Horses for courses: Analytical tools to explore planetary boundaries~~.~~

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Abstract

There is a need for ~~further~~more integrated research on ~~developing a set of~~ sustainable development ~~objectives, based~~and global environmental change. In this paper, we focus on the ~~proposed~~Planetary Boundaries framework ~~of planetary boundaries indicators. The relevant~~ to provide a systematic categorisation of key research questions ~~are divided in this paper into~~ in relation to avoiding severe global environmental degradation. The four ~~key~~ categories~~, related to~~ of key questions are those that relate to 1) the underlying processes and selection of key indicators~~,~~ for planetary boundaries, 2) understanding the impacts of ~~different exposure levels and influence of~~ environmental pressure and connections between different types of impacts, ~~a~~3) better understanding of different response strategies ~~and~~to avoid further degradation, and 4) the available ~~options~~instruments to implement ~~changes.~~such strategies. Clearly, different categories of scientific disciplines and associated ~~models~~model types exist that can ~~contribute to~~accommodate answering these questions. We identify the ~~necessary analysis, noting that~~strength and weaknesses of different research areas in relation to the ~~distinctions between them are fuzzy. In the paper, we both indicate how these models relate to the four~~question categories~~ of questions but also how further insights can be obtained by connecting the~~ , focussing specifically on different ~~disciplines (without necessarily fully integrating them). Research on integration can support planetary boundary quantification in a credible way,~~types of models. We discuss that more interdisciplinary research is need to increase our understanding by better linking human drivers and social and biophysical impacts. This requires better collaboration between relevant disciplines (associated with the model types), either by exchanging information or by fully linking or integrating them. As fully integrated models can become too complex, the appropriate type of model (the racehorse) should be applied for answering the target research question (the race course).

1 Introduction: knowledge support for sustainability science

Environmental assessments published in the last few years have emphasized that current global environmental change processes are likely to lead to serious impacts on humans and ecosystems. These include the Millennium Ecosystem Assessment (2005), the United Nations Environmental Programme's Global Environmental Outlook (UNEP, 2012), the various reports of the Intergovernmental Panel on Climate Change (e.g. IPCC, 2013), and the Convention on Biological Diversity's Global Biodiversity Outlooks (CBD, 2010). Further evidence is still needed to support policy making, including improved quantitative understanding of changes in the current state of the global environment, prediction of possible future impacts, and the evaluation of possible responses. In this paper, we use the Planetary Boundaries concept (Rockström et al., 2009, Steffen et al., 2015) as a useful framework for global environmental assessment. However, most of our considerations are relevant for environmental assessments in general.

The Planetary Boundaries framework ~~(Rockström et al., 2009, Steffen et al., 2015)~~ takes environmental stability to be an important enabler of human development. Rockström et al. (2009) hypothesized that Earth system perturbations crossing biophysical thresholds could have disastrous consequences for humanity. The planetary boundaries framework therefore defines a set of indicators associated with several of the planet's biophysical subsystems or processes. The set consists of nine boundaries for the extent of human perturbation to these processes, using the comparatively stable biophysical conditions of the Holocene as the baseline for a normatively defined 'safe operating space for humanity'. More concretely, they proposed quantitative precautionary boundaries for most of the nine processes.

The planetary boundaries framework has since received ~~a lot of~~much attention, by scholars, institutes publishing environmental assessments, and various other actors in policy, business and civil society (Carpenter and Bennett, 2011, Running, 2012, de Vries et al., 2013, Gerten et al., 2013, UN.GSP, 2012, WBCSD, 2014, Galaz, 2014, Raworth, 2012, Steffen and Stafford Smith, 2013, Dearing et al., 2014, Mace et al., 2014, Cole et al., 2014). The framework is clearly proving useful for indicating the multidimensional nature and urgency of current environmental degradation. By focusing on a suite of critical human-perturbed global environmental processes, the framework also highlights that further information is needed on the systemic relationships among various different forms of environmental change (e.g. land use and energy use, or pollution and climate). In that context, it is important to acknowledge that environmental goals will always need to be integrated in a larger set of sustainable development objectives, also dealing with human development goals and challenges (Raworth, 2012)~~.~~ ~~The Sustainable Development Goals (SDGs[1]) currently being adopted by the United Nations are broad set of indicators, and it has been proposed earlier to connect the PB framework to some of these goals~~. Recently, a set of Sustainable Development Goals (SDGs) have been adopted by the United Nations, representing a broad set of goals and targets on social, economic and environmental objectives (UN, 2015). While the planetary boundaries framework has not been mentioned explicitly in the SDGs, they are addressed in some way, either as the focus of specific goals or included in specific targets ~~(Griggs et al., 2013)~~(Griggs et al., 2013).

There are, however, also many open questions with respect to the planetary boundaries, certainly in terms of their place in a wider set of sustainable development goals. ~~If the planetary boundaries indicators are connected to the SDGs, they still need closer attention with regard to the choice of 'control variables' for the indicators, the determination of the 'boundary' values, and also the options for~~

~~[1] https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals~~

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~~societal pathways that stay within the boundary levels.~~ A key challenge in this context ~~will be developing~~ is to develop more ~~integrative~~integrated knowledge~~.~~ which leads to solutions. So far, the processes of global environmental change ~~are~~have often been addressed by different disciplines, in different and not easily commensurable ways. Broadly speaking, the physical and natural sciences (geophysical sciences) can provide insights into the behaviour of Earth systems. Geography and ecological sciences have looked into the impacts of global environmental change. Moreover, socioeconomic and technical disciplines can provide insights into the large-scale behaviour of human systems that both drive environmental degradation and respond to it. Clearly, while cooperation (or even integration) between disciplines is needed, such interdisciplinary cooperation is often difficult to achieve (Brown et al., 2015).

