

1 **Horses for courses: Analytical tools to explore planetary boundaries**

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10  
11 **Abstract**

12 There is a need for more integrated research on sustainable development and global environmental  
13 change. In this paper, we focus on the Planetary Boundaries framework to provide a systematic  
14 categorisation of key research questions in relation to avoiding severe global environmental degradation.  
15 The four categories of key questions are those that relate to 1) the underlying processes and selection of  
16 key indicators for planetary boundaries, 2) understanding the impacts of environmental pressure and  
17 connections between different types of impacts, 3) better understanding of different response strategies  
18 to avoid further degradation, and 4) the available instruments to implement such strategies. Clearly,  
19 different categories of scientific disciplines and associated model types exist that can accommodate  
20 answering these questions. We identify the strength and weaknesses of different research areas in  
21 relation to the question categories, focussing specifically on different types of models. We discuss that  
22 more interdisciplinary research is need to increase our understanding by better linking human drivers  
23 and social and biophysical impacts. This requires better collaboration between relevant disciplines  
24 (associated with the model types), either by exchanging information or by fully linking or integrating  
25 them. As fully integrated models can become too complex, the appropriate type of model (the  
26 racehorse) should be applied for answering the target research question (the race course).

27

## 28 **1 Introduction: knowledge support for sustainability science**

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

40  
41 The Planetary Boundaries framework takes environmental stability to be an important enabler of human  
42 development. Rockström et al. (2009) hypothesized that Earth system perturbations crossing biophysical  
43 thresholds could have disastrous consequences for humanity. The planetary boundaries framework  
44 therefore defines a set of indicators associated with several of the planet's biophysical subsystems or  
45 processes. The set consists of nine boundaries for the extent of human perturbation to these processes,  
46 using the comparatively stable biophysical conditions of the Holocene as the baseline for a normatively  
47 defined 'safe operating space for humanity'. More concretely, they proposed quantitative precautionary  
48 boundaries for most of the nine processes.

49  
50 The planetary boundaries framework has since received much attention, by scholars, institutes  
51 publishing environmental assessments, and various other actors in policy, business and civil society  
52 (Carpenter and Bennett, 2011, Running, 2012, de Vries et al., 2013, Gerten et al., 2013, UN.GSP, 2012,  
53 WBCSD, 2014, Galaz, 2014, Raworth, 2012, Steffen and Stafford Smith, 2013, Dearing et al., 2014, Mace  
54 et al., 2014, Cole et al., 2014). The framework is clearly proving useful for indicating the  
55 multidimensional nature and urgency of current environmental degradation. By focusing on a suite of  
56 critical human-perturbed global environmental processes, the framework also highlights that further  
57 information is needed on the systemic relationships among various different forms of environmental  
58 change (e.g. land use and energy use, or pollution and climate). In that context, it is important to  
59 acknowledge that environmental goals will always need to be integrated in a larger set of sustainable  
60 development objectives, also dealing with human development goals and challenges (Raworth, 2012).  
61 Recently, a set of Sustainable Development Goals (SDGs) have been adopted by the United Nations,  
62 representing a broad set of goals and targets on social, economic and environmental objectives (UN,  
63 2015). While the planetary boundaries framework has not been mentioned explicitly in the SDGs, they  
64 are addressed in some way, either as the focus of specific goals or included in specific targets (Griggs et  
65 al., 2013).

66  
67 There are, however, also many open questions with respect to the planetary boundaries (or global  
68 environmental problems in general), certainly in terms of their place in a wider set of sustainable  
69 development goals. A key challenge in this context is to develop more integrated knowledge which leads  
70 to solutions. So far, the processes of global environmental change have often been addressed by  
71 different disciplines, in different and not easily commensurable ways. Broadly speaking, the physical and  
72 natural sciences (geophysical sciences) can provide insights into the behaviour of Earth systems.  
73 Geography and ecological sciences have looked into the impacts of global environmental change.  
74 Moreover, socioeconomic and technical disciplines can provide insights into the large-scale behaviour of

75 human systems that both drive environmental degradation and respond to it. Clearly, while cooperation  
76 (or even integration) between disciplines is needed, such interdisciplinary cooperation is often difficult to  
77 achieve (Brown et al., 2015).

