Supplementary Information

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Supplementary Discussion

1. Dynamics of system change

In our analysis we seek to identify situations in which the response of global or regional scale systems have thresholds rather than responding gradually to changing conditions. We draw on analysis of ecosystem dynamics displayed in Fig. S1, which is of relevance also to important sub-systems of the Earth system. The most pronounced version of such thresholds arises if the equilibrium curve of the system has a so-called catastrophe fold (Fig. S1 c). In that case three equilibria can exist for a given condition. The arrows in the graphs indicate the direction in which the system moves if it is not in equilibrium (i.e., not on the curve). It can be seen from these arrows that all curves represent stable equilibria, except for the dashed middle section in panel c. If the system is pushed away a little bit from this part of the curve it will move further away instead of returning. Hence equilibria on this part of the curve are unstable and represent the border between the basins of attraction of the two alternative stable states on the upper and lower branches.

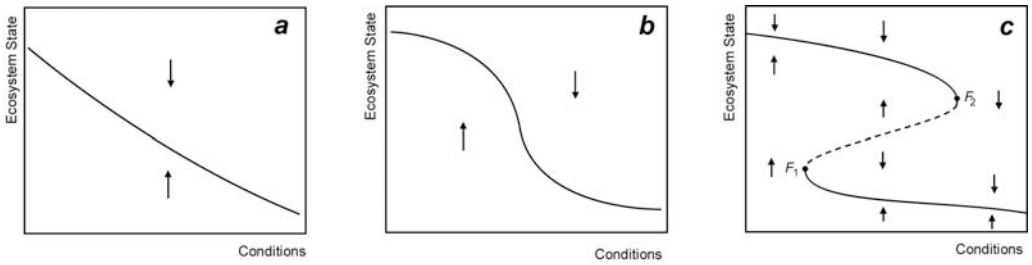

Figure S1. Different ways ecosystems can respond to change in conditions such as nutrient loading, land use change or temperature rise. Systems can respond smoothly to change in conditions (Fig S1a), they can sometimes change profoundly when conditions reach a critical level (Fig S1b) or have more than one stable state over a range of conditions (hysteresis) (Fig S1c). For **a** and **b** only one equilibrium state exists (as shown by arrows) for each change in conditions. For **c**, when the equilibrium curve is folded backwards three equilibrium states exist for a given condition. The equilibrium at the dashed hysteresis section is unstable and represents the border between basins of attraction of the two stable states on the upper (desired) and lower (undesired) branches. Source: Scheffer et al. (2001). Reproduced with permission of Earthscan Ltd www.earthscan.co.uk

Intuitively, sudden large shifts in the state of a system may be explained from massive perturbations of their conditions (Fig. S2a). However, systems with thresholds (Figs. S1 b and c respectively) may respond sharply even upon minor perturbations. For instance, if the system is very close to a fold bifurcation point (e.g. point F_1 or F_2) a tiny change in the condition, may cause a large shift to the lower branch (Fig. S2d). Also, close to such a bifurcation a small perturbation can push the system across the threshold between the attraction basins (Fig. S2c). Thus those bifurcation points are tipping points where runaway change can produce a large transition in response to a tiny perturbation. Small perturbations can also cause large changes in the absence of true bifurcations, provided that the system is very sensitive in a certain range of conditions (Fig. S2b).

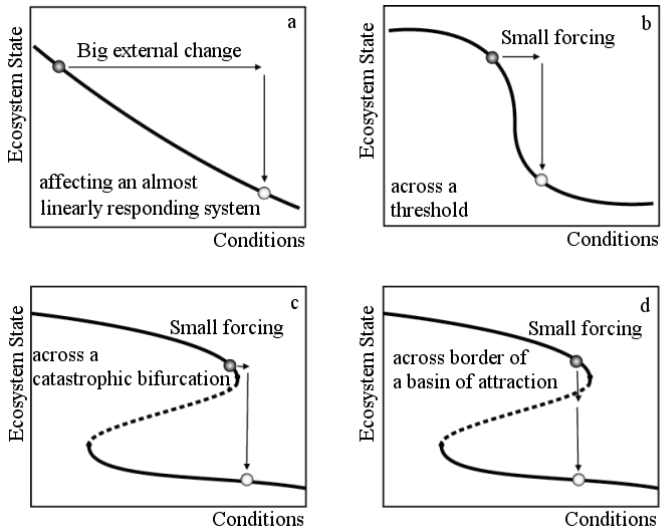

Figure S2. Degree of change in conditions required to generate large impacts in system state. For systems characterized by non-linear threshold dynamics a small forcing can generate large change, while systems responding largely linearly to change, will require big external change to cause large impacts. Source: Scheffer (2009).

In the analysis of planetary boundaries and associated threshold dynamics we have included Earth system processes that (to the best of our knowledge) present any of the three response behaviors to change represented in Fig. S1 (systems predominantly responding with linear gradual change (Fig. S1a), threshold behavior (Fig. S1b) and systems with a pronounced hysteresis effect (Fig. S1c)).

Our focus though is to identify planetary boundaries among processes in the Earth system that allows humanity to avoid non-linear and abrupt change (i.e., Fig. S1b and S1c dynamics). Our analysis indicates that this requires a broad diagnostics of the inter-connected nature of all Earth system processes (i.e., also systems with slow linear change dynamics), as these often constitute the key underlying parameters determining the resilience of the system, in this case the capacity of a system associated with non-linear threshold behavior to stay on the safe side of a non-desired threshold. Our key emphasis in this paper is to identify the risks of crossing thresholds due to non-linear change in key Earth system processes. Of largest concern are those non-linear changes that may be abrupt and irreversible. However, non-linear change may be both slow and reversible, and be caused by multiple drivers of change, including interactions between slow changing variables following essentially linear dynamics (over long time periods) and rapidly changing non-linear variables.

For example, while the climate sensitivity to fast feedbacks (water vapour, clouds, sea ice melt, aerosol change) triggered by a doubling of greenhouse gases (GHG) generally is estimated at ~3°C, slow feedbacks as a result of reinforcing sub-system interactions (as a result of slowly changing variables affecting surface albedo and shifts in sinks of greenhouse gases) may raise the sensitivity to ~6°C (Hansen et al., 2008).

While the nature of change dynamics is increasingly well understood for local ecosystems (such as lakes and terrestrial biomes) (Scheffer et al., 2001; Bellwood et al., 2004; Gordon et al., 2008), there is a need for more research in understanding the change dynamics for ecosystems and Earth system processes across temporal and spatial scales. The complexity is large, as although certain ecosystems present more pronounced non-linear dynamics than other systems, the response is not a fixed

property of a system but can instead vary depending on other parameters (e.g., the depth of a lake may determine the dynamics of turbidity change to increased nutrient loading (Scheffer and Carpenter, 2003)).

2. Setting boundaries – comparison with other approaches

For comparison of boundary-setting approaches, there are several relevant strands of literature: legal interpretations of the precautionary principle and the critical load concept; risk management; pollution, resource extraction and nature conservation standard-setting frameworks; global resource use forecasting models; environmental decision-making tools; etc.. Generally, these various approaches differ in terms of purpose (e.g., defining boundary conditions as input to or output of the main analysis), precision, geographical scale, and which part(s) of a cause-effect chain are considered (i.e., whether driving force, pressure, state, impact or response variables are of interest, see EEA 1999). With these differences in mind, selected examples of approaches are compared with the planetary boundaries approach below, in terms of choice of variables, the normative-scientific interface, and application of the precautionary principle.

