from disruptions of energy systems that can jeopardize nationally vital energy services’ (GEA 2012, p.329)
making an planning, and has a dual goal (Hussey 2010): i) to identify and implement synergistic policies and technologies (promoting mutual benefits and ‘no-regret’ policies); ii) to avoid conflicting policies that can lead to undesirable trade-offs and ‘knock-on effects’. Promoting sustainable growth and the resilience of the environment is also seen as a goal (Hoff 2011), but it is not a clear connection between the resilience and the security of supply.

Not addressing the water-food-energy nexus is nowadays recognized as a major risk for society\(^{14}\) (WEF 2011a). Although some of the drivers for the issues are global, it is consensual that the solutions are context specific (Hoff 2011). So far, some recurring opportunities have been identified (Hoff 2011; Bazilian et al. 2011; WEF 2011a; WEF 2011b):

- Recognizing and quantifying the trade-offs;
- Increasing resource productivity;
- Using waste as a resource;
- Resource pricing (specially water);
- Community level empowerment and integrated multi-stakeholder planning;
- Breaking the “silo thinking” in decision-making bodies through increased cooperation and policy integration;
- Economic and security-related benefits can provide impetus and guide cooperation
- Regionally-focused infrastructure development

So far, the water-food-energy nexus has been supported by few case-studies, developed using an array of fragmented analytical tools, which has led to the development of a new modelling framework (Bazilian et al. 2011), reviewed in section 2.5.1, p. 23.

2.5 Modelling

In a recent review of models in the context of Planetary Boundaries, Friedrich (2013) concluded that at current state, existing models are not capable of answering the kinds of questions that arise from the PB concept, notably the determination of thresholds and uncertainty zone. This is partially due to the fact that models cover different aspects of the complex causality chain that links human activities, changes in the environment and its impacts on human society.

An area that has seen most developments in terms of modelling is the climate change. It is worth reviewing it, as it already comprises many of the aspects of global environmental change that are related to Planetary Boundaries. Most of the research occurs in three interlinked research areas (summary in Table 3).

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\(^{14}\) In its Global Risk Report, the World Economic Forum listed this issue among the top global risk (WEF 2011a).
Table 3 Summary of modelling communities involved in climate change research

<table>
<thead>
<tr>
<th>Modelling community</th>
<th>Type of Models</th>
<th>Main Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate Modelling (WG I)</td>
<td>Earth System Models (ESM)</td>
<td>Climate simulations</td>
</tr>
<tr>
<td></td>
<td>Coupled General Circulation Models (CGCMs)</td>
<td>Temperature anomalies</td>
</tr>
<tr>
<td></td>
<td>Specific models for different sectors</td>
<td>Precipitation changes</td>
</tr>
<tr>
<td>Impacts, Adaptation and Vulnerability – IAV (WG II)</td>
<td>Integrated Assessment Models (IAMs)</td>
<td>Impacts</td>
</tr>
<tr>
<td></td>
<td>(Normally also use an simplified Earth System Model)</td>
<td>Adaptation Options</td>
</tr>
<tr>
<td>Integrated Assessment - IA (WG III)</td>
<td>Assessment of mitigation options</td>
<td>Investigation of emission pathways</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Development of social, economic pathways</td>
</tr>
</tbody>
</table>

Summary based on: DOE (2009)

A large spectrum of models is used in global change and climate change research (Figure 9). Earth System Models (ESMs) are comprehensive models that aim at describing the entire Earth system, normally coupling several models that describe different components. They include the Coupled General Circulation Models initially used for climate research, which nowadays are used in conjunction with models representing the biosphere and Earth System Models of Intermediate Complexity (ESMICs) (Claussen et al. 2002).

Source: Claussen et al. (2002)

Figure 9 Pictorial representation of the spectrum of models

Conceptual models normally sacrifice detail of the description and include fewer processes but allow high integration, and are used extensively for exploratory research. EMICs are used to search a balance, and can be a versatile tool less cumbersome than comprehensive models. All models have complementary functions in research.

The communities presented as in the Intergovernmental Panel on Climate Change (IPCC 2013): Working Group I (WG I) assesses the physical aspects of the climate system and climate change; WG II assesses the vulnerability of socio-economic and natural systems; and WG III assesses options for mitigating climate change.
EMICs tend to integrate climate system together with other bio-physical systems (focus on the natural science aspects) while Integrate Assessment Models (IAMs, Figure 10) tend to integrate many social systems together with climate system (focus on the interaction) (Friedrich 2013). A major difference to IAMs is the focus on policy advice (R. S. J. Tol 2005).

IAMs are interdisciplinary models combining scientific and economic aspects of global change, normally designed for exploring or optimizing policy options (Cornell et al. 2012). They often present a particular focus on energy systems and climate (DOE 2009). Early examples include the global models used in The Limits to Growth (Donella Meadows et al. 1972). Nowadays16, IAMs are used for global change research in a variety of fields, including food security (Bland 1999; Ingram et al. 2010) and water (Letcher et al. 2007).

IAMs are composed by one or more components of both human and natural systems, with a common emphasis on energy, and exchange data on greenhouse gases (GHG) and short-lived substance (SLS) emission with the climate modelling community. Contemporary IAMs have been increasing the number of components of the Earth system, leading some authors to classify them as ESMICs. One notable example is IMAGE 2.4 (Bouwman et al. 2006), which can be considered ESMIC thanks to the

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16 The AMPERE project presents more comprehensive list of IAMs and Energy Models used in for assessing climate mitigation options (PIK 2012). It includes 18 models, with at global scale, three of which are IAMs.
high degree on integration of different components of the Earth System (Claussen et al. 2002). ‘The IMAGE model is an integrated assessment model, consisting of a set of linked and integrated models, which, together, describe important elements in the long-term dynamics of global environmental change, such as air pollution, climate change, and land-use change’ (van Vuuren et al. 2010). This modelling framework is being used in a series of environmental assessments that go beyond the questions related to climate mitigation, and has often been used to provide land-use and other GHGs emission data for other models (Edenhofer et al. 2010). Two notable examples have been published by PBL (agency responsible for the IMAGE modelling framework): Growing within Limits (Van Vuuren & Faber 2009) and Roads from Rio+20 (Van Vuuren, M. T. J. Kok, Esch, et al. 2012). The former analysed a scenario with both constraints on greenhouse gases (in order to limit average global temperature increase to a maximum of 2°C) and on the expansion of agricultural land (in order to avoid further loss of biodiversity). The latter, analysed pathways to meet goals in food and energy access, reduction of biodiversity loss, mitigation of climate change and reduction in air pollution. It also presented a qualitative study of the trade-offs and knock-off effects of between these multiple constraints. Such examples demonstrate the possibility of using IAMs for analysing multiple interacting goals (discussions in section 3.3, p. 35).