In this context, this paper discusses some of ~~In all cases, computer models are often used~~ emerging, interdisciplinary questions related to planetary boundaries (i.e., the 'racecourses' in the title) and relates these to different tools that can be used to address the identified questions (i.e., the correct 'horse'). It should be noted that, depending on the discipline, very different tools and methods have been developed, ranging from qualitative case studies to quantitative model exercises. In this paper, we mostly focus on the assessment of, and responses to, future global environmental change. To assess future change, several disciplines use computer models as a means to achieve further integration of information and study global environmental change processes. ~~It should be noted that in the research fields relevant for the planetary boundaries, very different models, tools and methods have been developed~~Obviously, these models differ greatly across different research fields. In this paper, we focus specifically on how different types of models can be used to address the research agenda for planetary boundaries. This means that while we first define a broad research agenda in Section 2, in Section 3 we then focus on relevant model types, their strength and weaknesses, and how these models can be used to further current scientific knowledge. In Section 4, we illustrate these general considerations through case studies, informing some practical conclusions for all global change modelling communities.

2 A typology of key questions related to the Planetary Boundaries concept

~~2 A systems view on questions raised by the Planetary Boundaries concept~~

Since the first publications of the planetary boundaries framework in 2009, a number of key questions have been raised about the framework and its underlying rationale. While publications since then have tried to address some of these scientific questions (see also references in Steffen et al., 2015), they still provide a very important research agenda. These questions relate to a wide continuum of issues from those dealing mostly with biophysical systems to those dealing mostly with human systems, and often to the interactions between the two kinds of systems. Both types of systems are intrinsically complex. To structure the questions, we have below made an attempt to group the questions into four categories (summarised in Table 1). These categories are so generic that they will continue to be relevant for research for quite some time – and moreover they are not targeted specifically to a certain user group. Furthermore, these questions are also relevant well beyond the planetary boundaries framework (as many others have also suggested limits and threshold levels for environmental degradation). Finally, each scientific question type is also related to key policy questions as we indicate below.

Type 1 – Biophysical system dynamics:

What environmental processes are key to ecological stability, and what Earth system thresholds matter for human development?

Rockström et al. (2009) selected nine boundaries initially, on the basis of expert judgment, and the same set have been updated in Steffen et al. (2015). However, the basis for choosing these specific boundary processes is not entirely explicit. While the planetary boundaries framework deliberately focuses on a selection of Earth system processes where human perturbation is reaching critical levels (to avoid having too many indicators), a key question is whether together the set is indicative enough of a more comprehensive representation of the whole Earth system. Clearly, there might be other anthropogenic issues that play a critical role for global sustainability. For instance, the global human consumption of terrestrial primary productivity has been proposed as another key indicator (Running, 2012), while Akimoto (2003) suggested that air pollution exceeded global boundary levels. The latter is possibly represented in the 'atmospheric aerosol loading' and in the 'chemical pollution/release of novel entities' boundaries, but neither of these has been elaborated yet in a singular global quantification, despite the updates by Steffen et al. (2015). Steffen et al. (2015) also address the sub-global distribution of the human perturbation for some processes, including water use (see also Gerten et al. 2013).

Obviously, there is a systemic question about how many planetary boundaries can be addressed, and how many would be sufficient given the coupling of issues in the biophysical system. Rockström et al. (2009) frame boundaries in terms of a risk of crossing thresholds that *'trigger non-linear, abrupt environmental change within continental- to planetary-scale systems'*. However, they include some processes in the framework (such as freshwater use, and biodiversity loss) where the changes are progressively incremental (not abrupt), the processes of environmental degradation play out fundamentally at the local level, and the causal connection from local perturbation to large-scale change is possibly quite weak. Nordhaus et al. (2012) and Brook et al. (2013) responded to that conceptual looseness, arguing that there is no 'planetary tipping point' for several of the planetary boundary processes, and concluding that if global constraints are created for the regionally heterogeneous biophysical processes (aside from their impacts on climate) then misguided policies will arise.

It is an open question how important 'tipping points' actually are for each of the planetary boundaries. While tipping points have been hypothesized at the global level, their exact position has not been determined and is likely impossible to determine for most processes (Clark, 2011), and will often only be known years after they have been passed. It seems that the focus should be much more on sustaining the interplay of global physical, biogeochemical and ecological processes at a level that appears sustainable (and in accordance with human acceptance of environmental degradation and risks) than on finding arguments on absolute tipping points per se. In that sense some of the criticism might, in our view, be misguided by the focus of Rockström et al. (2009) on tipping points. A great deal remains to be investigated in terms of Earth system thresholds, and the human-environmental feedbacks that affect their position.

Some important policy questions relating to this type of question are: "Which issues are substantial enough to select for international policy making processes (agreeing on actual boundaries or targets) and how do these relate to other issues?" and "Are policy approaches that are based on a negotiated set of fixed targets – like the SDGs – appropriate in light of scientific information about complex global biophysical dynamics?" And finally, "What kinds of governance processes, institutions and policies are needed to respond to systemically connected global environmental risks?"

