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From Planetary Boundaries to national fair shares of the global safe operating space — How can the scales be bridged?

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ABSTRACT

The planetary boundaries framework proposes quantitative global limits to the anthropogenic perturbation of crucial Earth system processes, and thus marks out a planetary safe operating space for human activities. Yet, decisions regarding resource use and emissions are mostly made at less aggregated scales, by national and sub-national governments, businesses, and other local actors. To operationalize the planetary boundaries concept, the boundaries need to be translated into and aligned with targets that are relevant at these decision-making scales. In this paper, we develop a framework that addresses the biophysical, socio-economic, and ethical dimensions of bridging across scales, to provide a consistently applicable approach for translating the planetary boundaries into national-level fair shares of Earth's safe operating space. We discuss our findings in the context of previous studies and their implications for future analyses and policymaking. In this way, we link the planetary boundaries framework to widely-applied operational and policy concepts for more robust strong sustainability decision-making.

1. Introduction

Consumption of natural resources at global scale has increased rapidly in recent decades. This increase, largely driven by population growth, economic development, and lifestyle changes, has been a prime driver of changes in the Earth System and resulted in severe environmental degradation (Dasgupta and Ehrlich, 2013; Steffen et al., 2015a; Vitousek et al., 1997). Over time, many concepts have been proposed to communicate the undesirability of further environmental degradation, framing the impact in terms of transgression of critical levels with respect to system integrity. These include safe minimum standards (Bishop, 1978; Ciriacy-Wantrup, 1952; Crowards, 1998), critical loads (UNECE, 1979), carrying capacity (Daily and Ehrlich, 1992), limits to growth (Meadows et al., 1972), and tolerable windows or guardrails (Bruckner et al., 2003, 1999; WBGU, 1995). Examples of application of such concepts in national environmental policy include the Netherlands' use of ecocapacity (Weterings and Opschoor, 1992), and the development in Switzerland of the 'eco-scarcity' concept as part of a life-cycle assessment approach (Ahbe et al., 1990; discussed in Brand et al., 1998).

More recently, the Planetary Boundaries (PB) framework has been proposed to monitor trends with respect to Earth system-critical environmental challenges (Rockström et al., 2009; Steffen et al., 2015b). The PB approach is based on a set of human-perturbed, interlinked biophysical boundaries that mark out a 'safe operating space' at planetary scale, in which social and economic development can take place while maintaining the resilience of the Earth system as a whole. Since its publication in 2009, the global research community has taken up the PB concept as a scientific agenda by improving assessments of the individual boundary issues (Carpenter and Bennett, 2011; Gerten et al., 2013; Mace et al., 2014), proposing alternative boundary processes (Running, 2012), discussing the nature of thresholds (Barnosky et al., 2012; Reid et al., 2016), and developing new approaches to address their complex interactions and human impacts (De Vries et al., 2013; van Vuuren et al., 2016).

While these debates continue in the academic community, the planetary boundaries concept has become influential in the

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international policy discourse on global sustainability, notably in the context of the United Nations 2030 Agenda for Sustainable Development (Brandi, 2015; Griggs et al., 2013; Hajer et al., 2015; Lucas et al., 2014; SDSN, 2013). While the PB concept is not mentioned explicitly in the 2030 Agenda, all nine of its system processes are addressed in some way, either as the focus of a goal (water, land use, climate change, and biodiversity) or included in specific targets (ocean acidification, air quality, biogeochemical cycles, ozone depletion, and chemical pollution). The SDGs thereby integrate the concept of a biophysically safe operating space within the much broader concept of sustainable development. Both the 2030 Agenda and the PB framework acknowledge complex systemic interconnections — among the different goals and targets and among the different planetary processes, respectively. Both point to a need to address these connections in an integrated manner if actions taken are really to 'add up' to global sustainable development. But there are many challenges for integrated global environmental governance of planetary boundaries (Galaz et al., 2012). Importantly, decisions regarding environmental management and resource use are generally not made at the planetary scale, but by governments, businesses, and other actors operating at national, sub-national, and supra-national regional levels. Therefore, multi-level governance approaches are required to align policy making with the need to maintain the resilience of the Earth system (Biermann et al., 2015; Nilsson and Persson, 2012; Ostrom, 2010).

There is growing demand for the planetary boundaries to be translated from their global-scale viewpoint to support sustainability decision-making at other levels. This process is challenging because of the need to manage plural understandings of scale and interdependence in translating across biophysical and social systems (Cash et al., 2006; Gibson et al., 2000). Several researchers have already tried to translate the PB framework to specific national or regional contexts. Studies include analyses for Sweden (Nykvist et al., 2013), South Africa (Cole et al., 2014), Switzerland (Dao et al., 2015), and the European Union (Hoff et al., 2014). Dearing et al. (2014) applied an integrative boundary approach (with social as well as biophysical dimensions) to two regions in China, and Kahiluoto et al. (2015) assessed the nitrogen boundary for Finland and Ethiopia. However, to date there is little consistency in the approaches these studies use. Moreover, most of these studies have focused more on practical considerations rather than theoretical ones.

In this paper, we propose a more systematic conceptual framework for translating planetary boundaries to national or regional implementation. We are aware that there are still discussions on the PB concept itself, for instance regarding the various control variables and the boundary levels. However, here we accept the PB concept 'as it is' and focus on the issue of how to bridge from the global scale of the concept to the national levels of decision-making. We explore: (1) the key challenges for translation across scales; (2) possible approaches and tools for addressing these challenges; and (3) lessons learned from earlier studies. Our proposed framework can guide analysts and policy-makers to identify meaningful national or regional policy targets that are aligned with the planetary boundaries. Furthermore, although not the focus of this paper, the framework can also guide policy makers in translating global SDG targets to national ambitions and policies, especially those targets that relate to planetary boundary processes.