An important part of IAMs is the policy decision-support tools built in these models. In the case of IMAGE, this task is performed by a component denominated FAIR (‘Framework to Assess International Regimes for the differentiation of commitments’) (M. Elzen & P. Lucas 2005; Bouwman et al. 2006). This component allows the study of mitigation policies (following ten different archetypical multi-lateral regimes17), and aims at providing consistent and quantitative comparison of such multi-lateral regime proposals.

While IAMs are vastly used in the context of International environmental assessments, other models are used for energy systems analysis (energy-economy models18, see section 2.5.1 p. 23), largely due to a higher detail on the representation of the technologies and economic models. IAMs have a broader scope than individual sectoral models, tend not usually focused on security of supply but rather focused on climate change and environmental issues (R. S. J. Tol 2005; Bazilian et al. 2011).

Source: Bouwman et al. (2006)

17 In the context of the United Nations Framework Convention on Climate Change (UNFCCC), refers to the regimes that define how countries mitigation commitments should be established, based on criteria and rules for the distribution of greenhouse gases emission allowances (M. Elzen & P. Lucas 2005).

18 Notable examples include MESSAGE (IIASA-ENE 2012), MARKAL (IEA-ETSAP 2011), and LEAP (C. G. Heaps 2012).
Figure 11 IMAGE 2.4 modelling framework
Example of a modelling framework used in IAM. The framework combines a depiction of the social-economic system, the earth system (simplified if compared with climate models), and calculates a series of impacts that feedback into the decision making process and the social-economic system.

As Bazilian et al. (2011) point, ‘analysis of individual systems (such as energy or water systems) are undertaken routinely, but are often focused only on a single resource or have often been applied on an aggregated scale for use at regional or global levels and, typically, over long time periods’. This has led the authors to propose the Climate, Land, Energy and Water (CLEW) modelling framework, reviewed bellow.
2.5.1 CLEWs approaches

Aiming at responding the water-food-energy-climate nexus, a series of institutions have been contributing to the development of CLEWs\(^\text{19}\) (Climate, Land-use, Energy and Water strategies), a modelling framework for integrating existing models and highlighting the interdependences and trade-offs that the provision of resources creates, and to take consider the impact of climate change (Bazilian et al. 2011; Hermann et al. 2012).

This approach combines existing tools from different modelling communities. New ‘interface’ tools are being developed, aimed at improving the coupling of the diverse models used. Bellow, a list of the models used in the initial case studies (Hermann et al. 2012; Rogner et al. n.d.):

- LEAP (Long-range Energy Alternatives Planning System) (C. G. Heaps 2012)
- WEAP (Water Evaluation And Planning), an integrated tool for water resource planning (SEI 2012a).
- Global Agro-Ecological Zoning\(^\text{20}\) (GAEZ), a data service provided by FAO (Food and Agriculture Organization) and IIASA (International Institute of Applied Systems Analysis).

The integration between LEAP and WEAP is being promoted by the developers (SEI 2012b), aiming at tackling some of the interconnections of the water-energy (e.g., hydropower, desalination). However, the CLEWs framework still does not allow full coupling of these tools (Bazilian et al. 2011): data from one model is analysed and compiled an by the user before being used as input for the other components.

The CLEWs is focussed at lower scales than IAMs. So far, it has been used for modelling the interactions of the Nexus of an island state (Mauritius, Rogner et al. n.d.) and for a land-locked country (Burkina Faso, Hermann et al. 2012). In these case studies, the authors reported strategies for addressing the issues of the Nexus that would not be possible if only sectoral models had been used, including the usage of desalination (with its impacts on the energy demand), change in crops over time as a form of adaptation, and optimization of biofuel production (considering land-use and water constraints) for minimizing dependency on fossil-fuel imports.

A Global Clew Models is under development. In the spectrum of models proposed by Claussen et al. (2002), Figure 9, CLEWs can be considered a conceptual framework, with high degree of integration across the sectors, limited number of processes and limited detail, which can complement IAMs (discussion in section

\(^{19}\) The authors use this acronym for designating both the modeling framework and the approach.

\(^{20}\) Based on Agro-ecological Zones methodology, developed by FAO and IIASA, this approach generates information products that can be used by modellers. In its current version these product allow: quantification of land productivity, estimations of rain-fed or irrigated cultivation potential (including food, feed, fibre, and bio-energy feedstock production); identification of environmental constraints to agricultural production; and in the identification of potential hot-spots and shifts in agricultural land potentials due to changing climate (FAO 2013).
2.6 Scenarios

Scenario based approaches have been growing in importance, especially in the context of Global Environmental Assessments (for a review, vide Van Vuuren et al. 2012). The methodology behind scenario analysis have passed by recent developments, which might be useful in the context of the project, as they point at ways of connecting different knowledge systems and scales, and on process that allow multiple modelling communities to cooperate on scenarios that try to represent co-evolution of human systems and the Earth system.

Scenarios can be described as “plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships” (Henrichs et al. 2010, p.152). These are used in cases where it is necessary to assess future developments that involve complex developments and high uncertainty (Zurek & Henrichs 2007), as represented in Figure 12. Predictions are only possible in systems that are well known and that can be controlled (Van Vuuren, M. T. J. Kok, Girod, et al. 2012).

Source: Zurek & Henrichs (2007)

Figure 12 Scenarios as tools to address complexity and uncertainty
Often the terms used confused. The term projection is sometimes used to name the results from a scenario study, or the outputs of the model. Hereby, only the term scenario is used.