Type 2 – Impact diagnosis:

What is the ~~'dose-response'~~causal chain for the different processes ~~in terms of~~focusing on societal impacts? ~~How~~What are *acceptable* levels of pressure and how does this affect boundary positions?

One interpretation of the planetary boundaries concept is the suggestion that staying within the boundaries is not associated with environmental risks, while crossing them leads straight to a high risk of 'unacceptable environmental change'. Steffen et al. (2015) explains that the planetary boundaries framework applies the precautionary principle. While crossing a boundary does not necessarily directly lead to a catastrophic outcome, it increases the risk of regime shifts, destabilized system processes or reduced resilience, so the boundary value is set at the lower, 'safe' end of the zone of uncertainty about such threshold changes. Many questions still remain in this approach, particularly with regard to the societal impact of crossing boundaries. The risks that are referred to are altered likelihoods of biophysical change, not the likelihood of unwanted social impacts. In fact, the social dimensions of global sustainability are not dealt with at all in the planetary boundaries framework, even though *a)* human activities are the drivers of change, *b)* the nine processes have been selected on the basis that when they change, the safe operating space for humanity shrinks, and *c)* the connection from biophysical state change to societal impact will need to be made in order to mobilize policy responses for impact mitigation and adaptation.

A similar question remains as to whether unacceptable environmental and societal impacts are also associated with much lower levels of anthropogenic perturbation (Schlesinger, 2009). For instance, the 350 ppm CO_2 level proposed by Rockström et al. (2009) is associated with a global warming of 1.5^{o}C, which results in environmental risks such as the loss of unique ecosystems, and sea level rise that could result in serious impacts in low lying areas – and in fact, climate impacts are already reported now (IPCC, 2014). In other words, in most cases there will be little biophysical evidence about what changes (and what rates of change) are too large to deal with, and thus setting boundaries will be much more a societal choice on 'what changes or risks are acceptable' than a biophysical necessity (see also Nordhaus et al., 2012, Brook et al., 2013). This ~~does suggest~~suggests that the interactions among targets becomes a critical factor, given these are almost surely not simply additive.

A further challenge is that the Earth System is a complex, integrated system, which means that the boundaries are in fact interdependent. For example, the nitrogen and carbon cycles are tightly linked~~,~~ ~~and deforestation may impact water availability.~~ and deforestation will impact water availability via impacts on retention time of precipitation in ecosystems before reaching rivers and by influencing precipitation patterns (Foley et al., 2005). Crossing one boundary will affect the position of the others. There is a critical need for new integrative research to underpin the boundaries, by identifying the 'dose-response' for the different boundaries in terms of impacts associated with particular drivers and rates of environmental change, clarifying the potential links between biophysical and social system thresholds, and determining possible boundary positions. A systemic analysis of the interactions ~~of~~among the processes is still needed, because these interactions are a major reason for the large uncertainties in defining boundary positions.

Since human activities determine many of the interactions, and alter them in unprecedented ways, this analysis must also explicitly address human-environment interactions. The causal chains of environmental change (or more mechanistically 'dose-response functions') are strongly determined by the interactions *between* the biophysical and human systems, and are not only a product of the biophysical system ~~as implied in the simplified planetary boundaries framing. The question whether the planetary boundaries framing would still work thus depends strongly on how much certain indicators dominate environmental degradation (allowing for the simplifications being made).~~

~~The key policy question here is thus simply at what levels to set the boundaries. This is primarily determined by~~(as sometimes seems to be implied in the simplified planetary boundaries framing). For example, not only the impacts *of* climate change, but also the efficacy of responses *to* climate change, are known to be affected by levels of equity (e.g. (Mearns et al., 2010).The key policy question here is thus simply at what levels to set the boundaries. This is partly determined by acceptable human impacts of increasing pressures, such as damage costs or health impacts, but also by biophysical impacts. It is crucial to note that there are no biophysical laws that strictly determine target levels; these depend on human choices of acceptable risks and levels of change. The research community should therefore ~~do costs~~carry out inclusive cost-benefit analysis ~~of increasing~~(ie. including non-economic, long-term social and environmental values) of different planetary ~~boundaries~~boundary targets, taking into account the interrelations between the different boundaries.

Type 3 – Response and scenario analysis:

How can societies remain within the planetary boundaries while at the same ensuring a sustainable human development?[2]

As sustainable development is a long-term challenge, it is very important to look into the future consequences of decisions taken today. Steffen et al. (2015) emphasize that currently four of their nine planetary boundaries have already been overstepped – human activities are altering these aspects of the Earth system in irreversible ways, with global consequences. If boundaries informed by the current understanding of Earth system dynamics are taken as 'non-negotiable', the key questions are how to ensure the world's future development pathway stays within the planetary boundaries, and in doing so, how to ensure that the world's other societal goals can be met. For instance, an acceptable global sustainability outcome must mean eradicating extreme poverty – as agreed upon by nearly all countries worldwide as part of the Rio Declaration – as well as remaining within the boundaries (Raworth, 2012, Steffen and Stafford Smith, 2013). The focus of the research in type 3 is to identify actionable pathways that enable societies to remain within 'environmentally safe and socially just operating space'. One might even argue that the targets themselves can only be set in a useful way if there is also a serious plan of how they can actually be achieved (Brewer, 2009).