78  
79  
80 In this context, this paper discusses some of the emerging, interdisciplinary questions related to  
81 planetary boundaries (i.e., the ‘racecourses’ in the title) and relates these to different tools that can be  
82 used to address the identified questions (i.e., the correct ‘horse’). It should be noted that, depending on  
83 the discipline, very different tools and methods have been developed, ranging from qualitative case  
84 studies to quantitative model exercises (Verburg et al., 2015). In this paper, we mostly focus on the  
85 assessment of, and responses to, future global environmental change. To assess future change, several  
86 disciplines use computer models as a means to achieve further integration of information and study  
87 global environmental change processes. Obviously, these models differ greatly across different research  
88 fields. In this paper, we focus specifically on how different types of models can be used to address the  
89 research agenda for planetary boundaries. This means that we first define a broad research agenda in  
90 Section 2. In Section 3, we then focus on relevant model types, their strength and weaknesses, and how  
91 these models can be used to further current scientific knowledge. In Section 4, we illustrate these  
92 general considerations through case studies, informing some practical conclusions for all global change  
93 modelling communities.

## 94 **2 A typology of key questions related to the Planetary Boundaries concept**

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

107  
108 ***Type 1 – Biophysical system dynamics:***  
109 **What environmental processes are key to ecological stability, and what Earth system thresholds**  
110 **matter for human development?**  
111 Rockström et al. (2009) selected nine boundaries initially, on the basis of expert judgment, and the same  
112 set have been updated in Steffen et al. (2015). However, the basis for choosing these specific boundary  
113 processes is not entirely explicit. While the planetary boundaries framework deliberately focuses on a  
114 selection of Earth system processes where human perturbation is reaching critical levels (to avoid having  
115 too many indicators), a key question is whether together the set is indicative enough of a more  
116 comprehensive representation of the whole Earth system. Clearly, there might be other anthropogenic  
117 issues that play a critical role for global sustainability. For instance, the global human consumption of  
118 terrestrial primary productivity has been proposed as another key indicator (Running, 2012), while  
119 Akimoto (2003) suggested that air pollution exceeded global boundary levels. The latter is possibly  
120 represented in the ‘atmospheric aerosol loading’ and in the ‘chemical pollution/release of novel entities’

121 boundaries, but neither of these has been elaborated yet in a singular global quantification, despite the  
122 updates by Steffen et al. (2015). Steffen et al. (2015) also address the sub-global distribution of the  
123 human perturbation for some processes, including water use (see also Gerten et al. 2013).

124  
125 Obviously, there is a systemic question about how many planetary boundaries can be addressed, and  
126 how many would be sufficient given the coupling of issues in the biophysical system. Rockström et al.  
127 (2009) frame boundaries in terms of a risk of crossing thresholds that *'trigger non-linear, abrupt*  
128 *environmental change within continental- to planetary-scale systems'*. However, they include some  
129 processes in the framework (such as freshwater use, and biodiversity loss) where the changes are  
130 progressively incremental (not abrupt), the processes of environmental degradation play out  
131 fundamentally at the local level, and the causal connection from local perturbation to large-scale change  
132 is possibly quite weak. Nordhaus et al. (2012) and Brook et al. (2013) responded to that conceptual  
133 looseness, arguing that there is no 'planetary tipping point' for several of the planetary boundary  
134 processes, and concluding that if global constraints are created for the regionally heterogeneous  
135 biophysical processes (aside from their impacts on climate) then misguided policies will arise.

136  
137 It is an open question how important 'tipping points' actually are for each of the planetary boundaries.  
138 While tipping points have been hypothesized at the global level, their exact position has not been  
139 determined and is likely impossible to determine for most processes (Clark, 2011 ), and will often only be  
140 known years after they have been passed. It seems that the focus should be much more on sustaining  
141 the interplay of global physical, biogeochemical and ecological processes at a level that appears  
142 sustainable (and in accordance with human acceptance of environmental degradation and risks) than on  
143 finding arguments on absolute tipping points per se. In that sense some of the criticism might, in our  
144 view, be misguided by the focus of Rockström et al. (2009) on tipping points. A great deal remains to be  
145 investigated in terms of Earth system thresholds, and the human-environmental feedbacks that affect  
146 their position.