In Section 2 we discuss connections across scales for the different planetary boundaries and propose three dimensions to be considered in scaling planetary boundaries to the national level. In Section 3 we discuss relevant approaches and tools that can be useful in addressing these three dimensions. In Section 4 we discuss existing studies in terms of these dimensions, approaches and tools, and consider implications for future studies. Finally, in Section 5 we draw conclusions for the way ahead in national and regional implementation of the PB concept.

2. Three dimensions for bridging across scales

The planetary boundaries framework defines fundamental conditions for the Earth system to remain in a Holocene-like state (Rockström et al., 2009). Its authors assume that the Holocene-like state of the world ensures sufficient stability and resilience for ecosystems to support human wellbeing. They argue for a precautionary approach in setting boundary values at a safe distance from possible tipping points and regime shifts, proposing nine boundaries on biophysical processes that are already severely modified by human activities.

Earlier, it has been argued that the PB concept should be considered in the context of a wider sustainable development agenda, pointing specifically to principles of social equity as an important complement to the planetary boundaries (e.g., Raworth, 2012; Steffen and Stafford Smith, 2013). In the policy-oriented sustainable development literature, the dominant position is that sustainability consists of environmental, social, and economic dimensions (see e.g., Kates et al., 2001; UNCED, 1992a,b; UN, 2002). The PB framework brings global-scale environmental dynamics firmly into this picture. The non-linear emergent properties of the Earth system mean that linear responses – such as national policies targeted only at environmental degradation and resource use within national territory – are not adequate. Because human activities are altering the functioning of the Earth system (Waters et al., 2016), the distinct dynamics of social systems, such as international trade, are now important determinants of the ways that the PB indicators connect across scales. A system analytic perspective illuminates the connections of environmental and social systems, but on its own, it cannot resolve the dilemmas of fair and equitable implementation in real-world decision-making.

For translating the planetary boundary processes to the scales needed for implementation, we therefore argue that the biophysical, socio-economic, and ethical dimensions should be treated distinctly (Fig. 1) and in this sequence: the dominant scales of the biophysical dynamics of the boundary processes determine the scales at which socio-economic dynamics now need to be analyzed, and this in turn influences the ethical choices faced by different levels of society. For each dimension, analytical tools are available, as are integrative techniques that can help to preserve the connections among the various boundaries and bridge across the dimensions (Fig. 1). This approach corresponds usefully to the dominant sustainable development dimensions. It also allows us to develop different downscaling rules appropriate to each context, connecting the PB control variables to responsive indicators at smaller spatial scales and enabling policy targets to be derived at the various sub-global levels of governance. In the remaining sections of the paper, we discuss these three dimensions and outline how they can be applied.

2.1. Biophysical dimension — dealing with complex and dynamic interactions

The global boundaries proposed by Rockström et al. (2009) were defined in terms of 'transitions in the functioning of coupled human–environmental systems' and expressed using biophysical 'control variables'. Rockström et al. acknowledged the spatial heterogeneity of the underlying biophysical processes. Steffen et al. (2015b) went further and sought to quantify boundary values at sub-global level for some of these geographically heterogeneous processes. However, their aim was not to derive regional-scale sustainability targets for environmental problems; instead, they

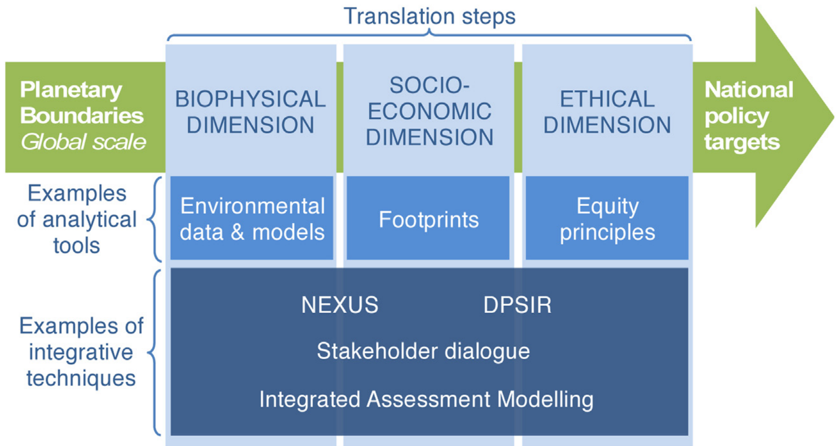

Fig. 1. A conceptual framework for translating the planetary boundaries to national or regional scale implementation.

argued that their approach better addressed the importance of sub-global dynamics in affecting the functioning of the Earth system as a whole.

We suggest that when the planetary boundaries are translated to less aggregated scales with the aim of informing sustainability decision-making, different translation methods will be needed for the biophysical dimension, depending on the dominant geographic scale of the human-environmental system in question. We propose two categories, based on differences in the functioning of the coupled systems.

In the first category, human activities are introducing a direct perturbation to an Earth system component (i.e., atmosphere, ocean, biosphere), pushing it away from the relatively stable global baseline of the Holocene. The processes we include in this category are climate change, ocean acidification, atmospheric ozone depletion, and systemic chemical pollution (novel entities in Steffen et al., 2015b; discussed in Persson et al., 2013). For these processes, the absolute magnitude of anthropogenic emissions is what determines the overall impact, and it does not substantially matter where on Earth the emissions are generated. Carbon dioxide, other long-lived greenhouse gases, and ozone-depleting substances accumulate and become well mixed in the atmosphere, and the rising CO_2 concentration in the atmosphere affects ocean pH and carbonate solubility. We include systemic chemical pollution in this category because it involves wholly new substances (the global baseline was initially zero), which become planetary concerns not because of their local and immediate ecotoxicological effects, however serious and widespread they may be, but because of their capacity to fundamentally disrupt the biophysical functioning of the Earth system at planetary scale (see also MacLeod et al., 2014). Like the CFCs that cause stratospheric ozone depletion and alter the ultraviolet radiation flux at Earth's surface, the substances of concern are long-lived or bioaccumulative, becoming 'well-mixed' via the biosphere, so that their eventual harm may be spatially diffuse or trophically far removed from their sources. These features mean that global coordination is needed for policy responses to these problems.