There is now a critical need for transdisciplinary analysis of what a coherent set of actions looks like that allows planetary boundaries and human development goals to be met at the same time~~.~~, particularly given the agreement on the SDGs. Such analysis can focus on individual boundaries, but it must also address the question of how multiple boundaries can be respected. Because boundaries are connected to each other in complex ways, ~~and, consequently,~~ a partial analysis focusing only on one boundary or solving only one issue at a time has a serious risk of shifting the problem elsewhere. A conceptual strength of the planetary boundaries framework is therefore its systemic approach, calling for attention to be paid to multiple environmental issues together. Some recent research has been published (PBL, 2012, van Vuuren et al., 2015, Riahi et al., 2012) focusing on response strategies that achieve multiple goals, and their associated synergies and trade-offs.

The type 3 policy questions ~~concern identifying~~aim to identify the different options to reduce environmental pressures and improve societal wellbeing; understanding the levers of change required in

[2] We distinguish type 3 and type 4 questions. While type 3 focuses on measures (i.e. physical changes to implement sustainable development strategies), type 4 questions focuses on how these response strategies can be implemented~~-~~.

both the human and Earth systems to meet planetary boundaries and sustainable development goals (e.g. technology and lifestyle change); and characterizing the synergies and trade-offs among different options, and their overall costs. There clearly is a regional dimension to this effort, as for both planetary boundaries and SDGs most of the targets are formulated at the global level, but policies are usually implemented at the national level.

Type 4: Implementation analysis:

How can different response strategies actually be implemented?

Type 4 questions differ fundamentally from types 1-3, because they relate primarily to the question of how to induce societal action rather than to the scientific knowledge on the "physical" consequences of different responses, but they are increasingly recognized as needing to be brought more firmly within the scope of global change research. Even when global change issues are well understood scientifically and are covered by multilateral international policies (not least the three 1992 Rio Conventions on Climate Change, ~~on~~ Biological Diversity and ~~to Combat~~Combatting Desertification), implementation gaps are a serious problem(UNEP, 2011).

The question of how to implement pathways for a global sustainability transition relates to the different societal actors (including scientists) that are involved in these transitions, their individual and mutual interests, and their responses to policy instruments. To some degree, models can inform these issues (e.g. models assessing the consequences of responses to different policy instruments, models looking at a specific sector's or nation's interests and, increasingly, actor-based models for issues like the dynamics of adaptation, structural change and policy/technology diffusion). However, in many cases the necessary knowledge is likely to come from more diverse sources, in both lay and expert-professional knowledge communities, with generic insights into transition processes and the interests of different actors~~.~~, particularly of winners and losers from significant change. Effective action-oriented research in this category is therefore likely to involve participatory processes as well as a concerted effort by researchers to bridge across multiple academic disciplines.

Key questions in this area therefore include understanding the role of specific actors, both within countries and possibly even the countries themselves within processes playing out at the international level; the influence of financial instruments versus regulation versus the provisioning of information to societal actors (linked to the respective roles of markets, governments and civil society); and the relationship between sustainable development transitions and other current events.

The combination of the different types of questions

This four-way typology is useful because it shows where the present suite of modelling approaches can be applied and where they need to be combined or even integrated, and it points to strategic new directions, as we will discuss in the next Sections. It should be noted, however, that our four categories of questions are not a 'hard' classification. For instance, determining acceptable levels of environmental degradation will sometimes involve trade-offs with human development goals. Similarly, a choice of pathway made now will determine the shape of the future operating space, including possible new indicators.

A question that cuts across all of the categories is how to address scale. Geographic scale plays an important role on the biophysical side, and thus for question types 1 and 2 – but also in terms of relevant response strategies as in most cases policies will need to be formulated and accepted at the national level.

3 Methods to study Planetary Boundaries-related questions and strategies for integration

Answering the different categories of questions raised in the previous section is not easy. Information that looks across multiple sets of interactions and decision-making on different time, space and organisational scales is needed. The questions also deal with interactions between human and biophysical systems[3]. In fact, Rockström et al. (2009) themselves indicate that the planetary boundaries concept was informed by Earth system science, insights from social-ecological resilience research, and ecological economics. While recent years have seen major progress in cross-disciplinary integration in global change research (Moss et al., 2010, Van Vuuren et al., 2012), it is clear that answering the integrated questions raised above still presents immense challenges~~.~~ (Brown et al., 2015).

Quite sophisticated research methods are needed to address these challenges. These methods range from qualitative case studies to quantitative model exercises. In this paper, we mostly focus at quantitative modelling tools developed by different disciplines as a means to represent and explore cross-scale linkages (spatial relationships), relationships between environmental issues, and time-related issues, and to deal with other sources of uncertainty. It is clearly evident that models have limitations too, as we will discuss further in this article. In that sense, it might be useful to distinguish at least three layers of reality that have a bearing on the relevant processes (following de Vries, 1992): 1) the physical world of tangible elements, like land-use, human infrastructure and climate change, 2) the world of intangible elements such as regulations, markets and prices governing behaviour, and 3) the underlying culture and lifestyle of humans. In general, mathematical models are most usefully applicable for those systems in which generic rules can be derived, which mostly ~~concerns~~concern the first and partly the second layer.