An approach commonly used in recent years is to develop a suite of scenarios depicting possible futures. The IPCC suite of scenarios (Nakicenovic et al. 2000; Fisher et al. 2007) and the Millennium Ecosystem Assessment scenarios (MEA 2005a) are two prominent examples. In general, scenarios explore the development of the relationship of human activities to environmental change but they do not attempt to identify key environmental parameters or boundaries associated with those parameters. Perhaps the IPCC stabilisation scenarios, which involve targets of maximum atmospheric CO_2 concentration at stabilisation, come closest to defining boundaries, but the CO_2 concentrations are not linked to specific thresholds or other features of the climate system.

One of the first attempts to analyse and quantify natural boundaries at the global level using a scenario approach is the set of World3 model simulations reported first in the Club of Rome's 1972 *Limits to Growth* report (Meadows et al. 1972), later revised twice (Meadows et al. 1992, 2004). Scenarios were constructed based on modelling of socio-economic variables (global population, food per capita, services per capita, industrial output per capita) and non-renewable resources and persistent pollution[i]. While the *Limits to Growth* approach argued that global ecological constraints would influence global development by diverting much capital and manpower to battle these constraints, it "did not specify exactly what resource scarcity or what emission type might end growth... simply because such detailed predictions can not be made on a scientific basis in the huge and complex population-economy-environment system that constitutes our world" (Meadows et al. 2004). The analysis thus did not foresee non-linear dynamics and abrupt change due to crossing of thresholds or points of overshoot, but instead that gradually increasing capital would need to be diverted to cope with resource and pollution problems to the extent that growth in industrial output would cease.

Among the variables modelled, persistent pollution is the one most relevant to the planetary boundaries concept. It represents the net effect of many different processes that sequester or convert long-lived toxic material ("such as organochlorines, greenhouse gases and radioactive wastes") so that they can no longer cause damage and is expressed as "the assimilation half-life of the environment – the time required for natural processes to render harmless half the existing pollution" (Meadows et al. 2004

p. 149). The authors acknowledge that they used a very optimistic estimate, namely that in 1970 the half-life of aggregate pollution was one year.

Comparing this approach with the planetary boundaries concept, there are several major differences. Beside the very high level of aggregation of the variable and the admittedly enormous uncertainty around the half-life assumption (Turner 2008), the description of the persistent pollution variable does not suggest that cumulative, non-linear threshold effects with potentially irreversible outcomes from pollution were considered. Further, there is no clear sophisticated understanding of the role of renewable resources or ecosystem services for the economy.

There are more similarities with the *Tolerable Windows Approach (TWA)* and its use of *'impact guardrails'*. TWA has been described as a climate policy guidance framework and was originally conceived by the German Advisory Council on Global Change (WBGU 1995) as an inverse methodology for proposing greenhouse gas (GHG) emission reduction strategies to avoid dangerous climate change. It has later been formalised methodologically (Bruckner et al. 2003) and applied with the ICLIPS model (Toth et al. 2002; Füssel et al. 2003). The approach starts with a set of hypothetical climate evolutions considered tolerable. Tolerability is related to two basic normative principles, "preservation of the Creation" and "prevention of excessive costs", which are treated as equally important constraints (WBGU 1995 p. 7). The principles are operationalised through the definition of impact guardrails, i.e., levels of climate change impacts perceived as intolerable by stakeholders and the level of tolerable economic cost (originally set at 5% of gross global product, GGP). The guardrails together delineate admissible climate change (the tolerable climate window). Through climate modelling, the concentration of GHGs over time and global emission profiles compatible with the tolerable climate window are then derived. The latter then inform development of emission targets and policy instruments.

From a boundary perspective, methods for defining guardrails for 'preservation of the Creation' are of interest, and comes very close to the normative planetary boundary assumption of sustaining a desired Holocene state of the Earth system. In the initial application, the ecological guardrail used a temperature range as a proxy for tolerable climate impacts, namely from 9.9 °C to 16.6 °C (representing fluctuation for the Earth's mean temperature in the late Quarternary period, plus 0.5 °C at both ends of the range). In addition, a maximum rate of temperature change of 0.2 °C per decade constituted a third guardrail since faster change would incur higher adaptation costs (WBGU 1995). The original definition of guardrails was later elaborated in the ICLIPS model, which facilitates geographical disaggregation. Climate impact response functions (CIRFs) provide the link from regionally acceptable impacts and the global climate change limit (Toth et al. 2002; Füssel et al. 2003). CIRFs are produced by driving multiple simulations of geographically explicit sectoral impact models with representative samples of future climate conditions. CIRFs had by 2002 been developed for agricultural crops, water availability, and natural vegetation. The ICLIPS model can run different guardrail levels (impact and socioeconomic) in a sensitivity analysis and thereby let policy-makers test different boundary levels.

Comparing TWA and planetary boundaries, guardrails in TWA are used as inputs for designing emissions strategies while the planetary boundaries approach as of yet focuses on boundary definitions only and not as a design tool of compatible action strategies. In principle, planetary boundaries could be seen as an extension of the TWA framework in that a more comprehensive set of Earth system processes, rather than those directly relevant to the climate system, are included. A fundamental difference, however, is that the planetary boundaries approach does not propose economic boundaries to be given equal weight, but that the ecological and biophsyical boundaries

should be non-negotiable, and that social and economic develop (should) occur within the safe operating space provided by planetary boundaries. From a conceptual and procedural perspective, however, key similarities include the concern with thresholds and discontinuities in the variables considered and the attempt to facilitate a clear division between scientific and normative judgments in the process. Finally, regarding application of the precautionary principle in relation to estimated thresholds, "broad" limits were used in the original TWA application to ensure that too pessimistic demands for climate policy would not result (WBGU 1995).

Using examples of more prevalent regional- and local-level methods for setting environmental standards, more detailed lessons can be learnt about the precautionary principle, i.e., where to set the boundary in relation to a more or less uncertain threshold location. However, reviews of how the principle has been applied in practice have shown the general lack of quantitative and precise interpretations (see Jordan and O'Riordan 1998; Raffensperger and Tickner 1998; Commission of the European Communities 2000; EEA 2001).

At the regional level, the *critical loads* concept and methodology was developed in the context of the United Nations Economic Commission for Europe (UNECE) convention on Long-Range Transboundary Air Pollution (LRTAP)[ii] (see Cresser 2000), and later used in European Union (EU) air pollution regulation. Like TWA, it is an effects-based or inverse approach to setting pollution limits, where the limits are derived from an assessment of critical levels of pollutants in different types of ecosystems upon which critical loads are estimated (Haines-Young et al. 2006). The official definition – "a quantitative estimate of an exposure to one of more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Spranger 2004 p. V-1) – suggests that there are several sources of uncertainty and normative judgement, such as what constitutes 'significant harmful effect', 'sensitive elements', and 'no occurrence' (e.g., zero or low probability). For example, it is considered unclear whether the concept means that a precautionary approach is adopted (i.e., setting a limit before *any* detectable damage has occurred) or the concept of maximum allowable damage (i.e., setting a limit where measurable damage can be shown) (Haines-Young et al. 2006; Skeffington 1999). While incomplete elimination of normative judgment can be expected, there is a lack of clarity and transparency on how the 'no damage' principle is indeed operationalised. Another aspect limiting the relevance of the critical loads methodology for defining planetary boundaries is that different critical loads are calculated for different regional ecosystems, whereas the planetary boundaries approach attempts to identify aggregate global boundary values (for boundaries including multiple drivers and processes by identifying the "weakest link in the process chain" and exploring the possibility of a global parameter that thereby can function as a global boundary – see e.g., our choice of aragonite saturation for ocean acidification).