In the second category, human activities at the local scale are changing the planetary 'system baseline' by altering the spatial patterns of the fundamental systemic interconnections between components of the Earth system. The processes in this category include atmospheric aerosol loading, loss of biodiversity, altered biogeochemical flows of nitrogen and phosphorus, fresh water use, and land-system change. These processes have not previously been considered to need global policy coordination but scientific understanding is growing about how local changes to land use, water flows, air quality, and ecosystems cascade through the global Earth system, changing physical and biogeochemical feedbacks. As an example, land-system change is a major driver of biodiversity loss and climate change, and climate change in turn impacts biodiversity and water availability in places far away from the location of the initial land-system change. For these boundaries, national allocation of the planetary 'safe operating space' is not a simple matter of sharing a global budget, because the local conditions, including temporal variability, play a crucial role in determining the level of sustainable use or tolerable emission and opening up opportunities for socioeconomic and equity co-benefits, as argued by Steffen and Stafford Smith (2013). Enabling sustainable development opportunities to be identified and attributing the national impact of these processes requires a multi-scale systemic approach.

2.2. Socio-economic dimension — considering production and consumption

The second step for bridging scales involves analysis of socio-economic patterns and their relationship to environmental impacts. Although the planetary boundaries are expressed in terms of biophysical control variables, each of the underlying processes is driven or perturbed by humans. The socio-economic drivers of environmental change have their own dynamics and their own policy contexts, and they need to be taken into account for operationalization of the planetary boundaries at sub-global scales.

Current socio-economic dynamics place all PB processes in a global context. One consequence of trade is that causal chains between the cause and impact of environmental degradation become more complex and spatially separated. It also makes it more difficult to attribute environmental impact to socio-economic behaviours. On the one hand, trade is a means to make overall production more efficient and allows countries to cope with local environmental constraints. For example, water intensive commodities can be imported to water scarce areas. On the other hand, international trade also allows a country's environmental impact to be externalized, for example by relocating resource-intensive or highly polluting industries in other countries. As a result, the production (and potential related environmental impacts) and consumption of goods increasingly happens in different locations and part of the territorially reduced environmental pressure in one country may come at the cost of increasing impact elsewhere (Hertwich and Peters, 2009; Lenzen et al., 2013; Wiedmann et al., 2013). If the PB concept is to be applied as a global sustainability framework, then a country's national targets should take into account the environmental impacts of all its consumption, including the impacts associated with production activities outside its territory and their societal consequences.

2.3. Ethical dimension — recognizing equity and justice

As a global framework, the PB concept makes no distinction between resource use and requirements of different groups of people (Raworth, 2012). However, by highlighting the rising biophysical risks to societies globally, the PB concept is also inextricably linked to ethical dilemmas at the sub-global level. Addressing these dilemmas is an important third step in translating planetary boundaries to national level.

Countries differ in their stage of development. As a result, current pressures on the planetary boundary processes differ widely between nations, while their environmental impacts are unevenly felt across the globe (Chakravarty et al., 2009; National Research Council, 2014; Turner et al., 2014). Countries contributing the most to environmental degradation are generally not the countries that feel the worst negative impacts of it. Furthermore, improving the economic conditions and quality of life of billions of people who are living in poverty could require an increase in their consumption of resources like land, water, and energy (Lamb and Rao, 2015; Rao and Baer, 2012; UNDP, 2014). Finally, countries differ in their ability to deal with environmental problems. When setting national targets, these differences between countries have implications for the issues of environmental justice, burden sharing, and allocation of scarce resources.

This ethical dimension has been debated internationally for several global environmental issues, including climate change, air pollution, and biodiversity loss. In the climate context, the debate addresses the distributive fairness in translating global emission reductions for climate change mitigation under the UN Framework Convention on Climate Change (Berk and den Elzen, 2001; Metz et al., 2002; Raupach et al., 2014; Ringius et al., 2002; Steininger et al., 2015; UN, 1992). The principle of 'common but differentiated responsibility' takes into account the diverse circumstances and capacities of nations in responding to environmental problems. This principle has been applied in other large-scale multilateral environmental agreements, notably the Montreal Protocol on Substances that Deplete the Ozone Layer and the Convention on Long-Range Transboundary Air Pollution (Honkonen, 2009; Pauw et al., 2014). Fair and equitable benefits sharing is one of the objectives of the international Convention on Biological Diversity, where procedural concerns have been expressed, as well as the those about international and intergenerational distributive justice (Schroeder and Pisupati, 2010). The growing understanding of Earth system changes implies that global ethical considerations also play a role in other PB processes, but where these processes are still seen only as local or regional concerns from the biophysical and socio-economic perspectives, the ethical dimension remains poorly defined.

3. Approaches and tools for cross-scale translation

Several widely applied approaches and tools can be applied to operationalize the PB framework at sub-global scales (Fig. 1). Here, we identify analytical tools that are suitable for specific dimensions, as well as integrative techniques, frameworks, and models that emphasize causal relationships and provide ways to bridge across all the three dimensions.

3.1. Analytical tools to link across scales

3.1.1. Environmental observations and quantitative analytical modeling

For the biophysical dimension, the central issue is to characterize the extent, locations, and trends of perturbations of the various processes. Mapping, monitoring, and projecting the biophysical dimension of planetary boundaries, both spatially and temporally, will rely on the use of observational data in combination with biophysical models and geographic information systems, bridging global to local scales (van Vuuren et al., 2016). Here, Earth System Models that combine physical climate, vegetation dynamics, ocean biogeochemistry, and hydrological processes play a key role in understanding coupled Earth system processes. In Table 1, we take land use change as an example to indicate the kind of information infrastructure that can be used (see also Cornell and Downing, 2014; Elmqvist et al., 2014).