In model-supported research on the four question types raised in Section 2, the challenge is to find a useful mix in being broad enough to answer the holistic questions – but still be able to control the complexities involved. Below, we briefly discuss several types of research approaches relevant for planetary boundaries analysis and also the way these approaches are trying to address the trade-offs between model comprehensiveness and complexity (see Figure 1).

One major field of relevant approaches is represented by so-called *Earth System Models* (ESMs; Table 2). These models have been used to study global environmental change problems from a geo/biophysical perspective. While many Earth system models exist, starting from different traditions (e.g. hydrology or air pollution), the most advanced ESMs consist of combinations of climate models (general circulation models, which determine the global distribution of energy) and models of land vegetation dynamics and ocean biogeochemistry (Scholze et al., 2012, Hajima et al., 2014). Increasingly, global hydrological process models (that resolve global water balance) are also becoming an important class (Gerten et al., 2013, Arnell and Lloyd-Hughes, in press). Earth system models are complex in terms of the number of processes modelled. Yet, by focusing on the natural system they can rely on a rigid framework of natural science laws, avoiding the additional complexities of describing issues like human choice and behaviour. Typically, these models describe human influences at best as an exogenous 'scenario' input. To date, the high priority given to climate change in both research and international policy has meant that these

[3] The concept of social-ecological system emphasizes that human systems are embedded in ecological systems. Here, we simply refer to the interaction without specifically indicating a hierarchy.

models are designed to address questions relating to climate interactions, such as the carbon cycle and land-use. These types of models have a major contribution to the type 1 and type 2 questions raised earlier, but lack ways to describe the possible feedbacks with human systems and the trade-offs between human system and environmental targets. A key question is whether the feedbacks included in these models (and model output) can also identify the thresholds and tipping points (or more broadly the dose response relationships) discussed for type 2 questions~~, which depend on the nonlinearities included in these models (Lenton et al., 2008).~~. This is far from easy as this depends on complex, non-linear processes that are hard to include in models, partly because they are not observed in the present system. A list of possible key feedbacks and the underlying processes such as hypothesized by Lenton et al. (2008) could provide a research agenda for improving the representation of these processes in the ESM models. Other model types (such as those discussed below) will be too simplified in the representation of the Earth-system to add much useful information here.

Integrated assessment models (IAMs; Table 2) aim to study the co-evolution of human and Earth systems to provide direct policy advice (Weyant et al., 1996). They are primarily designed to address type 2 and 3 questions. As the relevant questions are often bridging different geographical scales, timeframes and relate different environmental issues, these models need to deal with considerable complexity and uncertainty. Integrated assessment models often use simplified representations of human and Earth systems that are often based on introducing linear relationships. For instance, the climate system is represented through a set of equations that describe climate change as a linear response to increasing cumulative CO_2 emissions and annual emissions of short-lived gases (van Vuuren et al., 2011c). Such simple models are next calibrated to represent the behaviour of more complex models. Similarly, in some IAMs the human economy is also represented in a rather simplified form~~.~~ (e.g. the DICE model of Nordhaus focuses on the overall integration of earth system and human system, and represents the economy with only a few equations (Nordhaus, 2008)). Other IAMs, however, include a quite complex description of some human systems, ~~specifically~~either in monetary terms such as computable general equilibrium models (CGEs) or more model with more technology detail, focusing mostly on the energy system and agriculture/land use~~.~~ (for instance, the models that developed the representative concentration pathways (van Vuuren et al., 2011b)), and aim to represent key processes. While feedbacks play an important role in these descriptions, they tend to be described in a deterministic and linear way. The strategy of IAMs in the context of ~~planetary boundaries~~ research that is relevant ~~research~~to planetary boundaries is thus to be quite comprehensive, but to deal with complexity as far as possible by simplification. Scenarios and backcasting are used as a means to explore pathways to safe and just operating space. Examples of such studies include Riahi et al. (2012) and van Vuuren et al. (2015).

One could potentially define a group of models focused on the human system (~~Figure 1,~~ Table 2). It is, however, hard to define a coherent set of these models given the wide range of social topics studied (as argued by Goldspink (2000) - and the disciplinary focus of many human system models (e.g. economics, demographics or health). One clear ~~group~~ subgroup ~~include~~includes economic models, but even in this group, one can distinguish different ~~groups~~sets such as growth models (focusing on factors determining long-term economic growth), general equilibrium models (focusing on the dynamic interactions between different sectors and production factors), econometric models (such as input/output models), and agent-based models. General equilibrium models allow, for instance, ~~to identify~~the identification of least-cost policy responses to climate change, including the consequences for various sectors as well as trade impacts. Clearly, human system models are relevant for specific topics related to human development (type 3) and the implementation of response strategies (type 4). They need, however, to deal with high degrees of complexity (and ~~associated~~consequent uncertainty) associated with human behaviour. For instance, many economic models do so by assuming economically efficient behaviour, assuming a central agent (instead of describing individual actors), and by focusing on relatively short-term issues to avoid ~~the~~ long-term ~~uncertainty~~uncertainties.