A methodology offering a more precise interpretation of the precautionary principle is the *safe minimum standards* (SMSs) approach (Ciriacy-Wantrup 1952; Bishop 1978; Ready and Bishop 1991), which has been applied to environmental issues such as species population sizes, habitat designation for endangered species and water quality requirements. They specify a level below which a flow of defined ecosystem services or resources should not be permitted to fall. The rationale is to "minimise maximum possible social losses connected with avoidable irreversibilities" (Ciriacy-Wantrup 1952) and it has its roots in game theory and the minimax principle. Bishop (1978) demonstrates how an SMS approach is preferable to an 'extinction' approach, if there is a possibility of a catastrophic irreversible outcome and if the losses from extinction are higher than the present value of net benefits from the economic development leading to extinction.[iii] This suggests strong precaution. However, in reality losses from extinction

may be unknown, incurred on future generations rather than those making conservation decisions, i.e., the minimax strategy can be prohibitively conservative. Therefore, a modified minimax principle expresses the SMS approach: "adopt the safe minimum standard unless the social costs are unacceptably large" (p. 13). Clearly, what constitutes unacceptable cost is a normative decision that reflects risk preference (Farmer and Randall 1998).

Regarding setting the level of an SMS, the idea of non-linearity and thresholds was integral to the original conception of SMS (Ciriacy-Wantrup 1952). According to Margolis and Naevdal (2008), biologists and limnologists often treat thresholds as deterministic, whereas they would often be stochastic and the actual threshold location dependent on site specific conditions. Lacking sufficient data for establishing a deterministic threshold, they argue that probability bounds could be estimated. A bound below which the risk of catastrophe is zero is referred to as a risk threshold.

With its focus on thresholds the SMS concept is similar to the planetary boundaries approach. However, like other approaches it demonstrates the difficulty of escaping the need to make normative judgments on tolerable risk levels when setting a boundary in relation to a more or less uncertain threshold. Methodologies for estimating probability levels have been most systematically developed within the field of (environmental) *risk assessment*, although there is no unified guideline stemming from this practice regarding the probability level at which to set a boundary, i.e., at what point the precautionary principle should be triggered. This is generally characterised as a post-analysis normative decision for appointed decision-makers. Research on public perception of risk demonstrate the challenges in setting acceptable standards, where, for example, people tend to overestimate risks that are unseen, low probability but high magnitude, carcinogenic, involuntary, or inequitable (Slovic 1987). In health risk assessment, very low risk thresholds have typically been defined, such as 1/1,000,000. In environmental decision-making, higher risk thresholds appear to have been more common, such as 1/10,000 increased lifetime risk. However, these risk metrics are based on human life or health impacts (from medical or environmental risks). The planetary boundaries approach explicitly focuses on the Earth system's regulatory services, which even though directly linked to human welfare, are not easily captured in conventional risk assessment methodologies. Another potential problem with using quantitative risk assessment methods in the context of global environmental change is that it would be more difficult to construct reliable probability distributions.

To conclude, a comparative analysis of various approaches to address sustainable limits of boundary conditions, indicates that the proposed planetary boundaries approach can potentially fill a critical gap in the pursuit of sustainable development in the context of the Anthropocene. The two global-level approaches included in this assessment either did not address renewable resources and ecosystem services in a sophisticated way (Limits to Growth) or ecological boundaries were from the outset given equal weight as socio-economic boundary conditions (TWA). In order to draw useful lessons regarding application of the precautionary principle under conditions of uncertainty, more research on the actual practice of standard-setting is required. In the meantime, the conceptual framework for planetary boundaries proposes a strongly precautionary approach, by setting the discrete boundary value at the lower and more conservative bound of the uncertainty range.

3. Extended description of the climate change boundary

This discussion repeats the line of argument presented in the main body of the paper, but provides additional detail to support the suggested planetary boundary.

Limiting the magnitude of climate change is the most widely discussed planetary boundary around the world today. The debate is usually centred around (i) the definition of "dangerous climate change"; (ii) the upper limit of global mean temperature rise that will avoid dangerous climate change; and (iii) the stabilisation concentration of greenhouse gases that will maintain global mean temperature at or below the desired limit.

In our approach to setting the planetary boundary for climate change, we define dangerous climate change in broad terms as a significant departure from the patterns of natural variability that have typified the Holocene, the current interglacial period in which first agriculture and then human civilisations have developed. A more specific set of climate-related criteria could also be used to add detail to our definition. These criteria might include rapid sea level rise (~ 1 metre or more per century); disruption of regional climates through droughts, floods and other extreme events; and unacceptably large rates of biodiversity loss with consequences for the ecosystem services they support.

We take atmospheric CO_2 concentration as the proxy for radiative forcing due to changes in all greenhouse gas concentrations, on the basis that the current cooling effect of aerosols approximately counteracts the warming effect of non-CO_2 greenhouse gases. To account for possible changes in future in the relative effects of aerosols and non-CO_2 greenhouse gases, we also propose (below) a second, more fundamental boundary – change in the energy balance at the Earth's surface.

Returning to our atmospheric CO_2 concentration boundary, we propose a maximum concentration of 350 ppm, which implies that with a current concentration of 387 ppm we are already in overshoot. Three major lines of argument support our proposed boundary of 350 ppm CO_2.

The first, presented in detail in Hansen et al. (2008), is based on the use of palaeo-climatic data to analyse the equilibrium sensitivity of climate to greenhouse gas forcing and to explore the behaviour of the large polar ice sheets under climates warmer than those of the Holocene.

Climate sensitivity is currently estimated by the suite of models used in the IPCC assessments to be approximately 3 ^{o}C (a range of 2 – 4.5 ^{o}C) for a doubling of atmospheric CO_2 concentration above pre-industrial (IPCC 2007a). Most of the sensitivity is not due to the direct radiative effects of increasing CO_2, but rather to feedbacks within the climate system. Most contemporary climate models, however, include only "fast feedbacks", such as changes in water vapour, clouds and sea ice. An analysis of the change in radiative forcing and the observed temperature change between Last Glacial Maximum about 20,000 years BP and the Holocene includes "slow feedbacks" in the climate system, such as decreased ice area, changed vegetation distribution and inundation of continental shelves. When all of these feedbacks, which change the surface albedo, are included, the climate sensitivity becomes about 6 ^{o}C (a range of 4 – 8 ^{o}C) for doubled CO_2 concentration (Hansen et al. 2008). The implication is that the severity of climate change associated with current and projected greenhouse gas concentrations, as estimated by the current suite of models, is significantly underestimated.

Second, an analysis of the atmospheric, cryospheric, sea-level and climatic data from the Cenozoic era (from about 65 million years ago to the present) suggests that decreasing CO_2 concentration was the main cause of the observed cooling trend over that period (Hansen et al. 2008). Large ice sheets on Antarctica appeared about 34 million years ago, when atmospheric CO_2 concentration was in the range 350-500 ppm. The large northern hemisphere ice sheets appeared less than 10 million years ago, when CO_2 concentration and temperature were even lower. The Antarctic glaciation may have reversed temporarily about 26 million years ago (Lear et al. 2004), and the Laurentide and Fennoscandian ice sheets in the northern hemisphere have been reversible through the late Quaternary. These observations suggest that the glaciation that created the large polar ice sheets is reversible in climates associated with CO_2 concentrations in the 350-550 ppm range. There is, however, no consensus on possible hysteresis effects associated with major changes in ice cover.

Palaeo-observations from the most recent interglacial period about 125,000-130,000 years BP demonstrate the vulnerability of the large polar ice sheets. During that period sea level was 4-6 m higher than present, indicating that significant portions of the Greenland and West Antarctic ice sheets disappeared (Overpeck et al. 2006). Although Arctic summer insolation was roughly 11% greater than at present, the regional temperature differences of several degrees between then and now cannot be explained by the increased solar radiation alone but point to the strength of feedbacks in the climate system – reduced sea ice and the expansion of boreal forest northward at the expense of tundra in this case (CAPE Project Members 2006). It appears that the effects of changes in initial forcings – whether they be changes in incident solar radiation or GHG concentrations – are significantly amplified by these slow feedback processes.