Scenarios fulfil a purpose of supporting assessments of such uncertain and complex future possibilities. They lie in between stories and models (Figure 13), and can combine qualitative elements (organized in ‘narratives’ or ‘storylines’) and quantitative elements.
Quantitative scenarios studies rely strongly on models. The scenario provides the basic assumptions, including which are the drivers and what values certain parameters in the models assume, ‘numerical estimates of the future developments’ (Henrichs et al. 2010). E.g., in the low carbon transitions studied by Söderholm et al. (2011), the majority studies were found to be using carbon price as the main driver for changes in the energy sector – the price selected during scenario development was the input for models that would then calculate the least costly mix of energy technologies. In quantitative scenarios, the structure of the models used constraints the scenario development: it is only possible to study futures that can be modelled.

Source: Raskin et al. (2005)

Figure 13: Stories, scenarios and models
Scenarios can combine both qualitative and quantitative aspects. Narratives and storylines may be used to articulate a set of numerical trends and assumptions for modelling. They also allow exploring the effects of aspects that are hardly quantifiable, such as political trends, governance styles and institutional arrangements. Thus, quantitative and qualitative aspects can be combined to provide more complete depictions of the future (Henrichs et al. 2010).

Qualitative scenarios studies do not rely on models for the assessments. Instead, they are built based on narratives, phrases or images (Henrichs et al. 2010), and can be used to capture possibilities not covered by models. Most recent scenarios used in environmental assessments combine both elements, with varying degrees of emphasis in each (Raskin et al. 2005; van Vuuren, M. T. J. Kok, Girod, et al. 2012).

Several typologies for scenarios and scenario approaches have been proposed (for a review: Börjeson et al. 2006). A common typology distinguish at least three categories of scenario approaches, depending on what kind of question the scenarios aim at responding (Henrichs et al. 2010; Söderholm et al. 2011):

- Predictive scenarios, or reference scenarios, addressing the question “what is expected to happen”
- Explorative scenarios, addressing the question “what can or might help”
Normative scenarios, or anticipatory scenarios, which focus on assessing a more narrow set of goals or policy options. It includes ‘backcasting’ in which a desirable future is selected and different pathways for achieving such future are studied.

Henrichs et al. (2010) analysed the approaches for scenario formulation and proposed that they can be grouped in three types: inductive, deductive and incremental. Both inductive and deductive approaches follow a similar process (Figure 14). They differ in the way the logic is formulated – the former bases its analysis on specific facts or plot elements, while the latter starts from a systematic discussion and deduction on what constitutes the main driving forces. In incremental approaches, scenarios are built by questioning or expanding reference scenarios (business as usual): key threats to the reference are identified, and the driving forces are varied to explore alternatives (Henrichs et al. 2010). These approaches can be used in a complementary way. The method used is of great importance for the analysis of the results and should be reported.

Source: Henrichs et al. (2010)
In a recent review of scenarios used in Global Environmental Assessments and sectoral assessments, van Vuuren et al. (2012) presented six ‘scenario families’, in which scenarios are grouped according to their storyline and logic (i.e., basic underlying assumptions), summarized in Table 4. This reveals an important role of the qualitative elements of scenarios: they allow finding common traits in scenarios independently of the model used.

### Table 4 Key assumptions commonly found in different 'Scenario families'

<table>
<thead>
<tr>
<th>Economic Optimism</th>
<th>Reformed Markets</th>
<th>Global SD</th>
<th>Regional competition</th>
<th>Regional SD</th>
<th>Business-as-usual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic development</td>
<td>Very Rapid</td>
<td>Rapid</td>
<td>Slow-Rapid</td>
<td>Slow</td>
<td>Mid-rapid</td>
</tr>
<tr>
<td>Population Growth</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Technology Development</td>
<td>Rapid</td>
<td>Rapid</td>
<td>Mid-rapid</td>
<td>Slow</td>
<td>Low-rapid</td>
</tr>
<tr>
<td>Main Objectives</td>
<td>Economy growth</td>
<td>Various goals</td>
<td>Global Sustainability</td>
<td>Security</td>
<td>Local-sustainability</td>
</tr>
<tr>
<td>Environmental Protection</td>
<td>Reactive</td>
<td>Reactive &amp; proactive</td>
<td>Proactive</td>
<td>Reactive</td>
<td>Proactive</td>
</tr>
<tr>
<td>Trade</td>
<td>Globalization</td>
<td>Globalization</td>
<td>Globalization</td>
<td>Trade barriers</td>
<td>Trade barriers</td>
</tr>
<tr>
<td>Policies and Institutions</td>
<td>Policies create open markets</td>
<td>Policies reduce market failures</td>
<td>Strong global governance</td>
<td>Strong national governments</td>
<td>Local Steering; local actors</td>
</tr>
</tbody>
</table>

Source: van Vuuren et al. (2012). The authors summarized the assumptions in broad terms and presented ranges when differences within a family exist.

### 2.6.1 Multi-scale scenarios

In recent years, the methodology behind scenario development has evolved significantly. One important aspect of this development is the effort to develop multi-scale analysis. Current global environmental assessments and global energy assessments have mostly with a ‘disaggregation of the global system into a single-layer of comprised of major multinational regions’ (Raskin et al. 2005). The number of regions varies significantly across different studies.

Zurek & Henrichs (2007) suggested a series of approaches to enable development of scenarios for multi-scale assessments: i) linking scenarios developed for different special scales can be done by using the same elements (i.e., driving forces, assumptions, scenario logics, boundary conditions, decision-making paradigms, outcomes); ii) coupling scenarios through the development process (i.e., developing

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21 Ranging from slow to rapid.
the scenarios for different scales in a coordinated process). Figure 15 represents these possibilities.

According to Zurek & Henrichs (2007) the linkage of scenarios can occur in five degrees, as summarized in Table 5. The linkage depends strongly on the process used for the development of the scenarios (see Annex 2 for further details on the coupling and its influence on the linkage).

![Figure 15 Concepts for linking scenarios across scales](image)

Several degrees of coupling and linking are possible. The scenario building process influences the degree of linkage that is possible. Linkage refers to the degree of correspondence that exists in important scenario elements.