Finally, there ~~are~~is a ~~growing~~large number of ~~alternative~~models embracing approaches that focus on identifying system behaviour of combined human/Earth systems, focussing specifically on the representation of underlying process behaviour of actors and institutions (Schlüter et al., 2012, Rounsevell et al., 2012, Heckbert et al., 2010, Weber et al., 2005, Heitzig and Kittel, 2015). These include, for instance, some of the agent-based models and network analysis. Also here strategies are needed to deal with increasing complexity. ~~This may be done~~Some of these models do so by focusing on specific issues, but ~~also be focusing much~~others decide to focus more on the behaviour of the system than on real world outcomes. ~~The~~In these models, the technique ~~often~~ used ~~by these tool~~ to avoid too much complexity is abstraction. In Table 2, we have summarized this category as abstract, process-oriented models.

~~The integration of~~Cooperation among different model approaches ~~could provide~~is needed to further insights~~ as well~~ – but faces ~~similarly~~similar trade-offs between relevance ~~for~~to the questions at stake, comprehensiveness and complexity. While developing integrated human/Earth system models has frequently been mentioned as an important way forward (see also discussion by Lucht, this special issue), there ~~might often be possibilities for~~may be easier and more flexible forms of integration or cooperation (Van Vuuren et al., 2012)

~~More specifically,~~ . Given the complexity of some of the questions derived in Section 2, different forms of cooperation need to be considered, based on the strengths of the individual approaches – hence also the title of this article, "Horses for Courses". This idea in fact also complies to one of the principles for successful interdisciplinary research identified by Brown et al. (2015), emphasizing the need to connect to specific disciplines as well as to interdisciplinary research questions.
The three different forms of cooperation ~~could be distinguished~~we distinguish are:

1. Offline exchange of information between model types. This is a useful approach ~~in case~~where feedbacks are thought to be relatively weak ~~and/~~or relatively easy to capture via simplified representations.
2. Improve the representation of one model type ~~into~~within another. For example, IAMs could be expanded somewhat to represent better the behaviour of the Earth system~~, for instance~~ by including representation of other planetary boundaries. IAMs could also be expanded with a cohort component population model, or an in-depth representation of the economy to introduce feedbacks of environmental change on population dynamics and economic growth. The representation, however, would need to fit the IAM idea of simplification. Another example of this approach is to improve the representation of the human system in ESMs by adding simple 'behavioural rules'. This approach would not aim to truly represent human systems in ESMs but rather apply meta models that describe the main behaviour of human systems in a simplified manner. An example here would be land-use allocation rules.
3. Fully couple different model types, to create models that fully cover both human and earth system behaviour in full possible detail. This approach would allow for a more intensive interaction~~,~~ that could also capture strong, non-linear feedbacks. This, however, comes at the costs of greater complexity (also in terms of cross-disciplinary cooperation and model benchmarking). Complexity here also relates to the issue of scales~~. For instance~~, in ~~geographical sense~~both space (economy scale versus a detailed geographic grid representation required for

biodiversity or water scarcity) and time (short-term focus of economic models versus long-term focus of earth-system models).

The cooperation across different disciplines and research communities is only beginning to take off (e.g. cooperation between hydrological teams and IAM teams; the cooperation between ESMs and IAMS, and atmospheric chemistry models and IAMs). This means that in most cases it will be more interesting to ~~aim and prove~~test the existence of possible feedbacks in linkages using somewhat simpler approaches than directly aiming for the most complex forms of interaction.

4 Example applications

We will here briefly discuss what further research could look like for three example planetary boundaries. Earlier Van Vuuren et al. (2012) provided a detailed list of questions and approaches for climatic change research in relation to model cooperation. The category types proposed in Section 2 in fact align well with the boundaries of the three working groups of IPCC for climate change (question type 1 with Working Group 1, question type 2 with Working Group 2, and question ~~types~~type 3 with Working Group 3, and question type 4 with Working Group 2 and 3). Clearly in the field of climate research considerable progress can also be made by strengthening the research across the disciplines associated with each of the Working Groups. Here we briefly discuss the issue of water, nutrient management and biodiversity.

Water.

For type 1 and 2 questions, it is now clear that hydrological models can play an important role in advancing the state of understanding of the planetary boundaries for water. One of the most important issues here is the linkages between different scales: water scarcity issues are mostly relevant for catchment areas, but both social and physical global linkages exist, via trade and climate processes. Given the possible implications of local scarcity issues for global sustainability, Rockström et al. 2009 set a global threshold on water use. Gerten et al. ~~(2013)~~(2013) contributed to analysis of possible limits to global water use, using a coupled land/hydrology model. Their analysis was used and expanded in the recent update of the planetary boundaries by Steffen et al. ~~(2015)~~(2015). Still, considerable uncertainty exists with respect to the quantification of the global threshold and its relevance.

For type 3 questions, water is increasingly being included in IAMs ~~(Hanasaki et al., 2013a, Hanasaki et al., 2013b, Dooley et al., 2013,~~ (Hanasaki et al., 2013a, Hanasaki et al., 2013b, Dooley et al., 2013, Bijl et al., 2015) to address the water-land-energy nexus and the role of water in sustainable development strategies ~~(Hoff, 2011, van Vuuren et al., 2015)~~(Hoff, 2011, van Vuuren et al., 2015)~~,~~. Proper analysis ~~required~~requires fine-scale population maps. The recent publications of the IPCC Shared Socioeconomic Pathways ~~(van Vuuren et al., 2014)~~(van Vuuren et al., 2014) seems a way to couple comprehensive water demand scenarios to more detailed hydrological models. This will enable expected changes in water demand to be brought to the scale of countries and catchment areas.