Table 1
Indicative information resources for cross-scale analysis of Land system change boundary.

Issue	Resource
Land cover and land use measurement – observational data and statistics	Copernicus, the European Earth Observation Programme, http://land.copernicus.eu NASA Earth Observations, http://neo.sci.gsfc.nasa.gov NASA Land Cover and Land Use Change Program, http://lcluc.umd.edu UN Food and Agriculture Organization Statistics (FAO-Stat), http://faostat3.fao.org/home/E UN Environment Statistics, http://unstats.un.org/unsd/environment Global Land Cover Network, www.glcn.org
Interactions of land use with climate, biodiversity and biogeochemical change	Synthesis assessments: • IPCC Assessment Reports (e.g., IPCC (2014)) • Global Environment Outlook 5 (UNEP, 2012) • Global Biodiversity Outlook 4 (CBD, 2014)
Social and economic dimensions of land use	UN global assessment reports, e.g.: • Assessing Global Land Use (UNEP, 2014) • The Global Forest Resources Assessment 2010 (FAO, 2010) • The State of Food and Agriculture 2012 (FAO, 2013)
Modelling initiatives	Coupled Model Intercomparison Project, http://cmip-pcmdi.llnl.gov Dynamic land modeling, e.g., LPJ-mL global vegetation model, https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml Integrated modeling, e.g., IMAGE 3.0 (Stehfest et al., 2014) Regional modeling, e.g., Verburg et al. (2002)
International scientific coordination	Global Land Project (Future Earth core project), www.globallandproject.org

For those boundaries whose underlying processes can be characterized by global anthropogenic emissions budgets, national targets can often be derived using a top-down allocation approach, acknowledging that there are different ways to partition the global budgets among countries. However, it is still necessary to match the scales of scientific assessments and the management systems that use the scientific information (Cash and Moser, 2000). For example, dynamical downscaling techniques can be used to translate global climate model outputs to higher-resolution regional impacts (Flato et al., 2013), informing decisions about which greenhouse gas emissions sources should be prioritized to meet national commitments under global budgets.

For operationalizing the sub-globally systemic, spatially heterogeneous processes, linear partitioning of the PB framework's global targets is not sufficient. The most logical method for deriving national- or local-scale targets is to look for available (in-situ) data and information as well as sustainability criteria at that scale. This means assessing local resource scarcity and vulnerabilities, for instance in terms of water or land, local critical loads for aerosols and nutrient use, or potential ecological 'hotspot areas' that are particularly important for the resilience of the Earth system. Here, the temporal perspective is important because for sustainability, defining boundaries on an annual basis may not necessarily be enough. For example, in the case of water use, an annual average 'sustainable exploitation level' might not account for transient ecosystem needs, where the critical months of water scarcity matter the most (Gerten et al., 2013).

The scientific understanding of human influence on Earth system feedbacks through processes like land use and water extraction is still very limited (Ciais et al., 2013; Myhre et al., 2013; Oppenheimer et al., 2014). This means that the connection between the top-down and bottom-up approaches is still scientifically tentative. While this is a challenge for operationalizing planetary boundaries, it is also an international research priority.

Another challenge when integrating top-down and bottom-up approaches is the bridging from the biophysical to the social dimension: the sensible scale for biophysical investigation does not necessarily align with the required scale for socio-economic investigation, for instance following administrative borders (Cash and Moser, 2000). For example, a river basin may be located within several countries, requiring that the sustainable level of water use needs to be agreed among all riparian countries with their respective needs and priorities (e.g., Lebel et al., 2013).

3.1.2. Production and consumption measures: footprints and territorial approaches

In the socio-economic dimension, one important issue is a nation's environmental impact or footprint within versus outside its borders. This can be measured by using either production- or consumption-based approaches. The production-based performance refers to the emissions or resource use occurring within the territory of the country, both for national consumption and for export. Most current national statistics focus on production-based measures. For instance, in climate change negotiations, a production-based approach to measuring national responsibilities was adopted in the Kyoto Protocol. Countries that import significant amounts of final goods can have high standards of living with a relatively low level of domestic environmental impact (Peters and Hertwich, 2008).

A consumption-based perspective accounts for all global environmental impacts caused by national consumption, including imports. This means that the consumption-based approach includes the external dimension of domestic consumption. Consumption-based allocation would allow net-exporting countries to use more resources or have higher emissions. Different shared producer-consumer allocations has also been proposed as a middle road (Gallego and Lenzen, 2005; Kander et al., 2015; Lenzen et al., 2007).

Footprint indicators are based on tracking the environmental impact embodied in consumed commodities, by accounting for the human appropriation of natural resources or generated waste and emissions. Starting from the ecological footprint (Wackernagel et al., 1999), footprint thinking has expanded in the last two decades to land, carbon, material, nitrogen, water, and biodiversity footprints (Galloway et al., 2014; Hoekstra and Wiedmann, 2014; Lenzen et al., 2012; Peters et al., 2011; Wiedmann et al., 2013). Despite their name, these footprints are not yet spatially explicit indicators that refer to local impact. Instead, they mostly take a life cycle perspective by accounting for emissions generated or resources used throughout a supply chain to produce a good or service (Hertwich and Peters, 2009; Hoekstra and Mekonnen, 2012; Wiedmann et al., 2013).