### Table 5 Degrees of across-scale linkage scenario

<table>
<thead>
<tr>
<th>Degree</th>
<th>Main characteristics</th>
<th>Advantages/disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent across-scales</td>
<td>General logic, assumptions and the outcomes of the scenarios at one scale are transferred to the other scale</td>
<td>Key disadvantage is that the main questions the scenarios address at the global scale may not be relevant at the regional or local scale</td>
</tr>
<tr>
<td>Consistent across-scales</td>
<td>Main scenario assumptions, the selection of driving forces and their trends are consistent across-scales</td>
<td>Can also lose relevance at lower scales. Are usually more useful for academic analysis and for information purposes.</td>
</tr>
<tr>
<td>Coherent across-scales</td>
<td>Scenarios follow the same paradigm or are different representation of the same scenario archetype (or family, as shown in Table 4)</td>
<td>Have the advantage of helping to clarify the underlying assumptions within a range of different decision-making processes. Commonly aimed at informing decision-making.</td>
</tr>
<tr>
<td>Comparable across-scales</td>
<td>Scenarios constructed to be largely independent at different scales, connected by the issue they address.</td>
<td>Have the benefit that they give the scenario developers a lot of freedom to focus the most pertinent questions, while still maintaining a general link to other scenarios.</td>
</tr>
<tr>
<td>Complementary across-scale</td>
<td>Logics and assumptions in differ across scales</td>
<td>The scenarios can differ substantially and even contradict each other</td>
</tr>
</tbody>
</table>

Summary based on Zurek & Henrichs (2007)
The linkage of scenarios can be an important tool for studying the cross-scale processes that permeate the PB concept, notably the “slow variables”. This implies any scenario addressing the boundaries will require a certain degree of coupling and/or linking.

2.6.2 Scenarios for bridging across modelling communities

A new framework for the development of scenarios used for climate research is setting an important precedent by developing a set of scenarios that are used to bridge divides of the modelling communities. The set of scenarios currently being developed for the 5th Assessment Report of the IPCC is based on this framework, which combines Representative Concentration Pathways (RCPs) and Shared Socioeconomic reference Pathway (SSP) (Arnell et al. 2011; Moss et al. 2010; van Vuuren et al. 2011).

Each of the RCPs22 have been developed to represent a larger set scenarios in the literature (thus the word “representative”) (Moss et al. 2010; van Vuuren et al. 2011). ‘The words “concentration pathway” are meant to emphasize that these RCPs are not the final new, fully integrated scenarios (i.e. they are not a complete package of socio-economic, emission and climate projections), but instead are internally consistent sets of projections of the components of radiative forcing that are used in subsequent phases.’ (Van Vuuren et al. 2011). The RCPs can be used by all both the climate and IA modelling communities (see section 2.5).

In order to create the ‘complete package’, the SSPs are necessary: ‘The primary objective of the SSPs is to provide sufficient information and context for defining development pathways that can be used as a starting point for IAM and IAV analyses, at the same time differing significantly in the challenges to mitigation and adaptation. The SSPs thus comprise a set of narratives and quantitative information on the drivers of how the future might unfold.’ (Arnell et al. 2011) The different SSPs are used to explore the socioeconomic challenges to adaptation and to mitigation, and are characterized by a series of determinants of these outcomes (regarding, e.g. population, economic development, technologies, preferences).

The RCPs and SSPs can then be combined following a matrix architecture, meaning that a large combination of possible future scenarios can be explored (Arnell et al. 2011). This approach is very interesting for the context of the present study, where the divides across modelling communities is an important barrier (discussion in section 3.4).

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22 A set of four RCPs has so far been proposed, with radiative forcing levels of 8.5, 6, 4.5 and 2.6 W/m2, by the end of the century (Moss et al. 2010; van Vuuren et al. 2011)
3 Discussion

Planetary Boundaries can be understood both as a concept and as a framework (in its current form, with the preliminary set of nine boundaries proposed by Rockström et al., 2009b). The PB concept builds on a series of other approaches that aimed at determining global environmental constraints\(^{23}\). The major advantage of the PB concept is the aim in inclusion of non-linear behaviour. A common critique of the framework, however, is that processes currently included do not have a prominent threshold behaviour (Nordhaus et al. 2012; Brook et al. 2013). For the analysis in the next two chapters, this project will consider the processes as in the original framework, even recognizing that the control variables and values of the boundaries are passive of change as the research underpinning the concept advances.

One important contribution of PB concept is the recognition that the environmental constraints to which human activities are subject go beyond limitations on finite resources and sinks for pollution, widely studied in *Limits to Growth* (Donella Meadows et al. 1972; Donnella Meadows et al. 2004) and similar studies. The constraints in PB are directly linked to processes of the Earth System, which means that improvements in ESS could lead to better-defined boundaries.

The scientific foundation of the boundaries, however, does not eliminate the normative character of the boundary setting procedure, which is directly linked with the inherent uncertainty involved. The uncertainty in this case includes uncertainty due to limited knowledge, due to inherent variability of the system, due to human choice and to the due to different perceptions of the nature of risk itself Rougier et al. (2013). The boundaries, thus, should not be used as ultimate limits, but as reference points that allow the international community to help synthesising the various strands of information of global environmental change (as a ‘dashboard’ for sustainability). It also implies that efforts are necessary to quantify and distinguish the different sources of uncertainty.

As in the case of climate change, the selection of a goal can only be achieved through deliberation in the appropriated forum. At first glance, this differs from the views expressed by Rockström et al. (2009c) statement: ‘(...) that the ecological and biophysical boundaries should be non-negotiable, and that social and economic develop (should) occur within the safe operating space provided by planetary boundaries’ (p.5). This statement, however, appears in the context of comparison with other approaches that include the ‘prevention of excessive costs’, reaffirming the notion that the biophysical boundaries represent a *sine qua non* condition for human development (and economy). This has been reaffirmed later by Griggs et al., in the context of the SDGs: ‘As mounting research shows, the stable functioning of Earth systems — including the

\(^{23}\) Rockström et al. (2009c) provides a review of such approaches.
atmosphere, oceans, forests, waterways, biodiversity and biogeochemical cycles — a prerequisite for a thriving global society’ (2013), culminating in the proposition of a new definition for sustainable development (shown in the Introduction).