The third line of argument is based on observations of the contemporary "387 ppm CO_2 climate", still far from equilibrium, which show that the climate is moving out of the envelope of natural variability characteristic of the Holocene. This supports our proposed planetary boundary of 350 ppm CO_2, beyond which the risk of dangerous climate change rises sharply. The observations include:

- A rapid retreat of summer sea ice in the Arctic Ocean (Johannessen 2008).

- Retreat of mountain glaciers around the world (IPCC 2007a) and an increasing rate of mass loss from the Greenland ice sheet (currently about 150 Gt yr^{-1}) and from the West Antarctic ice sheet (currently about 100 Gt yr^{-1}) (IPCC 2007a; Cazenave 2006).

- A four-degree latitude poleward shift of subtropical regions (Seidel and Randel 2006), contributing to increasing aridity in the Mediterranean region, the southern United States, eastern Australia, and parts of Africa.

- Increased bleaching and mortality in coral reefs, driven in part by ocean acidification and rising sea surface temperature (Stone 2007).

- An accelerating rate of sea-level rise in the last 10-15 years (Church and White 2006), with projections for a 0.5 to 1.4 metre sea-level rise by 2100 above 1990 levels (Rahmstorf 2007).

- A rise in the number of large floods (Milly et al. 2002; MEA 2005a).

Contemporary observations also indicate that some of the slow feedback processes associated with the carbon cycle and surface albedo are becoming activated. These observations include a weakening of the oceanic carbon sink over the past several decades (Le Quéré et al. 2007); loss of buttressing ice shelves and accelerating ice streams in Antarctica (Rignot and Jacobs 2002; Zwally et al. 2002); and increasing surface melt and increasing loss of ice mass in Greenland (Tedesco 2007; Chen et al. 2006).

As noted earlier, a second, more fundamental, climate change boundary is set by the change in the energy balance at the Earth's surface, measured by the change in radiative forcing in W m^{-2}. We estimate this boundary to be +1 W m^{-2}, which corresponds to global mean temperature increase of slightly less than 1 ^{o}C (it should be noted that following the IPCC formula for radiative forcing of CO_2 gives a 1.23 W m^{-2} forcing for a 350 ppm CO_2 concentration). At present the proposed CO_2 and radiative forcing boundaries correspond roughly to the same estimated degree of climate change, due to the cooling effect of aerosols that counteracts the warming effect of non-CO_2 greenhouse gases. The result is a net radiative forcing approximately equal to that of CO_2 alone (IPCC 2007a; Ramanathan and Feng 2008). However, this fortuitous relationship may not continue into the future as the atmospheric concentrations of other greenhouse gases may change and as efforts are made at local and regional scales to reduce aerosol concentrations due to negative public health impacts. This may require adjustments to the CO_2 component of the boundary. Humanity has already transgressed both components, with a current CO_2 concentration of ca. 387 ppm and a net anthropogenic radiative forcing of ca. +1.5 W m^{-2} (IPCC 2007a).

4. Extended description of the global freshwater use boundary

In the following we add further in-depth justification for the freshwater boundary presented in the main text of the paper.

The global water challenge

The global hydrological cycle sustains life on the planet and provides humanity with freshwater for ecosystem goods (all biomass production generating food, fiber, fuel, and terrestrial biodiversity, and habitat for aquatic species) and services (e.g., carbon sinks and climate regulation) (Falkenmark and Rockström 2004) and water for domestic and industrial uses (Falkenmark 1986). Human pressure is now the dominating driving force determining change in function and distribution of the global freshwater system, threatening biological diversity, and ecological functions such as carbon sequestration and climate regulation at regional and global level.

Recent analyses (Rockström et al. 2009) indicate that freshwater use to produce food (by far the largest freshwater consuming economic sector) will have to increase by 2000 – 4000 km^3 yr^{-1} by 2050 from the current ~7000 km^3 yr^{-1}. The range is due to different assumptions in water productivity improvements.

Freshwater is a finite planetary resource and functions as a control variable for several other planetary boundaries (e.g., regulation of water vapour feedbacks and organic carbon feedbacks in the climate system).

We adopt a green and blue water approach in analyzing planetary water boundaries (Falkenmark and Rockström 2004). The flows and stocks of freshwater in the global hydrological cycle are determined by the partitioning in blue water flows, i.e. surface

runoff and base-flow in rivers, groundwater, and lakes (the liquid water flowing through landscapes), and green water flows, i.e. vapour flow of evaporation and transpiration back to the atmosphere (Figure S3). Blue water flows sustain aquatic ecosystems, irrigated agriculture, and human water supply. Green water flows sustain terrestrial ecosystem services (rainfed food, forests, grazing lands, and grasslands) and regulates the terrestrial moisture feedback that sustains the bulk of the rainfall over land areas on Earth.

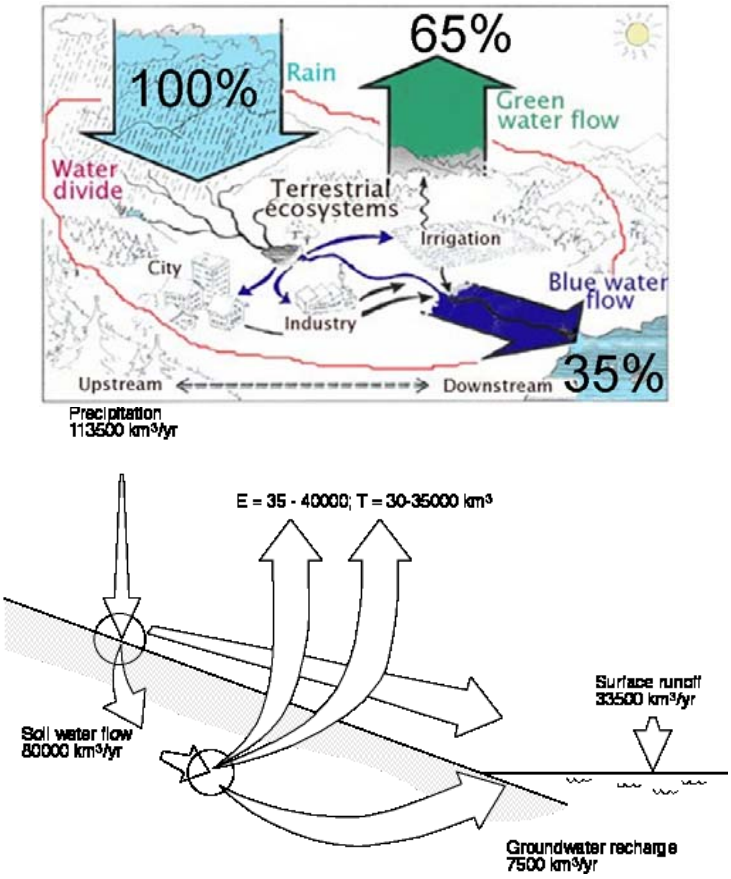

Figure S3. Partitioning of the global terrestrial hydrological cycle between runoff (surface and sub-surface flow) or blue water, and vapour flow from soil moisture or green water flow (1a); and estimate of flow partitioning into green vapour flows of evaporation (E) and transpiration (T) and surface and groundwater recharge (1b) (from Falkenmark and Rockström 2004, and based on Lvovich 1979). Reproduced with permission of Earthscan Ltd www.earthscan.co.uk

Green and blue water flows are intricately linked, where increased green water flows reduce blue water availability, and where decreased green water flows, reduces rainfall and thus on the long-term rainfall patterns and blue water generation. Furthermore, all consumptive use of water on the planet is in the form of green water flows, either directly from green water resources (infiltrated rainfall forming soil moisture in the root zone), or from evaporated blue water (from lakes, reservoirs, in irrigation schemes).