147  
148 Some important policy questions relating to this type of question are: "Which issues are substantial  
149 enough to select for international policy making processes (agreeing on actual boundaries or targets) and  
150 how do these relate to other issues?" and "Are policy approaches that are based on a negotiated set of  
151 fixed targets – like the SDGs – appropriate in light of scientific information about complex global  
152 biophysical dynamics?" And finally, "What kinds of governance processes, institutions and policies are  
153 needed to respond to systemically connected global environmental risks?"

154  
155 ***Type 2 – Impact diagnosis:***  
156 **What is the causal chain for the different processes focusing on societal impacts? What are *acceptable***  
157 **levels of pressure and how does this affect boundary positions?**

158 One interpretation of the planetary boundaries concept is the suggestion that staying within the  
159 boundaries is not associated with environmental risks, while crossing them leads straight to a high risk of  
160 'unacceptable environmental change'. Steffen et al. (2015) explains that the planetary boundaries  
161 framework applies the precautionary principle. While crossing a boundary does not necessarily directly  
162 lead to a catastrophic outcome, it increases the risk of regime shifts, destabilized system processes or  
163 reduced resilience, so the boundary value is set at the lower, 'safe' end of the zone of uncertainty about  
164 such threshold changes. Many questions still remain in this approach, particularly with regard to the  
165 societal impact of crossing boundaries. The risks that are referred to are altered likelihoods of  
166 biophysical change, not the likelihood of unwanted social impacts. In fact, the social dimensions of global  
167 sustainability are not dealt with at all in the planetary boundaries framework, even though *a)* human  
168 activities are the drivers of change, *b)* the nine processes have been selected on the basis that when they

169 change, the safe operating space for humanity shrinks, and c) the connection from biophysical state  
170 change to societal impact will need to be made in order to mobilize policy responses for impact  
171 mitigation and adaptation.

172  
173 A similar question remains as to whether unacceptable environmental and societal impacts are also  
174 associated with much lower levels of anthropogenic perturbation (Schlesinger, 2009). For instance, the  
175 350 ppm CO<sub>2</sub> level proposed by Rockström et al. (2009) is associated with a global warming of 1.5°C,  
176 which results in environmental risks such as the loss of unique ecosystems, and sea level rise that could  
177 result in serious impacts in low lying areas – and in fact, climate impacts are already reported now (IPCC,  
178 2014). In other words, in most cases there will be little biophysical evidence about what changes (and  
179 what rates of change) are too large to deal with, and thus setting boundaries will be much more a  
180 societal choice on ‘what changes or risks are acceptable’ than a biophysical necessity (see also Nordhaus  
181 et al., 2012, Brook et al., 2013, Lövbrand et al., 2015). This suggests that the interactions among targets  
182 becomes a critical factor, given these are almost surely not simply additive.

183  
184 A further challenge is that the Earth System is a complex, integrated system, which means that the  
185 boundaries are in fact interdependent. For example, the nitrogen and carbon cycles are tightly linked  
186 and deforestation will impact water availability via impacts on retention time of precipitation in  
187 ecosystems before reaching rivers and by influencing precipitation patterns (Foley et al., 2005). Crossing  
188 one boundary will affect the position of the others. There is a critical need for new integrative research  
189 to underpin the boundaries, by identifying the causal chain of environmental change (or more  
190 mechanistically, ‘dose-response’ functions) for the different boundaries in terms of impacts associated  
191 with particular drivers and rates of environmental change, clarifying the potential links between  
192 biophysical and social system thresholds, and determining possible boundary positions. A systemic  
193 analysis of the interactions among the processes is still needed, because these interactions are a major  
194 reason for the large uncertainties in defining boundary positions.