Nutrient management

Nitrogen is mostly dealt ~~with in~~within regional models, as the key problems associated with the imbalance of the nitrogen cycle are typically regional in nature (coastal zone water pollution, air pollution). Current modelling ~~approach~~approaches can, to some degree, address type 1 and 2 questions. The global nitrogen cycle is often represented in very general terms (Galloway et al., 2008) in modelling attempts, although some Earth system models have started to implement the nitrogen cycle in order to better understand the impacts of climate change on the carbon cycle. In most global models, however, the representation of nitrogen is at the level of parameters rather than a process description. De Vries et al. (2013) recently reconsidered the original implementation of the nitrogen planetary boundary, with meeting human needs for food as a requirement. In integrated assessment models, nitrogen is at the moment at best included in the form of a calculation of atmospheric emissions (Van Vuuren et al., 2011a). The most significant exception includes the work by Bouwman et al. (2013) who describe trends in the global nitrogen cycle coupled to the description of agriculture and atmospheric emissions of the IMAGE model, but also relate this to implications for eutrophication by coupling these scenarios to a global hydrology model. This allows for addressing certain type 3 questions. There have been calls for more systematic global nitrogen assessment that could be the basis of coupling IAM and ESM research in this area more systematically and ~~there improve~~thereby improving their potential to address type 3 questions~~..~~. This could also include a more detailed description of impacts.

Biodiversity

It is widely acknowledged that biodiversity underpins ecosystem functioning hence providing ecosystem services essential for human well-being (TEEB, 2011, MA, 2005, Hooper et al., 2012). The currently proposed control variables to be used for the planetary boundary on biodiversity (biosphere integrity) are genetic diversity and functional diversity, indicated by the extinction rate and the biodiversity intactness index (Steffen et al., 2015). In addition, Mace et al. (2014) proposed a wider range of variables, including biome integrity. While there are several models that address the impacts of human pressures on biodiversity, including on functional diversity (Alkemade et al., 2009, Visconti et al., 2015), there is a lack of tools that address the link between ecosystem functioning and ecosystem services. This lack of tools actually means that Type 1 and 2 questions are still very difficult to address. While there is some research that addresses the first part of Type 1 questions (Cardinale et al., 2012, Hooper et al., 2012), to properly address the Earth system thresholds for human development still requires a better understanding of the link between biodiversity and ecosystem functioning. For the Type 2 questions there is generally knowledge about the role of ecosystem degradation on ecosystem services, while the societal impacts (for example on health and recreation) are more problematic. Type 3 questions can be addressed with current available IAMs that include a wide range of drivers. For instance, they include land-use change, nitrogen deposition and climate change, that are linked to specific biodiversity indicators (van Vuuren et al., 2015). However, properly addressing these types of questions requires clear answers for Type 1 and Type 2 questions. The biodiversity context shows how IAMs can also be used for Type 4 challenges, as IAMs are being applied to look into progress towards the Aichi Biodiversity Targets (Tittensor et al., 2014) and goal structuring for the SDGs (Lucas et al., 2014).

4. Conclusions

~~There has been considerable~~Considerable attention has been paid to the planetary boundaries concept, also in relation to ~~a~~the wider set of ~~sustainable development goals.~~Sustainable Development Goals. At the same time there are still many open research questions. Many of these questions require a closer cooperation across the different disciplines studying future global environmental change. In this paper, we have identified some of the most important open questions and categorised them~~. Next~~, we ~~discussed how earth~~specifically looked at different relevant model types (Earth system models, ~~integrated~~Integrated assessment models, human system models, and other tools~~ can be used~~) and discussed how these relate to ~~answer these~~the key open questions. ~~This leads~~A key question is whether these models would need to ~~the~~ be fully integrated into “second generation” Earth-system models or whether cooperation between these models would be more fruitful. As we identified several differences with respect to focus, discipline, attitude towards complexity, and integration across the model types, we conclude that an interdisciplinary approach might often be based on cooperation instead of integration (hence the paper's title "horses for courses"). The following conclusions~~.~~ are derived:

- **There are several key questions with respect to the characterization of planetary boundaries and the consequences of policies designed to remain within them. These questions can be categorised in four key categories.** The planetary boundaries framework has been proposed as an important framework to derive targets and indicators in the context of global sustainability. In that case, the framework should be used in conjunction with a set of development targets. The research questions that are still connected to this framework are divided in this paper into four key categories, related to the 1) understanding of the underlying processes and selection of key indicators, 2) understanding the impacts of different exposure levels and influence of connections between different types of impacts, 3) a better understanding of different response strategies and 4) understanding the available options to implement changes. Together, these four types of questions provide a structured research programme for global environmental change problems.
- **Different types of analytical (modelling) tools can play an important role in analysing the key questions for the planetary boundary framework.** The formulated questions are complex: they involve relationships in time, across the different boundaries and across different geographical scales. Based on the grouping of the four very distinct types of questions, it is clear that insights of multiple scientific disciplines are needed to address the questions. Modelling tools (together with other research methods) are useful to analyse these complex relationships in more detail. In the paper, we both indicate how these models (and in particular earth system models and integrated assessment models) relate to the four categories of questions but also how further insights can be obtained by connecting the different disciplines (without necessarily fully integrating them).
- **It is important to increase interdisciplinary cooperation. Different existing modelling traditions can contribute in different ways to relevant insights on planetary boundaries. A richer picture – and one that can inform action – comes from combining these perspectives**. In this paper we have looked at different classes of models relevant for planetary boundaries research. A better cooperation across the different disciplines is needed to help informing policy makes about the four key question categories. It should be noted, however, that cooperation ~~can~~could be improved in different ways. Often exchanges of information between different types of models would be sufficient to make scientific progress. Fully linking different model types is also possible and ~~allows to~~ could enable the study of feedbacks, but runs the risk of providing ~~a too complex~~a description of the issues ~~at hand In~~ that ~~case, it would therefore~~is too complex, and hence that does not necessarily improve insights ~~more than by~~as much as exchanging information across the different modelling disciplines.