Catastrophic water related threats

Global freshwater resources circulate in a complex hydrological cycle, with water flows and stocks, determined by local to global interactions between land, ocean and atmosphere. Crossing water-induced thresholds causing catastrophes at planetary level may occur as a result of aggregate sub-system impacts at local (e.g., river basin) or regional (e.g., monsoon system) scales. A global water threshold may be crossed, if multiple sub-system thresholds are simultaneously crossed in many places on the planet, potentially resulting in planetary effects on Earth system processes (such as loss of carbon sequestration capacity or trigger of climate system changes due to cumulative changes in vapour concentrations in the atmosphere). They may also result in global social impacts, such as a collapse in food markets, famines and environmental refugees, due to regional or continental reduction on agricultural yields caused by changes in rainfall patterns and/or local water availability.

There is growing evidence of local and regional thresholds caused by agricultural changes in water quality and quantity (Gordon et al. 2008) (Table S1). It is particularly relevant to analyse water thresholds in agricultural systems, as crop and livestock production constitutes together with forestry the largest freshwater consuming economic sectors in the world.

Table S1. Regime shifts from agriculture changes in water quality and quantity, showing alternative regimes, consequences of the regime shift, key internal variables, agricultural drivers of change, other drivers and assessment of the evidence for the reality of each shift (Gordon et al. 2008)

Regime shift	**Regime A**	**Regime B**	**Impacts of shift from A to B**	**Internal slow variable**	**Agricultural driver**	**Other drivers**	**Evidence**
Freshwater eutrophication	Non-eutrophic	Eutrophic	Reduced access to recreation, drinking water, risk of fish loss	Sediment and watershed soil phosphorus	Nutrient and soil management	Flooding, landslides	Strong
Coastal hypoxic zones	Not hypoxic	Hypoxic	Fishery decline, loss of marine biodiversity, toxic algae	Aquatic biodiversity	Nutrient and soil management	Flooding	Strong
River channel position	Old channel	New channel	Damage to trade and infrastructure	River channel shape	Erosion, river channelization	Extreme floods, climate	Strong
Vegetation patchiness	Spatial pattern	No spatial pattern	Productivity declines, erosion	Vegetation pattern	Grazing, land clearing	Fires, droughts	Medium
Salinization	High productivity	Low productivity	Yield declines, salt damage to infrastructure and ecosystems, contamination of drinking water	Water table salt accumulation	Reduced evapotranspiration, irrigation	Wetter climate	Strong
Soil structure	High productivity	Low productivity	Yield decline, reduced drought tolerance	Soil organic matter	Biomass removal, fallow frequency	Droughts, dry spells	Weak
Wet savanna-dry savanna	Wet savanna	Dry savanna or desert	Loss of productivity, yield declines, droughts/dry spells	Moisture recycling, energy balance	Reduced net primary production and evapotranspiration	Droughts, fires	Medium
Monsoon circulation	Monsoon	Weak or no monsoon	Risk for crop failures, changed climate variability	Energy balance, advective moisture flows	Land cover change, irrigation	Change in sea surface temperature	Weak
Forest-savanna	Forest	Savanna	Loss of biodiversity, changed suitability for agricultural production	Moisture recycling, energy balance	Reduced net primary production	Fires	Weak
Cloud forest	Cloud forest	Woodland	Loss of productivity, reduced runoff, biodiversity loss	Leaf area	Land clearing	Fog frequency	Medium

There are two human driving forces that may threaten the stability of the quantitative flows in the global freshwater system; (i) human induced shifts in *green water* flows as a result of changes in precipitation (totals and patterns) and soil moisture generation, and (ii) human withdrawals of *blue water* impacting river flow dynamics.

Threats caused by changing green water flows can be related to either: (i) drying out of landscapes, due to land degradation and desertification (changes in soil moisture generation, or green water resource); (ii) moisture feedback from green water flow change causing shifts in precipitation (large shifts in green water flow from land-use, mainly related to deforestation). Both green threshold parameters (soil moisture availability and green water consumption) are linked to land-use change and affect the stability of the freshwater system, by shifting the balance between vapour flows and runoff, and subsequently river depletion.

We focus here on the highest risks of green water-induced threshold effects that may cause global impacts and conclude that the most volatile risks are concentrated in two regional hotspots: (i) rainforests concentrated in Latin America, Central Africa and South-East Asia, where changes in green water flows in those systems may alter for example regional monsoon patterns, and (ii) the savannah regions in the world, i.e., the dry semi-arid to dry sub-humid regions, hosting approximately 40% of global terrestrial ecosystems and providing a high degree of ecosystem services in biologically productive and diverse landscapes where water is the primary limiting biological growth factor.

Based on this reasoning, the following green water-related threats have been identified:

- Collapse of biological sub-systems as a result of regional drying processes, due to the existence of alternate stable wet and dry states, such as a wet and dry Sahel (Scheffer et al. 2001) and the risk of an irreversible savannisation of the Amazon rainforest as a result of reductions in green water flows (changing moisture feedback processes.
- Regional desertification when the green water resource declines below a critical threshold due to changes in rainfall patterns and land degradation
- Collapse in rainfed agricultural systems due to reductions in green water availability.

Blue water flows in rivers are determined by the partitioning of precipitation into green vapour flows and blue runoff flows, and the amounts of blue water withdrawals and use. For blue water withdrawals and use, beyond a certain level, river depletion leads to a whole set of threats, ecological as well as social:

- Collapse of *riverine ecosystems* due to stream flow reductions. Estimates indicate that 20-50 % of river flow needs to be safeguarded as environmental water flows to sustain aquatic ecosystem functions and services (Smakhtin et al., 2004; Smakhtin 2008).
- Collapse of the *estuary ecosystems*, leading to an ecosystem tipping point, replacing freshwater ecosystem with brackish water ecosystem.
- Collapse of *coastal ecosystems* when the river input decreases.

- Collapse of *internal lakes and their ecosystems*, Aral Sea being the classical example. As the shrinking lake ceases to influence the climate, positive feedbacks may further speed up evaporation. Decreasing inflow from the basin is at least a partial cause behind several cases of lake water level decrease (Lake Chapala, Lake Malawi, Caspian Sea, Dead Sea, Lake Victoria, Lake Chad). Arid zone lakes are particularly vulnerable.
- Collapse of *social irrigation-based systems* as demonstrated by several early irrigation-based civilizations.

Current water availability, consumption, and identification of boundaries

At a global level precipitation amounts to ~110,000-115,000 km^3 yr^{-1} with a variation of ± 15-25 % and an average runoff estimated at 42,500 km^3 yr^{-1} (with a range of 39,700-42,800 km^3 yr^{-1}) (Shiklomanov and Rodda, 2003) (Figure S3).

Green water

Total green water availability is ~70,000 km^3 yr^{-1} (Lvovich 1979), and estimates indicate that approximately 90% of the global vapour flows from land surfaces already today contribute to sustain terrestrial biomes (Rockström et al. 1999), including regulating functions such as carbon sequestration in soil and forests. Global food production, which causes the largest direct human manipulation of the freshwater cycle, consumes in the order of 7,000 km^3 yr^{-1} originating from river runoff (~2,000 km^3 yr^{-1}) in irrigated agriculture and soil moisture in rainfed agriculture (~5,000 km^3 yr^{-1}) (Rockström et al. 2007).

To avoid savannisation, green water generation (soil moisture from infiltrated rainfall), must be at least 900 mm yr^{-1} in tropical forests (Lvovich 1979). Similarly, analyses show that green water generation must reach a threshold of 300-500 mm yr^{-1} in order to generate blue water flows (Lvovich 1979), and in hot tropical regions productive grasslands and tree savannas only occur when green water resources reach in the order of 300 mm or above. This is the threshold, above which we start to experience sedentary rural societies practicing agriculture. Therefore, below this threshold, agropastoral and nomadic social societies have evolved, due to water scarcity.