195  
196 Since human activities determine many of the interactions, and alter them in unprecedented  
197 ways, this analysis must also explicitly address human-environment interactions. The causal  
198 chains of environmental change are strongly determined by the interactions *between* the  
199 biophysical and human systems, and are not only a product of the biophysical system (as  
200 sometimes seems to be implied in the simplified planetary boundaries framing). For example, not only  
201 the impacts *of* climate change, but also the efficacy of responses *to* climate change, are known to be  
202 affected by levels of equity (e.g. (Mearns et al., 2010). The key policy question here is thus simply at  
203 what levels to set the boundaries. This is partly determined by acceptable human impacts of increasing  
204 pressures, such as damage costs or health impacts, but also by biophysical impacts. It is crucial to note  
205 that there are no biophysical laws that strictly determine target levels; these depend on human choices  
206 of acceptable risks and levels of change. The research community should therefore carry out inclusive  
207 cost-benefit analysis (ie. including non-economic, long-term social and environmental values) of different  
208 planetary boundary targets, taking into account the interrelations between the different boundaries.

209  
210 ***Type 3 – Response and scenario analysis:***

211 **How can societies remain within the planetary boundaries while at the same ensuring a sustainable**  
212 **human development?**<sup>1</sup>

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

226  
227 There is now a critical need for transdisciplinary analysis of what a coherent set of actions looks like that  
228 allows planetary boundaries and human development goals to be met at the same time, particularly  
229 given the agreement on the SDGs. Such analysis can focus on individual boundaries, but it must also  
230 address the question of how multiple boundaries can be respected. Because boundaries are connected  
231 to each other in complex ways, a partial analysis focusing only on one boundary or solving only one issue  
232 at a time has a serious risk of shifting the problem elsewhere. A conceptual strength of the planetary  
233 boundaries framework is therefore its systemic approach, calling for attention to be paid to multiple  
234 environmental issues together. Some recent research has been published (PBL, 2012, van Vuuren et al.,  
235 2015, Riahi et al., 2012) focusing on response strategies that achieve multiple goals, and their associated  
236 synergies and trade-offs.

237  
238 The type 3 policy questions aim to identify the different options to reduce environmental pressures and  
239 improve societal wellbeing; understanding the levers of change required in both the human and Earth  
240 systems to meet planetary boundaries and sustainable development goals (e.g. technology and lifestyle  
241 change); and characterizing the synergies and trade-offs among different options, and their overall costs.  
242 There clearly is a regional dimension to this effort, as for both planetary boundaries and SDGs most of  
243 the targets are formulated at the global level, but policies are usually implemented at the national level.

244

245 ***Type 4: Implementation analysis:***

246 **How can different response strategies actually be implemented?**

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

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<sup>1</sup> 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.

254  
255 The question of how to implement pathways for a global sustainability transition relates to the different  
256 societal actors (including scientists) that are involved in these transitions, their individual and mutual  
257 interests, and their responses to policy instruments. To some degree, models can inform these issues  
258 (e.g. models assessing the consequences of responses to different policy instruments, models looking at  
259 a specific sector's or nation's interests and, increasingly, actor-based models for issues like the dynamics  
260 of adaptation, structural change and policy/technology diffusion). However, in many cases the necessary  
261 knowledge is likely to come from more diverse sources, in both lay and expert-professional knowledge  
262 communities, with generic insights into transition processes and the interests of different actors,  
263 particularly of winners and losers from significant change. Effective action-oriented research in this  
264 category is therefore likely to involve participatory processes as well as a concerted effort by researchers  
265 to bridge across multiple academic disciplines.

266  
267 Key questions in this area therefore include understanding the role of specific actors, both within  
268 countries and possibly even the countries themselves within processes playing out at the international  
269 level; the influence of financial instruments versus regulation versus the provisioning of information to  
270 societal actors (linked to the respective roles of markets, governments and civil society); and the  
271 relationship between sustainable development transitions and other current events.

#### 272 273 **The combination of the different types of questions**

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

281  
282 A question that cuts across all of the categories is how to address scale. Geographic scale plays an  
283 important role on the biophysical side, and thus for question types 1 and 2 – but also in terms of relevant  
284 response strategies as in most cases policies will need to be formulated and accepted at the national  
285 level.