Available footprint approaches and tools can be used to assess the role trade plays in a country's total consumption-based global appropriation of limited resources or emissions. Sandin et al. (2015) have used Life Cycle Assessment (LCA) impact categories to assess product-scale impact on several planetary boundaries. Fang et al. (2015a) have shown that for most of the PB processes there is now a thematic footprint measure that could be used as an approximation of the national impact on the planetary boundaries (Table 2). They argue that a synthesis of methods makes it possible to benchmark sustainable footprints.

The carbon footprint has been quite a successful concept, partly because it is independent of location (because CO_2 emissions are well mixed in the atmosphere). In contrast, the footprint indicators for spatially heterogeneous processes must currently be used with caution. For these processes, the local conditions can be crucial for defining a sustainable footprint level. For example, Lenzen et al. (2013) found that the water footprint changes significantly when the water use for export production is weighted by the respective water scarcity in the producing location. Similarly, for the

Table 2
Examples of footprint measures that can be used to estimate national performance on different PB processes. Based on Fang et al. (2015a,b).

Planetary boundaries	Footprints
Climate change	Carbon Footprint (Wiedmann and Minx, 2008), Ecological Footprint (Wackernagel et al., 1999)
Ocean acidification	Carbon Footprint (Wiedmann and Minx, 2008)
Stratospheric ozone depletion	Chemical Footprint (Sala and Goralczyk, 2013)
Chemical pollution (novel entities)	Chemical Footprint (Sala and Goralczyk, 2013)
Nitrogen cycle	Nitrogen Footprint (Leach et al., 2012), Gray Water Footprint (Hoekstra and Mekonnen, 2012)
Phosphorus cycle	Phosphorus Footprint (Wang et al., 2011), Gray Water Footprint (Hoekstra and Mekonnen, 2012)
Biodiversity loss	Biodiversity Footprint (Lenzen et al., 2012)
Land system change	Land Use Footprint (Weinzettel et al., 2013), Ecological Footprint (Wackernagel et al., 1999)
Fresh water use	Blue and Green Water Footprint (Hoekstra and Mekonnen, 2012)
Atmospheric aerosol loading	PM10 Footprint (Moran et al., 2013)

ecological footprint, van Vuuren and Bouwman (2005) and van Vuuren and Smeets (2000) pointed out that land productivity is an important factor that determines the actual amount of land used. To harmonize the footprint methodologies, Ridoutt et al. (2015) propose the development of a coherent set of footprint indicators based on Life Cycle Assessment.

3.1.3. Application of equity-based allocation principles

Beyond the biophysical and socio-economic principles described above, equity principles can be used to explore different allocation rules for sharing the global safe operating space. A core principle accepted in international policy is that of 'common but differentiated responsibility' discussed in Section 2.3. This underlines that responses to environmental problems should allow for differences in countries' diverse circumstances and capacities (Pauw et al., 2014; Schroeder and Pisupati, 2009).

Various proposals for equitable burden sharing for climate change mitigation have been discussed in the literature. Fleurbaey et al. (2014) provide an overview of equity principles along four key dimensions: responsibility, capacity, equality, and the right to sustainable development (see also Table 3). den Elzen et al. (2003) developed a similar typology of equity principles, categorizing them into rights- or duty-based approaches. Approaches based on equality, sovereignty, and right to develop principles establish a right to emit, while approaches framed in terms of responsibility and capability establish a duty to contribute to mitigation. den Elzen et al. (2003) further argue that several burden-sharing proposals discussed in literature relate to more than one equity principle. We suggest that the present-day debates also include a voluntarist principle, where every country decides its own response, without directly taking other countries' actions into account.

The challenge for policymaking is that the different equity definitions can lead to very different outcomes (den Elzen et al., 2003; Müller, 2002; Raupach et al., 2014; Steininger et al., 2015; Sullivan, 2012). Moreover, there is no global agreement on which equity principle should be used to set a global regime. The many burden sharing approaches suggested so far have never been formally used for setting national targets from a global perspective. Under the UN Framework Convention on Climate Change, the Kyoto Protocol's national targets were negotiated, while in the Copenhagen Accords and the Paris Agreement they are based on national pledges. From a regime perspective these pledges represent a voluntarist approach, where global rights and duties are not explicit. The same holds for the SDGs, as national targets are to be determined by countries themselves, in line with the global ambition set out in the 2030 Agenda. However, global regime calculations could be used to assess if a country's or region's pledge corresponds with what could be considered fair, applying different ethical principles. Furthermore, countries themselves can decide to use a specific principle, or mix of principles, for setting their own national targets, i.e. national fair shares.

Different equity principles may need to be applied for the different planetary boundary processes. The globally manifest processes (climate change, ocean acidification, ozone depletion, and systemic chemical pollution) can be treated as global commons problems. As such, all humans might have use rights but not exclusion rights, along with shared responsibility for addressing these problems. For these processes, in theory, all principles could be applied.

For the spatially heterogeneous systemic processes, the equitable allocation issue is less straightforward, as these processes cannot directly be treated as global commons. Based on biophysical considerations alone, there is no direct reason why for example someone from a wet region of the world might be responsible for water scarcity problems in an arid region. Yet, when social-economic aspects are included, primarily through international trade, there might be a shared responsibility between the producer and consumer for local environmental degradation. For example, if country A consumes water-intensive agricultural commodities produced in country B that might contribute to local water scarcity, an assessment in country A of its national impact on planetary boundaries or its entitlement to water resources globally might want to take this into account. Ways to apply this 'shrink and share' perspective on global equity have been discussed for land and water resources (Hoekstra and Wiedmann, 2014; Kitzes et al., 2008). Considering emergent opportunities, Steffen and Stafford Smith (2013) argued that managing the biophysical aspects of the spatially heterogeneous processes at sub-global levels could be compatible with enhancing various aspects of social equity, such as improved access to resources, increased food security, and economic development in developing nations.