Blue water

Estimates indicate that 12,500 km^3 yr^{-1} of river runoff is potentially available for human appropriation (Postel 1998), the rest of global runoff being constrained by remote location and storm flow.

The global withdrawals of runoff water amount to approximately 4,000 km^3 yr^{-1}, of which approximately 2,600 km^3 yr^{-1} consists of consumptive use (Shiklomanov and Rodda 2003), which has resulted in severe deterioration of aquatic habitats and water shortage for downstream water dependent social and ecological systems. An estimated 25 % of the world's rivers run dry during periods of the year due to river depletion (Molden 2007). By 2025 the risk is that a majority of the world's population will experience water shortage, while 30-35% will suffer chronic water shortage (i.e. < 1,000 m^3 of blue water availability per capita and year) (Shiklomanov 2003), indicating dramatic human pressures on the global freshwater system.

Constraints in the global water system have primarily been analysed from a human water shortage perspective (Falkenmark et al. 1989) and more recently from an environmental water flow perspective (King et al. 2003). Experience shows that severe water shortage is experienced when per capita availability falls below 1,000 m^3 yr^{-1} per capita. As shown by the UN Comprehensive Freshwater Assessment (SEI 1997) and

subsequent work (Vörösmarty et al. 2000; Alcamo et al. 2003), when withdrawals of runoff water exceed 40% of available blue water resources, regions experience severe water scarcity, which at a global level corresponds to withdrawals exceeding 5,000 km^3 yr^{-1}.

DeFraiture et al. (2001) estimated the utilisable blue water resource at ~15,000 km^3 yr^{-1} (a global average of 36% of the total renewable water resource of ~42,500 km^3 yr^{-1}), and assessed that physical water scarcity is reached when withdrawals of water exceed 60% of the utilisable resource. This estimate indicates that water withdrawals exceeding ~6,000 km^3 yr^{-1} is a threshold above which physical water scarcity is reached.

Defining a global water boundary – rate of river depletion

The deleterious green water changes discussed above, occur "upstream" of, and are interlinked with, river depletion. Therefore, river depletion in the form of consumptive blue water use is chosen as a proxy for the full complexity of the highest risk for global water thresholds. It should be noted though that there are large uncertainties related to all three human manipulations of the global freshwater system (how much humans impact precipitation shifts; soil moisture trade-offs between different biomass producing systems; and withdrawals of runoff for irrigation, domestic use and industry). Only on runoff withdrawals, the uncertainty exceeds 1,000 km^3 yr^{-1} (Vörösmarty et al. 2000).

We thus propose that 4,000-6,000 km^3 yr^{-1} of consumptive blue water use constitutes a danger zone and a range that should not be transgressed, as it takes us too close to the risk of blue and green water induced thresholds that could have deleterious or even catastrophic impacts. Further, in line with the conceptual framework, we propose to set a boundary at the lower proposed uncertainty range, i.e., at 4,000 km^3 yr^{-1}.

This may appear as a large degree of freedom for humanity, given that current consumptive water use is around 2,600 km^3 yr^{-1} (Shiklomanov and Rodda 2003). However, most likely this boundary is further constrained by future increases in freshwater withdrawals for irrigation and industry, and the fact that freshwater is both a major prerequisite to attain the climate boundary of 350 ppm atmospheric CO_2, and is strongly affected by climate change. Moreover, the suggested boundary for river depletion of 4,000 km^3 yr^{-1} assumes no aggregate green water impacts on precipitation totals (i.e., moisture feedback effects) and no deterioration of precipitation due to climate change. This is obviously optimistic.

Firstly, projections of increased river depletion (consumptive water use for irrigation, industry and water supply) are in the range of 400 - 800 km^3 yr^{-1} until 2050. Secondly, terrestrial ecosystems will have to play a continued key role for carbon sequestration. Hansen et al. (2008) estimates that 1.6 Gt C/yr will have to be sequestered through increase in biomass growth, primarily forests, in order to enable reaching the climate boundary. This will consume large volumes of new freshwater. We estimate this additional freshwater boundary function to 430-3,700 km^3 yr^{-1} in 2050, depending on assumptions on how much carbon per unit area that can be stored in the system (5,000-40,000 gC/m^2, Schulze et al. 2002), and assuming that forests use twice as much of the total incoming precipitation for green water flows (60% compared to 30%). On average, this gives an estimated 2,000 km^3 yr^{-1} of additional green water use by the year 2050. Assuming that only 50% of this increased green water use will cause river runoff reduction (moisture feedback compensates the rest through increased precipitation levels), this gives an estimated 1,000 km^3 yr^{-1}. The "committed" water consumption thus rises to approximately 4,000 – 4,400 km^3 yr^{-1} in 2050, which

suggests that the current degree of freedom within the proposed planetary water boundary may already be committed to meet growing water demands over the coming decades. This leaves very little room for additional blue water consumption to meet future food and bioenergy demands.

5. Additional description of interaction between boundaries

Below, two more examples of interaction between boundaries are described, as well as an illustration of the interaction discussed in the main article text.

Land system and climate change – an example from Borneo

The Bornean rainforest serves as an illustration of human-induced thresholds in interconnected human-environment systems in the Anthropocene. Bornean rainforests are ecologically driven by El Niño-induced droughts that trigger mass reproduction among trees and fauna. In this sense El Niño serves as a trigger for regenerating the rainforest and its biodiversity helps sustain forest resilience. The rainforest has evolved ecologically to turn crisis (El Niño Southern Oscillation events) into opportunity for continuous development. Curran et al. (2004) have shown that in Indonesian Borneo (Kalimantan), concession-based timber extraction, oil palm plantation establishment, and weak institutions have resulted in highly fragmented and degraded forests. Fragmentation and land cover change is predominantly driven by demand for tropical timber and palm oil through international markets. This demand has resulted in degradation of the rainforest (and the capacity for beneficial use of El Niño events) to a point where El Niño events have shifted from regenerative to de facto destructive forces in the Bornean landscape. Deterioration of the status of two planetary boundary parameters (land system change and biodiversity loss) interacts with the climate system, to cause a higher sensitivity to extreme climate events (erosion of resilience in land and biodiversity boundaries reduces the safe space for the climate boundary).

Currently, El Niño disrupts fruiting of the rain forest trees, interrupts wildlife reproductive cycles, erodes the basis for rural livelihoods, and triggers droughts and wildfires (Curran et al. 2004). Page et al. (2002) estimated that the widespread El Niño related wildfires of Borneo in 1997 released between 0.81 and 2.57 Gt of carbon to the atmosphere, equivalent to 13–40% of the mean annual global carbon emissions from fossil fuels. A globalized world of human actions tipped the interplay between climate events and biodiversity into an undesirable dynamics and created vulnerable landscapes of Borneo.

Land use, water and climate change

Fig. S4 below illustrates the mechanisms linking Amazonian land cover change with temperature in Asia discussed in the main article text (Snyder et al, 2004 a, b).