286

### 287 **3 Methods to study Planetary Boundaries-related questions and strategies for** 288 **integration**

289  
290 Answering the different categories of questions raised in the previous section is not easy. Information  
291 that looks across multiple sets of interactions and decision-making on different time, space and  
292 organisational scales is needed. The questions also deal with interactions between human and  
293 biophysical systems<sup>2</sup>. In fact, Rockström et al. (2009) themselves indicate that the planetary boundaries  
294 concept was informed by Earth system science, insights from social-ecological resilience research, and

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<sup>2</sup> 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.

295 ecological economics. While recent years have seen major progress in cross-disciplinary integration in  
296 global change research (Moss et al., 2010, Van Vuuren et al., 2012), it is clear that answering the  
297 integrated questions raised above still presents immense challenges (Brown et al., 2015).

298  
299 Quite sophisticated research methods are needed to address these challenges. These methods range  
300 from qualitative case studies to quantitative model exercises. In this paper, we mostly focus at  
301 quantitative modelling tools developed by different disciplines as a means to represent and explore  
302 cross-scale linkages (spatial relationships), relationships between environmental issues, and time-related  
303 issues, and to deal with other sources of uncertainty. It is clearly evident that models have limitations  
304 too, as we will discuss further in this article. In that sense, it might be useful to distinguish at least three  
305 layers of reality that have a bearing on the relevant processes (following de Vries, 1992): 1) the physical  
306 world of tangible elements, like land-use, human infrastructure and climate change, 2) the world of  
307 intangible elements such as regulations, markets and prices governing behaviour, and 3) the underlying  
308 culture and lifestyle of humans. In general, mathematical models are most usefully applicable for those  
309 systems in which generic rules can be derived, which mostly concern the first and partly the second  
310 layer.

311  
312 In model-supported research on the four question types raised in Section 2, the challenge is to find a  
313 useful mix in being broad enough to answer the holistic questions – but still be able to control the  
314 complexities involved. Below, we briefly discuss several types of research approaches relevant for  
315 planetary boundaries analysis and also the way these approaches are trying to address the trade-offs  
316 between model comprehensiveness and complexity (see Figure 1).

317  
318 One major field of relevant approaches is represented by so-called *Earth System Models* (ESMs; Table 2).  
319 These models have been used to study global environmental change problems from a geo/biophysical  
320 perspective. While many Earth system models exist, starting from different traditions (e.g. hydrology or  
321 air pollution), the most advanced ESMs consist of combinations of climate models (general circulation  
322 models, which determine the global distribution of energy) and models of land vegetation dynamics and  
323 ocean biogeochemistry (Scholze et al., 2012, Hajima et al., 2014). Increasingly, global hydrological  
324 process models (that resolve global water balance) are also becoming an important class (Gerten et al.,  
325 2013, Arnell and Lloyd-Hughes, in press). Earth system models are complex in terms of the number of  
326 processes modelled. Yet, by focusing on the natural system they can rely on a rigid framework of natural  
327 science laws, avoiding the additional complexities of describing issues like human choice and behaviour.  
328 Typically, these models describe human influences at best as an exogenous ‘scenario’ input. To date, the  
329 high priority given to climate change in both research and international policy has meant that these  
330 models are designed to address questions relating to climate interactions, such as the carbon cycle and  
331 land-use. These types of models have a major contribution to the type 1 and type 2 questions raised  
332 earlier, but lack ways to describe the possible feedbacks with human systems and the trade-offs  
333 between human system and environmental targets. A key question is whether the feedbacks included in  
334 these models (and model output) can also identify the thresholds and tipping points (or more broadly  
335 the dose response relationships) discussed for type 2 questions. This is far from easy as this depends on  
336 complex, non-linear processes that are hard to include in models, partly because they are not observed  
337 in the present system. A list of possible key feedbacks and the underlying processes such as  
338 hypothesized by Lenton et al. (2008) could provide a research agenda for improving the representation  
339 of these processes in the ESM models. Other model types (such as those discussed below) will be too  
340 simplified in the representation of the Earth-system to add much useful information here.