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Table 1: ~~Summary~~Typology of key questions ~~and indications of relevant characteristics of analytical tools~~for research related to planetary boundaries.

Question type	Type 1 – biophysical system dynamics	Type 2 – impact diagnosis (biophysical/societal system interactions)	Type 3 – Response analysis (societal system)	Type 4 – implementation of response strategies
Generic research questions	What environmental processes are key to ecological stability, and what Earth system thresholds matter for human development?	What is the 'dose-response' for the different processes in terms of societal impacts? How does this affect possible boundary positions?	How can societies remain within the planetary boundaries while at the same ensuring a sustainable human development?	How can strategies be implemented that can ensure social and environmental sustainability?
Derived questions	What planetary boundaries do we need to look at? How do different issues of scale influence planetary boundary selection?	Is it possible to identify biophysical threshold levels above which societal risks clearly increase? Are thresholds related to human development goals?	What is the potential for mitigating environmental pressures? What are key synergies and trade-offs in response strategies? Which pathways would lead to a fair distribution of the safe operating space?	What are the interests of different actors involved in response strategies? Which policy instruments are effective in implementing response strategies?
Policy questions	Which environmental change issues are substantial enough that scientific assessment and policy responses are needed at the global and large-regional level? Are policy approaches based on fixed targets appropriate in light of complex global biophysical dynamics?	At what level do targets need to be set? What are the costs and benefits of different planetary boundary protection levels?	Which technologies need further investments? What strategies for more sustainable development can be pursued?	How can situations be created that would allow these pathways to be implemented?
What should analysis tools be able to deal with?	Systemic interdependence between natural processes, across spatial scales, across timeframes	Systemic interdependence between social and biophysical systems	Causal links between social and environmental change, expressed in policy- or action-relevant metrics	Heterogeneity and complex interactions between relevant actors
What properties enable useful analysis?	• Well-characterized natural dynamics – so that human perturbation is detectable, attributable • Decomposable multi-dimensional natural dynamics	• Well-characterized system properties – 'stable states'/regimes and thresholds • Clear causal links between environmental and social change (endogenous or exogenous/scenario) • Defined drivers of change, relationships across different boundaries and human development goals	• Detailed description of key linkages across different planetary boundaries • Both spatially and institutionally resolved information • Transparency for diverse users	• Diverse potential opportunities across multiple actors • Ways of accounting for winners and losers • Transparency for diverse users

Table 2: Different categories of models for Planetary Boundary related questions

	Earth ~~system models~~System Models	*Integrated Assessment Models*	*Human system models (economy models)*	*~~Process~~Abstract, process-oriented models*
Key focus	Understanding of Earth system behaviour	Understanding of linkages between different parts of Earth and human systems	Understanding of some component of human system	Various
Temporal dimension	Often long-term	Medium to long-term	Short and medium term	Various
Methods of dealing with complexity	Focus	Simplification	Focus; often short-term	Abstraction
Strengths	Detailed description of key natural system components, including feedbacks; description of natural scale processes across scale	Causal links between social and environmental change; detailed description of key linkages across different planetary boundaries	Detailed description of human systems; often directly linked to policy instruments	Models focus on specific processes that may play a key role
Weaknesses	Human behaviour often only via exogenous scenarios	Most processes are described by linear equations;	Models focus mostly on the short-term; relatively large uncertainties	Quantitative results are not directly applicable
Integration	Mainly within the environment system (between planetary boundaries)	Human and environment system	Mainly within the human system	Various
Type of questions	Type 1 and type 2	Type 3; types 1, 2 and 4 more indirectly	Type 3 and type 4.	Type 1-3 (but often via qualitative insights)

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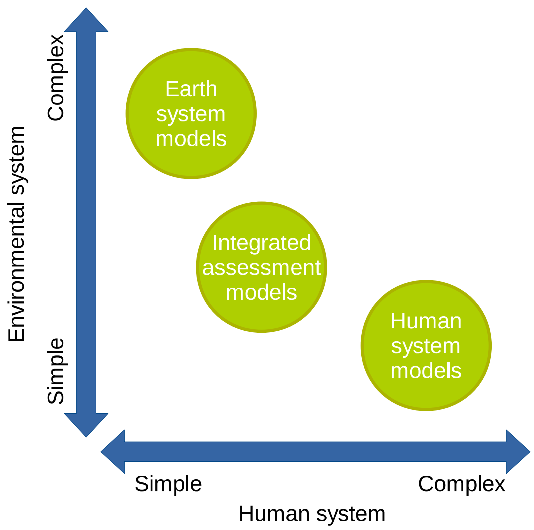

Fig. 1. Different models relevant for integrated sustainable development/Planetary Boundaries research