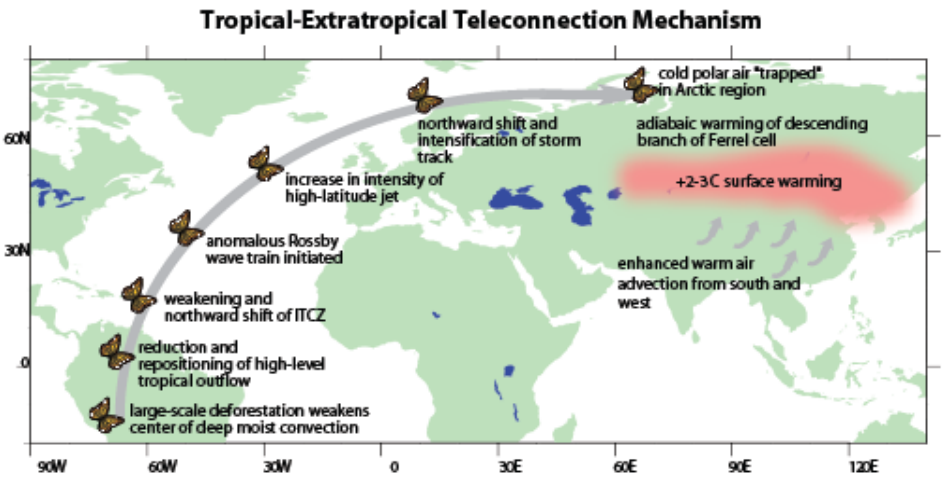

Figure S4. The mechanisms linking Amazonian land cover change with temperature in Asia.

Ocean acidification, marine biodiversity and stratospheric ozone

Acidification of the ocean is a major stressor on many important kinds of marine biota. Ocean acidification, however, is only one of many stressors on marine biota. Smith et al. (1992) show that increased UV radiation at the sea surface near Antarctica (caused by a thinning of the stratospheric ozone layer in the region) led to a 6 to 12% reduction in marine primary production in the marginal ice zone of the Bellingshausen sea, and estimate a 2% reduction in the yearly biological production in the Antarctic marginal ice zone.

Coral reefs are a case in point for the interactions between several of the planetary boundaries. De'ath et al. (2009) showed that calcification in 69 reefs in the Great Barrier Reef in Australia has decreased by 14.2% since 1990. They found the magnitude and rapidity of the decrease to be unprecedented in the last 400 years. While they could not establish a complete causal relationship, the evidence indicates that increasing temperature stress and a declining saturation state for seawater aragonite may be diminishing the ability for the reef corals to deposit calcium carbonate. Bellwood et al. (2004) explored how multiple stressors (for instance increased nutrients and fishing pressure) could move corals into different, less desirable ecosystem states. They showed the importance of redundancy in critical functional groups for maintaining the resilience of coral reefs. Guinotte and Fabry (2008) show that ocean acidification will have significant consequences for marine taxa, and that changes in species abundance and distribution could propagate through marine food webs. Increasing temperatures, surface UV radiation levels and ocean acidity all stress marine biota, and the combination of these stresses may well cause perturbations in the abundance and diversity of marine biological systems that go well beyond the effects of a single stressor acting alone.

Supplementary Methods

1. Method for identifying and defining planetary boundaries

The methodology for identifying and defining boundaries was based on expert solicitation and literature review undertaken in three steps. Candidate boundaries and selection criteria were discussed during three scientific expert meetings, two smaller workshops in Stockholm in April and May 2008 and a larger international scientific workshop in Tällberg, Sweden, in June 2008. In conjunction with the latter workshop, discussions were also held with stakeholders from the private sector, government and civil society at the Tällberg Forum event on the overall relevance and validity of the conceptual approach. Individual boundary proposals (relevant Earth system processes and associated control variables) were generated during the first two scientific workshops and documented in a background report. The set of proposed boundaries were then tested against the selection criteria (see Box 1) and categorised according to the matrix in Table 1, in an iterative process, in the June workshop and its follow-up. Finally, the conceptual framework described in Fig. 1 was used as a basis for defining specific boundary values in relation to uncertainty zones.

2. Data and data treatment for computing Figure 4

Formal description of the mapping of control variables

Figure 4 is constructed by mapping all control variables to a single scale showing relative transgression of the boundaries. The mapping applied is a simple linear transformation of each control variable $Y = a + Xb$, where Y is the rescaled indicator and X the original control variable a and b are obtained by solving the simple system of

$$\begin{cases} y_1 = a + x_1 b \\ y_2 = a + x_2 b \end{cases} \Rightarrow a = y_1 - x_1 b, b = \frac{y_2 - y_1}{x_2 - x_1} \ ,$$

in which $y_1 = 0$, $y_2 = C$ $x_1 = B$, and $x_2 = PI$. B is the boundary, PI is the pre-industrial value, and C is a constant set to 100.

Table S2: Definition, units, data, and data sources for each planetary boundary displayed in Figure 4.

Earth system process	Control variable	Boundary	Pre-industrial*	1950	1970	1990**	Latest data	Data source***
Climate change	Atmospheric CO_2 concentration, ppm	350	280	311	326	354	387	IPCC (2007a); NOAA (2009)
Ocean acidification	Global oceanic aragonite saturation ratio	2.75	3.44	n.a.	n.a.	n.a.	2.90	Guinotte and Fabry (2008)
Stratospheric ozone depletion	Stratospheric O_3 concentration, DU	276	290	n.a.	292	282	283	Chipperfield et al. (2006)
Nitrogen cycle (Part of a single biogeochemical flow boundary)	Amount of N_2 removed from the atmosphere for human use, Mt yr^{-1}	35	0	4	39	98	121	Galloway et al. (2003, 2008)
Phosphorus cycle (Part of a single biogeochemical flow boundary)	Quantity of P flowing into the oceans, Mt yr^{-1}	11	1.1	3.4	6.0	8.5	10.3 (9) ****	Mackenzie et al. (2002)
Global fresh-water use	Consumptive use of withdrawn runoff, km^3 yr^{-1}	4,000	415	887	1,536	2,192	2,600	Gleick (2003); Shiklomanov and Rodda (2003)
Land system change	Percentage of global land cover converted to cropland, % (Mha)	15 (1,995)	5 (665)	n.a.	10.71 (1,424)	11.45 (1,522)	11.68 (1,554)	Klein Goldewijk (2001); FAO (2008); Ramankutty et al. (2008)
Biodiversity loss	Extinction rate in number of species per million per year, E/MSY	10	1	n.a.	n.a.	n.a.	>100	Pimm et al. (2006); Mace et al. (2005)
Atmospheric aerosol loading ***Not yet quantified***	-	-	-	-	-	-	-	-
Chemical pollution ***Not yet quantified***	-	-	-	-	-	-	-	-

* Pre-industrial averages are found in the first reference listed in the data source column. For global freshwater and land system change a specific year is used (1900 and 1700) and for biodiversity we used the geological average.
** Data for the indicated year with the following exceptions. For stratospheric ozone, the year 1993 is deliberately selected instead of 1990 to illustrate the highest point of depletion during the last century.
*** Data sources for pre-industrial, years 1950, 1970, 1990, and latest values. For references used in defining each boundary, see main text.
**** 9 Mt is estimated current value from early 21st century. 10.3 Mt is the modelled value for 2008 adopted from data in Mackenzie et al. (2002) including sewage water and detergents and this value is used in figure 4.
n.a. No data available.

Supplementary Notes

1. Additional references for Supplementary Information

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. and Siebert, S. Global estimation of water withdrawals and availability under current and "business as usual" conditions. *Hydrological Science* **48**, 339-348 (2003).

Bruckner, T., Petschel-Held, G., Leimbach, M. and Tóth, F. Methodological aspects of the Tolerable Windows Approach. *Climatic Change* **56**, 73-89 (2003).

CAPE Project Members. Last interglacial Arctic warmth confirms polar amplification of climate change. *Quaternary Science Reviews* **25**, 1383-1400 (2006).

Chen, J.L., Wilson, C.R. and Tapley, B.D. Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet. *Science* **313**, 1958-1960 (2006).

Commission of the European Communities. *Communication from the Commission on the precautionary principle*. COM 2000 (1) (2000).

Cresser, M.S. The critical loads concept – milestone for the new millennium? *The Science of the Total Environment* **249**, 51-62 (2000).