341



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

363  
364 One could potentially define a group of models focused on the human system (Table 2). It is, however,  
365 hard to define a coherent set of these models given the wide range of social topics studied (as argued by  
366 Goldspink (2000) - and the disciplinary focus of many human system models (e.g. economics,  
367 demographics or health). One clear subgroup includes economic models, but even in this group, one can  
368 distinguish different sets such as growth models (focusing on factors determining long-term economic  
369 growth), general equilibrium models (focusing on the dynamic interactions between different sectors  
370 and production factors), econometric models (such as input/output models), and agent-based models.  
371 General equilibrium models allow, for instance, the identification of least-cost policy responses to  
372 climate change, including the consequences for various sectors as well as trade impacts. Clearly, human  
373 system models are relevant for specific topics related to human development (type 3) and the  
374 implementation of response strategies (type 4). They need, however, to deal with high degrees of  
375 complexity (and consequent uncertainty) associated with human behaviour. For instance, many  
376 economic models do so by assuming economically efficient behaviour, assuming a central agent (instead  
377 of describing individual actors), and by focusing on relatively short-term issues to avoid long-term  
378 uncertainties.

379  
380 Finally, there is a large number of models embracing approaches that focus on identifying system  
381 behaviour of combined human/Earth systems, focussing specifically on the representation of underlying  
382 process behaviour of actors and institutions (Schlüter et al., 2012, Rounsevell et al., 2012, Heckbert et al.,  
383 2010, Weber et al., 2005, Heitzig and Kittel, 2015). These include, for instance, some of the agent-based  
384 models and network analysis. Also here strategies are needed to deal with increasing complexity. Some  
385 of these models do so by focusing on specific issues, but others decide to focus more on the behaviour of  
386 the system than on real world outcomes. In these models, the technique used to avoid too much  
387 complexity is abstraction. In Table 2, we have summarized this category as abstract, process-oriented  
388 models.

389

390 Cooperation among different model approaches is needed to further insights (Verburg et al., 2015)– but  
391 faces similar trade-offs between relevance to the questions at stake, comprehensiveness and complexity.  
392 While developing integrated human/Earth system models has frequently been mentioned as an  
393 important way forward (see also discussion by Lucht, this special issue), there may be easier and more  
394 flexible forms of integration or cooperation (Van Vuuren et al., 2012). Given the complexity of some of  
395 the questions derived in Section 2, different forms of cooperation need to be considered, based on the  
396 strengths of the individual approaches – hence also the title of this article, “Horses for Courses”. This  
397 idea in fact also complies to one of the principles for successful interdisciplinary research identified by  
398 Brown et al. (2015), emphasizing the need to connect to specific disciplines as well as to interdisciplinary  
399 research questions.

400 The three different forms of cooperation we distinguish are:

- 401 1. Offline exchange of information between model types. This is a useful approach where  
402 feedbacks are thought to be relatively weak or relatively easy to capture via simplified  
403 representations.
- 404 2. Improve the representation of one model type within another. For example, IAMs could be  
405 expanded somewhat to represent better the behaviour of the Earth system by including  
406 representation of other planetary boundaries. IAMs could also be expanded with a cohort  
407 component population model, or an in-depth representation of the economy to introduce  
408 feedbacks of environmental change on population dynamics and economic growth. The  
409 representation, however, would need to fit the IAM idea of simplification. Another example of  
410 this approach is to improve the representation of the human system in ESMs by adding simple  
411 ‘behavioural rules’. This approach would not aim to truly represent human systems in ESMs but  
412 rather apply meta models that describe the main behaviour of human systems in a simplified  
413 manner. An example here would be land-use allocation rules.
- 414 3. Fully couple different model types, to create models that fully cover both human and earth  
415 system behaviour in full possible detail. This approach would allow for a more intensive  
416 interaction that could also capture strong, non-linear feedbacks. This, however, comes at the  
417 costs of greater complexity (also in terms of cross-disciplinary cooperation and model  
418 benchmarking). Complexity here also relates to the issue of scales, in both space (economy scale  
419 versus a detailed geographic grid representation required for biodiversity or water scarcity) and  
420 time (short-term focus of economic models versus long-term focus of earth-system models).