3.2. Integrative techniques

Participatory processes, integrative frameworks, and models that emphasize causal relationships provide ways to bridge across all three dimensions and facilitate the operationalization of the PB concept (Fig. 1). Even though these approaches were not in the first place developed for (comprehensive) cross-scale translation, they can support the translation process from specific perspectives, i.e., horizontal and vertical integration and policy coherence (nexus methods), identifying entry points for interventions (the DPSIR framework), supporting horizontal integration and testing

Table 3
Examples of equity principles for sharing the planetary safe operating space, based on Fleurbaey et al. (2014) and Den Elzen and Lucas (2005).

Principle	Description	Examples
Equality	All people have equal rights to the ecological space	Contraction and Convergence (C&C): Allocation of the global emission allowances based on a convergence of per capita emission levels of all Parties
Sovereignty	All countries have a right to use the ecological space. Current use constitutes a 'status quo right'	Grandfathering: Allocation of the global emission allowances proportional to Parties' present emissions
Right to development	A right to an exemption from obligations to poor Parties	CSE convergence: Per capita emission convergence (C&C) combined with basic sustainable emission rights
Responsibility (Polluter pays)	The greater the contribution to the problem, the greater the share of the user in the mitigation/economic burden	Brazilian Proposal: Reduction targets based on Parties' historic contribution to temperature increase
Capacity (Ability to pay)	The greater the capacity to act or pay, the greater is the share in the mitigation/economic burden	Ability to pay: Allocation of global emission allowances based on per capita income levels
Voluntarism	Every country determines its own response, and is responsible and has the rights for the impact in its own territory	National pledges: Reduction targets are set by countries themselves, without directly taking other countries' actions into account

alternative pathways at the global level (Integrated Assessment Models), and integrating science and policy making (stakeholder dialogues).

3.2.1. The Nexus approach

Nexus approaches integrate the management of environmental resources and society's need for energy-, food-, and water-security (Hoff, 2011; Howells et al., 2013). Hoff (2011) argues that social equity is a guiding principle of a nexus approach, when decisions are made about allocation of limited resources. These nexus approaches extend the current scientific integration across planetary boundaries by focusing on the interconnectedness of environmental resource flows and decisions and policies that bridge sectors and scales, and by providing links to economic methods for assessing resource use efficiency and sustainable patterns of production, consumption and trade. Linking insights from global environmental modeling to full life-cycle analyses, footprinting methods, and similar assessment tools can help inform decision- and policy–making about the relevance of planetary boundaries for them. For national application it is important to look at the different footprints together, to avoid the risk of problem-shifting among environmental issues.

3.2.2. Social-ecological system perspective: the DPSIR framework

The Driver-Pressure-State-Impact-Response (DPSIR) framework (EEA, 1999; OECD, 1993) is a simple way to structure exploration of the causal links and interdependencies of environment and human activities. In this multi-scale systemic framework, social and economic development drivers create pressure on the environment. Changes in the state of the environment lead to unwanted impacts that build up until they generate a societal response. Responses could include adaptation to the impacts, remediation of the environmental damage, or mitigation actions targeted at the social driving forces. The framework can therefore be seen as a form of adaptive cycle (Gunderson and Holling, 2002), accommodating options that support resilience to change and also enable transformation in response to change.

The DPSIR framework can help analyze planetary boundary processes at different scales while also making the human drivers behind the environmental pressures explicit (Nykvist et al., 2013). This can be useful in pointing towards the most appropriate metrics and targets for national application of the PB framework. For example in the case of the climate change boundary, at country level it can be easier to monitor national greenhouse gas emissions than to assess the national contribution to atmospheric CO_2 concentration or energy imbalance. Moreover, the role of national sectors causing the pressure can be analyzed to inform policy decisions.

3.2.3. Integrated assessment models

Integrated Assessment Models (IAMs) link insights from different disciplines within a single framework, aiming for advising policy-making. Generally, IAMs use simplified representations of human and Earth systems to bridge different geographical scales and timeframes and relate different environmental issues. Many IAMs are built on the DPSIR framework and can be used for nexus analysis as they include a broad range of PB processes. van Vuuren et al. (2015) analyzed alternative global pathways along which a set of the sustainable development goals (both environmental and poverty-related) could be reached, taking account the interlinkages, trade-offs, and synergies between them. For the national application of the planetary boundaries, this kind of pathway analysis can be useful in highlighting the required short-term societal actions in reaching long-term environmental goals. Furthermore, IAMs can be used to assess regional impacts (environmental and economic) of different regimes for global climate mitigation (Tavoni et al., 2013; van Vuuren et al., 2007).

3.2.4. Stakeholder dialogues

Defining nationalized boundaries offers an opportunity for exchanging and developing relevant knowledge about global sustainability and national responsibilities. The only way that informed decisions can be made about what social and environmental trade-offs are possible in a particular location, and which national-level needs should be prioritized, is through dialogue among diverse knowledge holders and stakeholders at the relevant scales (Dietz et al., 2003). Close liaison with national stakeholders is consistent with the international commitment made at the 1992 Rio Earth Summit, to develop local strategy and action programs for implementing sustainable development, under Agenda 21, which recognizes the importance of participation for improved sustainability governance.

Finding better ways to address the mismatch in scale of global processes and local agency is thus a task that extends beyond the academic community (Cash and Moser, 2000 Wilbanks and Kates, 1999). Better approaches for public and policy engagement are needed, that go beyond 'applying the science' to supporting informed processes for agreeing the terms for action. Here, co-design and co-generation of relevant knowledge among diverse knowledge producers and stakeholders play a crucial role for the integration of contributory knowledge and values (Kirchhoff et al., 2013; Mauser et al., 2013). Multi-level participatory modeling (see e.g., Smajgl, 2010) and other participatory tools such as multi-scale systems analysis or scenario planning (see e.g., Butler et al., 2014) can support this co-generation of knowledge that bridges across scales.