Curran, L.M., Trigg, S.N., McDonald, A.K., Astiani, D., Hardiono, Y.M., Siregar, P., Caniago, I. and Kasischke, E. Lowland forest loss in protected areas of Indonesian Borneo. *Science* **303**, 1000-1003 (2004).

De'ath, G., Lough, J.M. and Fabricius, K.E. Declining coral calcification on the Great Barrier Reef. *Science* **323**, 116-119 (2009).

EEA (European Environment Agency). *Environmental indicators: Typology and overview*. Technical Report No. 25. (EEA, Copenhagen, 1999).

EEA European Environment Agency) *Late lessons from early warnings: the precautionary principle 1896-2000*. Environmental Issue Report No. 22. (EEA, Copenhagen, 2001).

Falkenmark, M. Freshwater – Time for a modified approach. *Ambio* **15**, 192-200 (1986).

Falkenmark, M., Lundqvist, J. and Widstrand, C. Coping with water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. *Natural Resources Forum* **13**, 258-267 (1989).

Falkenmark, M. and Rockström, J. *Balancing Water for Man and Nature: The New Approach in Ecohydrology* (Earthscan, London, 2004).

Farmer, M.C. and Randall, A. The rationality of a safe minimum standard. *Land Economics* **74**, 287-302 (1998).

FAO. FAOSTAT Database. Accessed July 2009. URL: http://faostat.fao.org/default.aspx.

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee Morlot, J., de la Chesnaye, F., Hourcade, J.-Ch., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., Rana, A., Riahi, K., Richels, R., Rose, S., van Vuuren, D. and Warren, R. Issues related to mitigation in the long term context. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change* (Eds. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer) (Cambridge University Press, Cambridge, 2007).

Füssel, H.-M., Toth, F.L., van Minnen, J.G. and Kaspar, F. Climate impact response functions as impact tools in the tolerable windows approach. *Climatic Change* **56**, 91-117 (2003).

Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Cowling, E.B. and Cosby, B.J. The nitrogen cascade. *BioScience* **53**, 341-356 (2003).

Galloway, J.N., Townsend, A.R, Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. and Sutton, M.A. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* **320**, 889-892 (2008).

Gleick, P.H. Water use. *Annu. Rev. Environ. Resour.* **28,** 275-314 (2003).

Haines-Young, R., Potschin, M. and Cheshire, D. *Defining and identifying environmental limits for sustainable development*. Final Full Technical Report to Defra. URL: http://randd.defra.gov.uk/Document.aspx?Document=NR0102_4078_FRP.pdf (2006).

Jordan, A. and O'Riordan, T. The precautionary principle in contemporary environmental policy and politics. In: *Protecting human health and the environment: Implementing the precautionary principle* (Eds. Raffensperger, C. and Tickner, J.) (Island Press, Washington DC, pp. 15-35, 1998).

King, J.M., Brown, C.A. and Sabet, H. A scenario-based holistic approach to environmental flow assessments for rivers. *River Research and Applications* **19**, 619-640 (2003).

Klein, Goldewijk., K. Estimating global land use change over the past 300 years: The HYDE database. Global Biogeochemical Cycles 15:417-434 (2001).
Lear, C.H., Rosenthal, Y., Coxall, H.K. and Wilson, P.A. Late Eocene to early Miocene ice-sheet dynamics and the global carbon cycle. *Paleoceanography* **19**, PA4015, doi:10.1029/2004PA001039 (2004).
Lvovich, M.I. *World Water Resources and Their Future* (Translation by the American Geophysical Union). (LithoCrafters Inc., Chelsea, 1979).
Margolis, M. and Naevdal, E. Safe minimum standards in dynamic resource problems: conditions for living on the edge of risk. *Environmental Resource Economics* **40**, 401-423 (2008).
Meadows, D.H., Meadows, D.L., and Randers, J. *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future.* (Chelsea Green, White River Junction, 1992).
Molden, D. (Ed.) *Water for food, water for life: A Comprehensive Assessment of Water Management in Agriculture* (Eartscan, London, and IWMI, Colombo, 2007b).
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenham, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.-Y., Kram, T., La Rovere, E.L,. Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Reohrl, A., Rogner, H.H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. and Dadi, Z. *Special report on emissions scenarios. Working Group III, Intergovernmental Panel on Climate Change (IPCC)* (Cambridge University Press, Cambridge, 2000).
NOAA (2009) NOAA database (Mauna Loa Observatory), Database 0065. Accessed July 2009. URL: http://www.mlo.noaa.gov.
Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B. and Kiehl, J.T. Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. *Science* **311**, 1747-1750 (2006).
Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.-D.V., Jayak, A. and Limink, S. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420**, 61-65 (2002).
Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E., Somerville, R.J.C. et al. Recent climate observations compared to projections. *Science* **316**, 709 (2007).
Ready, R.C. and Bishop, R.C. Endangered species and the safe minimum standard. *American Journal of Agricultural Economics* **73**, 309-311 (1991).
Rignot, E. and Jacobs, S.S. Rapid bottom melting widespread near Antarctic Ice Sheet grouding lines. *Science* **296**, 2020-2023 (2002).
Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S. and Gerten, D. Future water availability for global food production: The potential of green water for increasing resilience to global change. *Water Resour. Res.* **45**, W00A12, doi:10.1029/2007WR006767 (2009).
Schulze, E.-D., Beck, E. and Müller-Hohenstein, K. *Plant Ecology*. (Springer Verlag, Berlin, 2002).
SEI (Stockholm Environment Institute SEI) (Ed.) *Comprehensive Assessment of the Freshwater Resources of the World.* (SEI, Stockholm, 1997). --TBC
Shiklomanov, I.A. World water use and water availability. In: *World Water Resources in the Beginning of the 21st Century* (Eds. Shiklimanov, I.A. and Rodda, J.C.) (Cambridge University Press, Cambridge, pp. 369-384, 2003).
Skeffington, R.A. The use of critical loads in environmental policy making: a critical appraisal. *Environmental Policy Analysis* **33**, 245-252 (1999).
Slovic, P. Perception of risk. *Science* **236**, 280-285 (1987).
Smakhtin, V., Revenga, C. and Döll, P. A pilot global assessment of environmental water requirements and scarcity. *Water International* **29**, 307–317 (2004).
Smakhtin, V. Basin closure and environmental flow requirements. *International Journal of Water Resources Development* **24**, 227-233 (2008).
Spranger, T. (Ed.) Mapping manual 2004: UNECE Convention on Long-Range Transboundary Air Pollution: Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends. URL: http://icpmapping.org/cms/zeigeBereich/11/manual_english.html (2004).
Toth, F.L. Bruckner, T., Füssel, H-M., Leimbach, M., Petschel-Held, G. and Schellnhuber, H-J. Exploring options for global climate policy: an analytical framework. *Environment* **44**, 22-34 (2002).

Tedesco, M. Snowmelt detection over the Greenland ice sheet from SSM/I brightness temperature daily variations. *Geophysical Research Letters* **34**, L02504, doi:10.1029/2006GL028466 (2007).

Turner, G. A comparison of the Limits to Growth with thirty years of reality. *CSIRO Working Paper Series 2008-09*. URL: www.csiro.au/files/files/plje.pdf (2008).

Zwally, H.J., Abdalati, W, Herring, T., Larson, K., Saba, J. and Steffen, K. Surface melt-induced acceleration of Greenland ice-sheet flow. *Science* **297**, 218-222 (2002).

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[i] For a comparison of the 1972 scenarios with observed data from 1970 to 2000, see Turner (2008).

[ii] The first two substances to have critical loads defined were sulphur and nitrogen (for acidity and for eutrophication), followed by heavy metals (cadmium, lead and mercury).

[iii] Crowards (1998) argues that in addition to losses from irreversible effects, benefits from the conservation ensured by an SMS should also be incorporated into the equation.