421  
422 The cooperation across different disciplines and research communities is only beginning to take off (e.g.  
423 cooperation between hydrological teams and IAM teams; the cooperation between ESMs and IAMs, and  
424 atmospheric chemistry models and IAMs). This means that in most cases it will be more interesting to  
425 test the existence of possible feedbacks in linkages using somewhat simpler approaches than directly  
426 aiming for the most complex forms of interaction.

#### 427 **4 Example applications**

428 We will here briefly discuss what further research could look like for three example planetary  
429 boundaries. Earlier Van Vuuren et al. (2012) provided a detailed list of questions and approaches for  
430 climatic change research in relation to model cooperation. The category types proposed in Section 2 in  
431 fact align well with the boundaries of the three working groups of IPCC for climate change (question type  
432 1 with Working Group 1, question type 2 with Working Group 2, and question type 3 with Working  
433 Group 3, and question type 4 with Working Group 2 and 3). Clearly in the field of climate research  
434 considerable progress can also be made by strengthening the research across the disciplines associated

435 with each of the Working Groups. Here we briefly discuss the issue of water, nutrient management and  
436 biodiversity.

437

#### 438 *Water.*

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

448

449 For type 3 questions, water is increasingly being included in IAMs (Hanasaki et al., 2013a, Hanasaki et al.,  
450 2013b, Dooley et al., 2013, Bijl et al., 2015) to address the water-land-energy nexus and the role of water  
451 in sustainable development strategies (Hoff, 2011, van Vuuren et al., 2015). Proper analysis requires fine-  
452 scale population maps. The recent publications of the IPCC Shared Socioeconomic Pathways (van Vuuren  
453 et al., 2014) seems a way to couple comprehensive water demand scenarios to more detailed  
454 hydrological models. This will enable expected changes in water demand to be brought to the scale of  
455 countries and catchment areas.

456

#### 457 *Nutrient management*

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

475

#### 476 *Biodiversity*

477 It is widely acknowledged that biodiversity underpins ecosystem functioning hence providing ecosystem  
478 services essential for human well-being (TEEB, 2011, MA, 2005, Hooper et al., 2012). The currently  
479 proposed control variables to be used for the planetary boundary on biodiversity (biosphere integrity)  
480 are genetic diversity and functional diversity, indicated by the extinction rate and the biodiversity  
481 intactness index (Steffen et al., 2015). In addition, Mace et al. (2014) proposed a wider range of  
482 variables, including biome integrity. While there are several models that address the impacts of human

483 pressures on biodiversity, including on functional diversity (Alkemade et al., 2009, Visconti et al., 2015),  
484 there is a lack of tools that address the link between ecosystem functioning and ecosystem services. This  
485 lack of tools actually means that Type 1 and 2 questions are still very difficult to address. While there is  
486 some research that addresses the first part of Type 1 questions (Cardinale et al., 2012, Hooper et al.,  
487 2012), to properly address the Earth system thresholds for human development still requires a better  
488 understanding of the link between biodiversity and ecosystem functioning. For the Type 2 questions  
489 there is generally knowledge about the role of ecosystem degradation on ecosystem services, while the  
490 societal impacts (for example on health and recreation) are more problematic. Type 3 questions can be  
491 addressed with current available IAMs that include a wide range of drivers. For instance, they include  
492 land-use change, nitrogen deposition and climate change, that are linked to specific biodiversity  
493 indicators (van Vuuren et al., 2015). However, properly addressing these types of questions requires  
494 clear answers for Type 1 and Type 2 questions. The biodiversity context shows how IAMs can also be  
495 used for Type 4 challenges, as IAMs are being applied to look into progress towards the Aichi Biodiversity  
496 Targets (Tittensor et al., 2014) and goal structuring for the SDGs (Lucas et al., 2014).