4. What can be learned from previous studies?

Several studies have already applied the planetary boundaries concept to the national or regional level, using very different translation approaches. In this Section, we assess them in the light of the conceptual framework developed in Section 2. In Table 4 we summarise how the different studies dealt with the biophysical, socio-economic, and equity dimensions. By evaluating their strengths and limitations, we point towards a robust way forward for future studies.

Three studies have applied the PB framework as global sustainability criteria to define 'top-down' national boundaries. Nykvist et al. (2013) followed the PB framework strictly to derive equal per capita boundaries for Sweden. They evaluated the Swedish environmental impact and assessed national responsibility for each process in the global context set by the planetary boundaries, with a cross-country comparison of consumption and production (territorial) performance. To 'mainstream' PB thinking at national level, Nykvist et al. assessed policy coherence with current national environmental targets and policies, and applied the DPSIR framework to identify policy-relevant entry points for national level boundary indicators. Hoff et al. (2014) used a similar top-down approach to estimate the contribution of European consumption to total environmental pressures on planetary boundaries, using environmental footprints. Their approach highlights the role of EU's production and consumption pattern in contributing to the current state of planetary boundary processes. Dao et al. (2015) also used footprinting methods to define national limits for consumption impacts in Switzerland, compared with global limits for several of the planetary boundary processes. They addressed intergenerational equity aspects by estimating per capita boundaries until 2100, taking into consideration world population growth and similar rights for resources for the past, current, and future generations.

Table 4
Comparison of the national and regional planetary boundaries studies (Rockström et al. (2009) is abbreviated to R2009).

Study	Country or region	Biophysical dimension: indicators and approaches used	Socio-economic dimension: environmental performance measure	Equity dimension: allocation principles	Strengths	Limitations
Nykvist et al. (2013)	Sweden	Top-down boundaries following the R2009 framework. DPSIR framework is used to convert 'state' indicators to 'pressure' indicators. Water scarcity is suggested to be included when defining context-specific water boundaries.	Production and consumption-based indicators are compared.	Equal per capita shares.	Addresses national responsibilities for global sustainability. Provides a comparison of counties' environmental performance. Links PB processes to existing national environmental objectives. DPSIR framework allows the identification of more policy-relevant indicators.	Top-down derived boundaries do not take location-specific environmental conditions into consideration. Equal per capita allocation does not address for example historical responsibility for the impacts.
Hoff et al. (2014)	European Union	Follows the R2009 framework.	Consumption-based footprint indicators compared with production based indicators.	Equal per capita shares.	Uses consumption-based footprints to address global impact of regional consumption patterns.	Top-down derived boundaries do not take location-specific environmental conditions into consideration. Equal per capita allocation does not address for example historical responsibility for the impacts.
Dao et al. (2015)	Switzerland	Follows the R2009 framework with modification to indicators and control variable values. Water use boundary is excluded.	Consumption-based footprint indicators.	An equal share per capita compared with a "hybrid-allocation" considering also the past impact and future generations.	Time perspective is recognized by considering shares over time, including inter- and intra-generational equity considerations.	Top-down derived boundaries do not take location-specific environmental conditions into consideration.
Dearing et al. (2014)	Two Chinese regions	Boundaries based on observation records of regional system behavior on selected regionally relevant environmental processes. Biophysical boundaries are complemented with evaluation of state of national social priorities.	Production-based territorial indicators.	No allocation is applied because regional boundaries are derived from regional sustainability considerations.	Biophysical data and models used to derive regional boundaries. The dynamics of the processes presented.	The analysis does not use the original planetary boundaries as a starting point but considers only regional sustainability criteria. The derived processes and boundaries are only vaguely related to the planetary boundaries.
Cole et al. (2014)	South Africa	Bottom-up boundaries based on priority national environmental concerns, identified using a decision-based methodology including stakeholder dialogue. R2009 framework structure is kept to large extent. All the control variables are adjusted to suit national circumstances and data. Trends in the control variables are shown.	Production-based territorial indicators based on national and international databases and studies.	No allocation is applied because boundaries are based on national conditions.	Uses stakeholder dialogue to define national boundaries.	No connection was made between the global sustainability criteria and regional sustainability criteria. Related to that, fairness in sharing the global safe operating space was not addressed.

Dearing et al. (2014) applied the conceptual approach of defining precautionary boundaries to avoid socially harmful environmental thresholds in large geographic regions, arguing that the sub-global scale is important for both biophysical and decision-making processes. Dearing et al. did not analyse the interaction between the environmental conditions and human wellbeing in the study areas, but following Raworth's (2012) conceptual framework, they considered that nationally defined social priorities should be the basis of the social foundation. They argue that their empirically based 'regional safe and just operating space' framework is complementary to the PB framework because respecting sub-global boundaries is necessary (but not necessarily sufficient) for reducing the aggregated effects on several of the planetary boundaries. They sought to define boundaries for key ecosystem services based on observed biophysical thresholds and dynamic interdependencies in two Chinese regions. Capturing location-specific environmental sustainability concerns depends on the availability of time series data to show the trends and thresholds in these variables. Their selected environmental processes therefore differ from the Earth system processes and related control variables used in the PB framework, and they present no explicit 'translation' procedure from global to regional or vice versa.

Cole et al. (2014) used a bottom-up stakeholder-engagement approach to determine national level indicators and boundaries, presenting a 'national barometer' for sustainable development in South Africa. Their approach elicited expert opinion on nationally relevant environmental issues and boundary values. For 'global boundaries', Cole et al. used national policy positions on international agreements (ozone) and national pledges (climate) as national level boundaries. For the other processes, they considered local natural resource availability (water and land), as well as specific national conditions for nutrient use, acceptable level of air pollution for human health, sustainable level of marine harvesting, and biodiversity loss. Although their study demonstrated that it is possible to apply the procedural approach of the PB framework in ways that are relevant in the national context, no direct link between the national scale sustainability and global scale impact was made. The study also focused only on territorial environmental impact, and did not discuss the possible external impact of the national consumption. Due to their national focus, the ethical dimension of sharing the global safe operating space was not discussed.