The basic assumptions that connect environmental conditions and human well being in the Planetary Boundaries concept have been criticized by Nordhaus et al. (2012). The closest account of the conflicting world views and assumptions is perhaps the discourse analysis of Dryzek (2013): while PB presents many similarities to Limits to Growth (Donella Meadows et al. 1972), the view expressed by Nordhaus align with a tradition of ‘technological optimism’, where mounting risks of environmental change are outpaced by human ingenuity. In the same analysis, Ecological Modernization discourses present strong similarities with the Nexus approach, in its framing of the solutions as an issue of proper management and planning and its reliance on technology (rather than societal change) as the primer leverage point.

More than resolving this conflict, Dryzek (2013) analysis demonstrate how these concepts cannot be understood as purely objective scientific facts, but rather that the interpretation of the facts (evidences of global change) and the framing of solutions (reliance and optimism towards technology) are strongly underpinned by the political conception of the actors involved. The debate around Planetary Boundaries and the Nexus and its potential implementation has so far not addressed this point. The lack of clarity regarding the conceptions and discourses that underpin and that are reaffirmed by the usage of these approaches to inform policy is thus the first aspect hindering the utilization of these concepts (Q1 & Q2).

Both PB and Nexus are receiving great attention from policy makers. This means that necessarily these concepts will have to pass through scrutiny in terms of their political and societal implications. Considering the importance of the processes in which PB is being used (notably the SDGs process), it is worrying that only a handful of peer-review articles has been published, analysing business (Whiteman et al. 2012), economical (van den Bergh & Kallis 2012) and governance implications (F Biermann 2012; Galaz, Crona, et al. 2012; Galaz, Frank Biermann, et al. 2012; Westley et al. 2011). This situation highlights the second aspect that hinders the utilization of the PB concept (Q1): the scientific development behind the framework is being outpaced by the speed with which the concept is uptake by the policy arena.

Even thought the framework (with the set of nine boundaries proposed in Rockström et al. 2009b) was recognized by its authors as a preliminary estimate of the boundaries, only two other studies aimed at reviewing or proposing new boundaries (Carpenter & Bennett 2011; Running 2012). While an overall review of the framework is awaited, it is not possible to predict its outcomes, and the degree with which

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24 Refering to the research questions 1 and 2, as stated in section 1.1, p. 3
25 Personal communication with Johan Röckstrom and Will Steffen.
these will address the critiques received, provide better estimates of the boundaries, or quantify the boundaries that have not been quantified (i.e. chemical pollution and aerosol loading). And even considering that the global change community is improving its integration and developing joint efforts, no common research agenda has yet been proposed, nor has this subject been studied in a systematic manner by the broader international community (e.g., through an international assessment such as the Millennium Ecosystem Assessment or Global Environmental Outlook).

A third issue that hinders the integration of Planetary Boundaries and Nexus approaches is the relative disconnection of the research communities involved (Q1&Q2). While Planetary Boundaries is already a significant achievement in terms of interdisciplinary research, bridging across several sectors of the Global Change community, the research around it remains fairly enclosed in the natural sciences, with few studies bridging to other areas. Most notably, the developments surrounding the Nexus have occurred across sectors (integrating water, energy and agricultural scientists and engineers), but with low interaction with Global Change community or with the Integrated Assessment Community (which has made similar efforts for cross-sectoral integration, but focussing on the global scale, and very connected to climate change research).

This brings to mind the notion of ‘boundary management’ proposed by Cash et al. (2003), where the processes of communication, translation and mediation across the normal divides of science and policy are managed (with different institutional arrangements that may or not include ‘boundary organizations’). In the context of the present study, it is clear that not only a science-policy interface needs to be managed, but also the science-science (or engineering) interface needs special arrangements to avoid the insularism of these concepts. It is interesting to observe how the global change community developed complex, international networks and research agendas that remain fairly distant from areas that aim at responding at the same questions.

The three points raised so far are mostly ‘process related’, which are especially relevant for scientific concepts being developed so closely to the science-policy interface. Together, they point at an apparent paradox. On one hand, Global Change research is facing a ‘call to action’ to be useful in a context of urgent global issues, and is expected to deliver assertive, right-on-time messages to policy makers. On the other, for these same scientific messages to be relevant and legitimate, they need to be based on a sound scientific process and subject to scrutiny through appropriate

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26 The latest Global Environmental Outlook, GEO5 (UNEP 2012, chap.7) uses the concept, without mentioning the debate or criticism it received, or

27 Here the word boundary refers to the interfaces between different arenas of science and policy.
debate fore (at least for the political aspects of the message). This paradox seems crucial as it currently affects the development of research and its outcomes.

### 3.1 New Constraints

Other ‘content related’ issues are also relevant in the context of this study. The first one is that the idea of respecting the ‘environmental ceiling’ defined by Planetary Boundaries imply that new kinds of constraints might affect future practices in management and planning of resources, arising from the understanding that not only the local environmental change caused by the extraction or use of resources needs to be addressed, but that aggregated effects could affect the Earth System to the point of causing large-scale changes.

In the systemic, planetary-scale processes listed in the PB framework (climate change, ocean acidification and ozone depletion, as shown in Figure 6, p.11), the need for constraining the pressures is evident. The current efforts around climate change and the case of ozone depletion are examples of such constraints. In the case of ozone, international processes that led to the restriction of the substances causing the problem are an interesting success story. Even if current climate negotiations have not yet created clear constraints, these are under debate, and countries have started to create their own pledges (which, if enforced at national level, would have a similar effect). In these three boundaries, the control variable is a state variable (in DPSIR), and the degree of knowledge is relatively high (Table 1 p.12).

The trait of the systemic processes is that emissions of the CO₂ or Ozone depleting substances have the same systemic effect independently of where they occur. The same does not apply to the other boundaries presented in the framework and that have been quantified (land-use, water-withdraws, biodiversity and altered biogeochemical flows), and for the two that have not been quantified (chemicals and aerosol loading). This means that the effect of change depends heavily on where in the world this changes are happening, and that important regional ‘tipping elements’ could be crossed even at safe levels of the planetary boundary.