#### 497 **4. Conclusions**

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

- 510 • **There are several key questions with respect to the characterization of planetary boundaries**  
511 **and the consequences of policies designed to remain within them. These questions can be**  
512 **categorised in four key categories.** The planetary boundaries framework has been proposed as  
513 an important framework to derive targets and indicators in the context of global sustainability. In  
514 that case, the framework should be used in conjunction with a set of development targets. The  
515 research questions that are still connected to this framework are divided in this paper into four  
516 key categories, related to the 1) understanding of the underlying processes and selection of key  
517 indicators, 2) understanding the impacts of different exposure levels and influence of  
518 connections between different types of impacts, 3) a better understanding of different response  
519 strategies and 4) understanding the available options to implement changes. Together, these  
520 four types of questions provide a structured research programme for global environmental  
521 change problems.
- 522 • **Different types of analytical (modelling) tools can play an important role in analysing the key**  
523 **questions for the planetary boundary framework.** The formulated questions are complex: they  
524 involve relationships in time, across the different boundaries and across different geographical  
525 scales. Based on the grouping of the four very distinct types of questions, it is clear that insights  
526 of multiple scientific disciplines are needed to address the questions. Modelling tools (together  
527 with other research methods) are useful to analyse these complex relationships in more detail.  
528

529 In the paper, we both indicate how these models (and in particular earth system models and  
530 integrated assessment models) relate to the four categories of questions but also how further  
531 insights can be obtained by connecting the different disciplines (without necessarily fully  
532 integrating them).

- 533 • **It is important to increase interdisciplinary cooperation. Different existing modelling traditions**  
534 **can contribute in different ways to relevant insights on planetary boundaries. A richer picture**  
535 **– and one that can inform action – comes from combining these perspectives.** In this paper we  
536 have looked at different classes of models relevant for planetary boundaries research. Better  
537 cooperation across the different disciplines is needed to help inform policy makers about the  
538 four key question categories. It should be noted, however, that cooperation could be improved  
539 in different ways. Often exchanges of information between different types of models would be  
540 sufficient to make scientific progress. Fully linking different model types is also possible and  
541 could enable the study of feedbacks, but runs the risk of providing a description of the issues  
542 that is too complex, and hence that does not necessarily improve insights as much as exchanging  
543 information across the different modelling disciplines.

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549 **References**

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551 **Table 1: Typology of key questions 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?	<ul style="list-style-type: none"> <li>Well-characterized natural dynamics – so that human perturbation is detectable, attributable</li> <li>Decomposable multi-dimensional natural dynamics</li> </ul>	<ul style="list-style-type: none"> <li>Well-characterized system properties – 'stable states'/regimes and thresholds</li> <li>Clear causal links between environmental and social change (endogenous or exogenous/scenario)</li> <li>Defined drivers of change, relationships across different boundaries and human development goals</li> </ul>	<ul style="list-style-type: none"> <li>Detailed description of key linkages across different planetary boundaries</li> <li>Both spatially and institutionally resolved information</li> <li>Transparency for diverse users</li> </ul>	<ul style="list-style-type: none"> <li>Diverse potential opportunities across multiple actors</li> <li>Ways of accounting for winners and losers</li> <li>Transparency for diverse users</li> </ul>

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553

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

	<i>Earth System Models</i>	<i>Integrated Assessment Models</i>	<i>Human system models (economy models)</i>	<i>Abstract, process-oriented models</i>
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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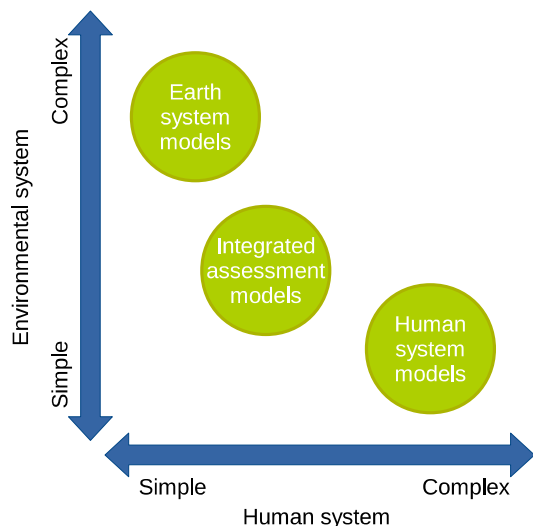


Fig. 1. Different models relevant for integrated sustainable development/Planetary Boundaries research

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