This means that necessarily more regionalized information on potential ‘tipping elements’ will have to be available. This ‘downscaling’ of the boundaries to define regionalized constraints based on the risk of regional thresholds, however, has still not occurred (largely due to difficulties in the identification of these thresholds), which constitutes a major setback in the operationalization of the framework (Q1).

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28 For a more detail description of the Ozone Story and how the constraints were successfully imposed, *Back from Beyond the Limits: The Ozone Story* (Donnella Meadows et al. 2004, chap.5)

29 Two promising initiatives that are recording information on thresholds and regime shifts are: i) the Regime Shift database, maintained by the SRC (SRC 2013b), ii) the Thresholds and Alternate States in Ecological and Social-Ecological Systems, maintained by the Resilience Alliance and the Santa Fé Institute (RA 2013).
Most thresholds reported in the literature have been identified exactly because they have been crossed, which highlights the importance of developing techniques for early warning (e.g. Lenton 2011).

Another aspect of the aggregated boundaries hinders the search for ‘downscaled’ boundaries: the link Driver-Pressure-State is not as clear as in the case of the aggregated boundaries. Biodiversity loss, for example, is an impact with multiple, interacting drivers, which are highly context dependant and that require multiple conservation paradigms (Brooks et al. 2006). For these boundaries, clarifying the relation with the Nexus at the appropriated scale is also necessary.

PB could become an important tool understanding the contribution of different regions or sectors for global environmental change (Naturvårdsverket 2013). This, however, is not possible with the current PB framework that does not include clear methodologies for identifying, accounting and aggregating pressures from lower scales for aggregated boundaries. For that reason, rather than trying to encompass the complexity of such processes with a singular constraint that can be easily input into integrated resource assessment models, the best contribution of Planetary Boundaries for non-systematic process might be the raised awareness around other issues that otherwise would be considered insignificant.

Current Nexus approaches barely comment on the connections of the water-food-energy sectors to degradation of biodiversity, alterations in biogeochemical flows and emissions of aerosols. By focusing on the provision of key resources with a strong focus on security of supply, and conceptualizing the environment outside the Nexus, does not include other environmental issues in more elusive processes (Q2). Current CLEWs approaches, for example, include analysis of water availability, energy and agricultural yields, but cannot represent biodiversity loss, nutrient runoff and water quality issues. While integrating the different resources is already a formidable challenge, it is equally important to acknowledge what escapes current modelling capabilities, and develop other methodologies to cover these blind spots. As the ‘CLEWs blueprints’\(^{30}\) are currently being developed, a unique window of opportunity is open.

3.2 Classification of resources

The classification of resources that distinguishes renewable and non-renewable resources or technologies is used ubiquitously across policy, science and engineering. This classification, however, does not address any of the environmental impacts of the associated resource systems. The need creating metrics and indicators for the

\(^{30}\) The procedures for CLEWs studies, currently under development. Personal communication with Sebastian Hermann
exploration of the implications of PB, suggests that a new classification might be necessary. Desirable features of this classification include:

- Comparability across different studies;
- Generality, as it should be applicable to the different resources involved in the Nexus, not only to one of the sectors;
- Applicable at different scales;

One possibility is trying to define if the resources themselves figure in the PB concept. Water withdraws, cropland and the fixation of nitrogen from the air figure in the current framework. This suggests that the availability of these resources would have to be constrained in order to respect ‘the safe operating space’ delimited by PB framework. Identifying these ‘availability-constrained’ resources is necessary in order to highlight that these resources could be subjected to planetary constraints, even if they are available at local/regional levels.

Other resources, such fossil fuels and phosphorus do not figure in the PB framework due to their availability, but rather due to the pressures generated by its usage. The combustion of fossil fuels, for example, is the major cause of CO₂ emissions and aerosol emission. In such cases, identifying that these resources are ‘use-constrained’, and which PB are affected by each resource system would significantly help the task of searching for the metrics that allow data aggregation and comparison of different Nexus strategies.

Due the characteristics of the PB framework this kind of classification is currently not possible. First, there is no account of the main drivers and behind each PB, making it hard to identify which sectors would be constrained.

### 3.3 Sustainability Pathways

Many studies have assessed social pathways of development for mitigating and adapting to the effects of climate. However, few studies have so far assessed pathways under multiple constraints or goals that mimic PB. A trend towards integrating different policy objectives into these studies can be detected, notably the ones performed using IAMs. The use of PB and Nexus for framing and deriving such goals deserves special considerations.

The PB framework as presented by Rockström et al. (2009b) was not meant to for application in analysing future sustainability pathways or Nexus strategies. In its current form, the thresholds around which the uncertainty zone is defined are set as static thresholds, with no clarity on how the position of the PB would be affected by changes in the Earth system. The PB in the current framework are also determined independently for each other, meaning that the transgression of some of the boundaries does not affect the position of the other boundaries. This constitute important simplifications, that may hinder the possibility of applying planetary
boundaries (Q1). So far, no study has demonstrated the significance of these changes, mostly due to the limitations of modelling specifically for PB (Friedrich 2013).

IAMS generally cover aspects of both Drivers and Pressures, and in some cases (such as IMAGE) use a simplified Earth System Model that allows to cover the State of key processes (providing information such as temperature anomalies) and some initial estimations of impacts (e.g. effects on crops). These models normally are used at global scale, and are appropriate to evaluate mid-long term dynamics. The usage of IAMs with current static boundaries could be tried by using scenarios for studying the policies that would be required for remaining within the boundaries. However, the current IAMs do not included all processes described by PB (Friedrich 2013).

Equally important are the decision-making models built in the IAMs, which currently are capable of accessing decisions related to climate. The assessment of multi-goals in current models is likely to be hindered by the current state of these models. Thus, developing decision-making support tools capable of dealing with multiple constraints/goals is extremely important.

In this context, CLEWs models and other conceptual models can play an important role, as they may be used to explore and rapidly prototype solutions for: i) integrating new modules that cover other aspects of the environment neglected by IAMs, ii) develop and test decision-making support tools; iii) calculating the quantitative part of scenarios or scenario sets exploring multi-goals-multi-constraints pathways.

Table 6 Comparison of IAMs and CLEWs approaches
The different modelling frameworks can be used complementarily. CLEWs present a high degree of flexibility, and can be used to create prototypes and test hypothesis in efforts to integrate constraints from PB.

<table>
<thead>
<tr>
<th>Modelling Framework</th>
<th>Scale</th>
<th>Time frame</th>
<th>Integration</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAMs</td>
<td>Global, with sub-continental regions</td>
<td>Long term (often 2050 and 2100)</td>
<td>High, components are coupled</td>
<td>Integration with simplified earth system models is increasing the detail of the model. Sophisticated policy-making support tool are becoming more common.</td>
</tr>
<tr>
<td>CLEWs</td>
<td>Regional (country wide, so far used in small countries)</td>
<td>Mid term (20-50 years)</td>
<td>High, but currently data needs to be handled by the user. The models can be easily adapted to include other components.</td>
<td>Water model can be used at basin level. Energy-Water coupling is well detailed. Land-use model still has low resolution.</td>
</tr>
</tbody>
</table>

CLEWs and other water-energy models, also focus on the Drivers and Pressures. Being done at local/regional scale, they can include more accurate descriptions of hydrology and soils (even though the case-studies so far have used data from global
surveys with a resolution comparable to the one used in most IAMs). As regional climate models are still fairly limited in its capabilities, CLEWs relies on climate projections from normal climate models. The Energy-Water coupling can be done with LEAP-WEAP, with high level of detail (including individual power plants and if necessary).

Table 6 provides a summary of the comparison between IAMs and CLEWs.

3.4 The role of scenarios

The necessity of covering multiple geographic scales is widely accepted as one of the major challenges in modelling and scenario studies. For that reason, the IA community has continuously strived towards higher resolutions in their models. However, relying in increased resolution comes at a price in terms computational power, which is a limiting factor for highly integrated and complex models. This points to the possibility of using multi-scale scenario studies (section 2.6.1), as proposed by Zurek & Henrichs (2007) to create sets of consistent or coherent studies (Q3).

The scenarios, in the context of PB and Nexus integration, could also be developed using concepts similar to the new generation of scenarios used in climate research (section 2.6.2), which provide a powerful tool for connecting multiple modelling communities (Q3).

Scenarios have a third role in studies connecting Nexus and PB concepts: building the internally consistency of the assumptions and logics through adequate narratives (Q3). Currently, the logic followed by Nexus (focussing on security of supply) and PB (development within a ‘safe operating space’) would need a harmonization that cannot be achieved singularly through quantitative scenarios and modelling.

This leads to a fourth consideration around the usage of scenarios. Scenarios are nowadays created for fulfilling a variety of roles. The wealth of scenarios available, however, requires continuous improvements in methodologies for comparison across scenarios and models. In the context of climate research, this has been solved by the creation of clearly defined frameworks for the creation of scenarios, which provide an important concrete example.

For scenarios to play a more prominent role in the definition sustainability pathways that are relevant for policy-making, the process of learning from the scenarios needs to be improved. Most of the scenario studies are communicated through lengthy reports unpalatable even for experts. New communication tools including interactive websites and interactive tools for exploring multiple scenarios are becoming more common (e.g. GEA 2012; van Vuuren, M. T. J. Kok, Esch, et al. 2012). The creation of databases of scenarios that go beyond single studies would also be a valuable development. Scenarios can only be relevant if they foster discussion and if they evolve and build from previous experiences.
3.5 Safe Operational Space

The current PB concept aims at defining ‘a safe operating space’, where the boundaries demark a safe distance from thresholds and dangerous states. Its current incarnation, the PB framework, partially realises that aspiration. It present, however, limitations and caveats that should be addressed if this framework is to be used in relevant policy process and as a shared research agenda.

As the work of Raworth (2012) (Figure 3, p.3) and the Nexus approach emphasise, framing the safety only in terms of biophysical processes is not enough. In order to encompass the material needs of human development, it might be necessary to include in the framework other dimensions. Considering this, the present study suggests an alternative formulation that could be used for future revisions of the framework:

- **Safe operating space**, delimited by planetary boundaries set accordingly to the planet current thresholds, preferably expressed in control variables that capture Pressures. These boundaries should not be considered static, but rather dependant of the state of the Earth system
- **Safe operational space**, defined as the pressures that would result from providing current population basic needs with available technology and practices
- **Operational space**, defined by the pressures currently exerted by human activities

The idea here is that separating these three spaces, it is possible to explore and represent the human activities in a better way. The division between ‘Safe Operational’ and ‘Operational space’ could be used for highlighting the fact that environmental pressures are likely to increase significantly if the access to basic services is extended to the population that nowadays faces scarcity; currently efforts to mitigate the environmental pressures are faced with the challenge of allowing ‘room for development’. A large portion of future environmental pressures is likely to be exerted in the future have a direct connection the need of meeting has been called a ‘shared development agenda’ (Nilsson et al. 2012). An advantage of this framing is to clearly state that the current operational state is not safe, both from an environmental perspective and from a social perspective, as it falls short in the provision of basic needs for a large portion of the global population.
Figure 16 Conceptual depictions of the 'three spaces'
This sketch represents the idea of representing the spaces separately. The numbers used were selected arbitrarily, aiming only to depict the idea.
This idea is currently being explored at the Planetary Boundaries research initiative, and is presented here to illustrate the kind of conceptual development that might be necessary for improving the usability of the PB concept.
4 Conclusions

4.1 Bridging the gap

This study explored the knowledge gaps that exist between Planetary Boundaries and integrated resource modelling and the Nexus approach, providing valuable insights for the development of the PB framework. It found that the current framework presents a series of characteristics that hinder its utilization. In order to continue the development of the PB concept, it is necessary to build from the experiences of other communities, which include the communities involved in climate research, and in sectoral analysis such as the ones represented in the Nexus.

The PB concept and framework are rapidly gaining prominence in the policy arena. However, the debate reviewed in this study demonstrates that both are far from being consolidated. One of the most important aspects of these debates concerns the boundaries that cover aggregated process. These are the weakest link in the framework. They are also the area in which the Nexus approach can be more valuable: the Nexus sectors are an important driver behind these processes.

This study helps putting the Nexus approach in perspective: the strong focus on security of supply contrasts strongly with the focus on biophysical processes seen in the PB concept. The foundation for the provision of the resources in the Nexus depends on the state of the environment, but this dependence is not explicit.

Developing strategies that consider both the security of supply and the safety of the environment is a formidable challenge and, as this study showed, is likely to involve i) new developments in modelling; ii) new approaches to scenario studies; iii) development of qualitative indicators (a new resource classification); and iv) conceptual developments on both frameworks.

In what concerns modelling, IAMs, CLEWs and other conceptual tools were found to be potential tools for bridging the gap between the Nexus and PB. For that to happen, current efforts of integrating other process and in developing conceptual representations to explore missing links need to continue. A crucial aspect of this interconnection is the development of policy-making support tools capable of dealing with multi-goal / multi-constraints problems.

Scenario studies are absolutely necessary to explore solutions and strategies to tackle the combined challenge of mitigating dangerous pressures on the environment and providing the resources that are necessary for human well being. This study found in the literature two emerging scenario construction techniques that will help dealing with the cross-scale dynamics (creating scenarios that are linked or coupled across scales) and the divide across modelling communities (developing frameworks for scenario construction that are provide consistency for multi-model analysis).
The present study also suggests that qualitative indicators can be developed to help analysing the results from current IAMs and CLEWs analysis under the lenses of PB. For that, a new classification of resources is necessary: it is necessary to distinguish between resources with their availability directly constrained, and resources/practices which lead to pressures that need to be constrained. The degree to which PB can be applied as constraints is a contentious matter that needs the scrutiny of policy and civil society.

Finally, this study concluded that conceptual development is necessary to take PB and Nexus ahead, from tentative frameworks to scientifically robust, policy relevant instruments. This should involve a clarification of the assumptions surrounding the causality of the environmental pressures, and the search for common representations of the processes. The study presented an initial concept that is currently under development.

### 4.2 Managing interfaces

The challenge of sustainability is being addressed by a series of conceptual frameworks and methodologies, which are developed and used by a growing number of research communities and policy arenas. Planetary Boundaries, Nexus approach, international environmental assessments are examples of such frameworks. This variety reflects the multitude of issues that constitute the challenge.

This study demonstrated that the wealth of tools, however, require efforts to clarify, explore and bridge the knowledge gaps that lie between these conceptual frameworks. There is a need to transform these gaps into interfaces: areas where different scientific communities and policy arenas actively exchange findings, data, concepts and that promote inter-community learning.

The analysis presented here identified three important aspect related to the process of development of the PB and Nexus approach that hinder the development of such interfaces: i) the lack of clarity regarding the conceptions and discourses that underpin and that are reaffirmed by the usage of these approaches to inform policy; ii) the fact that the scientific development behind the framework is being outpaced by the speed with which the PB concept is uptake by the policy arena; iii) the relative disconnection of the research communities involved in their development.

A series of global change programs currently try to tackle this challenge, creating interfaces and meeting arenas for a large number of formerly isolated disciplines, and so do the different communities involved in climate change research, notably through the working groups of the IPCC. These two cases highlight the importance of shared and relevant agendas, the need for actual cooperation across the interface, and the need of actors dedicated to managing the exchanges.
These interfaces need to be designed and maintained to enable the co-development of concepts, the sharing of data and the confrontation of different perspectives on the shared challenge of exploring potential pathways for sustainability. For the results to be relevant for policymaking, these interfaces should also allow the participation of decision-makers.

This study explored the gap that exists between Planetary Boundaries and Nexus, and it is clear that this gap is far from being transformed into an active interface, but the existence of this study and the following steps that are being planned hopefully will help creating such interface.

4.3 Looking forward

A series of activities is being planned as a follow up of this study. The first is a series of workshops that are being organized by the SRC, its partners of the Planetary Boundaries Research Network, and the Division of Energy System Analysis at the Royal Institute of Technology (KTH). The exact format is still to be determined, but it is likely to include three workshops: PB concept and implications, modelling for PB and modelling for CLEWs. The Network has the potential to serve as an interface management body, and hopefully these workshops will help defining a clear research agenda to address the multiple issues raised by the present study.

The second activity planned is the development of a scenario database aimed at compiling information on scenarios used in international environmental assessments and IAMs, aiming at enabling learning from and across these communities. This database will complement the modelling database which was set up at the SRC by Johannes Friedrich (Friedrich 2013).

The conceptual developments that were initially explored in this project will require further investigation and development. This is likely to occur in the next few years in a PhD thesis that will follow this study.

The PB framework is currently under review, and a publication with an updated framework is awaited. More importantly, the debate around the concept and its implications must continue. The implications of not acting accordingly to the evidences of global change currently available are daring. However, the implications of using one specific framing of the problem are very significant and should at all times be subject to scrutiny from science, policy and society.
References


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UNEP, 2012. *Global Environment Outlook 5 - Environment for the Future we want*,


Annex 1 – DPSIR Framework

Figure 17 DPSIR as presented in the Global Environmental Assessment 5

Source: UNEP (2012)
Annex 2 – Coupling and linking scenarios

In its seminal work, Zurek & Henrichs (2007) propose that scenarios studies can be developed for multi-scale applications. The authors propose that these scenarios can be coupled through their building processes or linked through common elements.

Coupling scenarios (Figure 18) can occur in different degrees. In *joint processes*, the same group of scenario developers creates scenarios at each geographical scale within a single assessment. In *parallel processes*, scenarios are developed: (i) to address the same focal question; (ii) applying the same development procedure; (iii) using the same sources or (iv) sharing the same physical location (e.g. during a workshop). Parallel process can allow flexibility to adapt the focus of the scenarios to different problems relevant at different scales (Zurek & Henrichs 2007).

Source: Zurek & Henrichs (2007)

Figure 18 Coupling scenarios across scales
The picture represents the different degrees of coupling in the scenario construction process.

In *interactive processes*, a draft is scenarios is produced at one scale, used to inform the scenario developments and then reviewed; the process can be cumbersome, but contributes to learning about cross-scales processes. In *consecutive processes*, scenarios are created at one scale at the time; resulting scenarios can still present a strong consistency if a follow up process is included. At last, *independent processes* occur without formal connection of the scenario development, allowing scenarios to be built responding specific questions at different scales. Most scenario exercises up to date belong to this last category (Zurek & Henrichs 2007).