Regarding the biophysical dimension, most studies identified environmental data as an important tool for national implementation, and data availability as an important factor determining the choice of the control variables. In some cases, the selected environmental processes were changed to better match local conditions and environmental concerns. However, in these cases the link to the PB global sustainability framework has remained unclear. As Dearing et al. (2014) found, defining precautionary boundaries to avoid local or regional environmental thresholds probably leads to a different set of critical processes than Rockström et al. (2009) identified. The corollary is that a range of different processes may need to be targeted if local interventions are made to control the PB perturbations. The temporal perspective also needs more attention, because both the individual processes and their interactions are dynamic. Some of the studies note that the regional boundary values change over time.

Concerning the socio-economic dimension, many studies took the national or regional contribution and responsibility for global environmental sustainability into account, generally by comparing both production and consumption-based approaches. These studies are based on footprints and underlying Multi-Regional Input-Output (MRIO) model as tools. The bottom-up studies tend to focus only on the environmental pressures caused by internal production. Future bottom-up studies should include the consumption-based perspective.

From an ethical point of view, some of the studies focused only on national or regional scale sustainability and thus disregarded the international social equity aspect of their nationalized boundaries. Other studies applied the equality principle as a tool and calculated equal per capita allocations, based on current population numbers. In future studies, the different implications of alternative allocation procedures based on the other principles should be further analyzed.

Regarding the tools and techniques presented in Fig. 1 and Section 3, some of them were applied in the previous studies (see also Table 4), but not in a consistent or comparable way. In future studies, sensitivity or scenario analysis, with respect to data uncertainties and different choices in the socio-economic and ethical dimensions, would be needed to enable policy decision-making.

5. The way forward: insights for national applications

In this paper we have assessed key challenges for translating Planetary Boundary processes to national policy targets. It is important to provide means to link environmental targets across different scales to make them operational for policy making. The planetary boundaries have complex interactions, so in practice blunt simplifications need to be made to enable and mobilise societal action for global sustainability. In this paper, we have discussed several key concepts, methods, and tools to do this. Our concluding messages are the following:

Bridging scales needs to address distinct biophysical, socio-economic, and ethical dimensions. In translating the planetary boundaries into national level policy targets, these three dimensions should be considered explicitly. The biophysical dimension deals with the geographical scales of the planetary boundaries processes and their interactions. The socio-economic dimension addresses the sub-global links created by production and consumption patterns and through international trade. Finally, the ethical dimension addresses equity in sharing the global safe operating space and recognizing the differences between countries' rights, abilities, and responsibilities. The reason for us to distinguish between the socio-economic dimension (e.g., via trade) and the ethical dimension (via equity and fairness considerations) in translating and operationalizing the PBs is that the former is given in a globalizing world, while the latter is yet to be established. We see it being debated in global governance, as is currently happening in the climate negotiations and agreements. Therefore, for national policy-making, these two dimensions of PB translation present very different points of departure. So far, national PB studies have made different choices about how to apply and balance these dimensions. We have looked closely at five studies that provide important examples of how sub-global targets can be derived. Combining insights from these previous studies within our three-dimensional approach provides a framework for good practice guidelines for future applications.

A key distinction can be made between planetary boundary processes that directly impact the (relatively) stable global Holocene baseline of a major Earth system component and the spatially heterogeneous processes connecting multiple components. For globally manifest processes, the decision about national responsibility for biophysical impact is analytically relatively straightforward. It is mostly about the contribution of countries to global commons problems, for which principles for allocation are well explored. The spatially heterogeneous, systemically connected processes have only recently been seen as global problems through scientific insights about Earth system dynamics and global socio-economic connectivity. These may not show up as nationally important issues if only territorial approaches are applied. It takes a more in-depth life cycle or consumption-based analysis to show where there is a substantial national responsibility. Fairness and equity debates that are currently articulated for climate, chemical pollution, and biodiversity are probably going to need to extend to other issues relating to land, water, and air quality, as the globally systemic nature of their connections becomes more evident.

There is a need to better connect top-down and bottom-up approaches to operationalizing the PB concept at the sub-global scale because relevant processes operate at different scales. A major challenge is that integrative approaches at the global scale (Earth system science) and local scale (social-ecological resilience, local sustainability assessments) are usually based on different methodologies and disciplines. Concepts, techniques, and tools need to be developed and adapted based on the more theoretical considerations we have outlined. The techniques and tools presented in this paper can help to bridge the gaps between global and local scale approaches and targets and with that foster vertical policy coherence (across scales) and also horizontal policy coherence (across environmental issues, PBs, and sectors).

The links among the boundaries need to be better addressed, as do the links between the boundaries and human wellbeing. Achieving sustainable development means staying within global environmental boundaries and at the same time ensuring adequate resources for all. When apportioning the global safe operating space to country scale, the fairness aspect becomes crucial. Understanding the implications of different equity principles can give more insights to fairness discussions. A nexus approach is useful for linking environmental and social policy objectives in ways that can point more directly to national interests. For example, requirements for food, energy, and water security link ecosystems and resource management at multiple scales with human wellbeing.

The Sustainable Development Goals could be used as a basis for reframing the PB concept towards a safe operating space agenda. The SDGs are a globally agreed framework of goals and targets, together addressing a broad range of interrelated challenges for sustainable human development. The 2030 Agenda thereby provides a facilitating context for the governance of the planetary boundaries. It places the PB concept in the broader context of sustainable development. By more explicitly linking the PBs to their underlying and interrelated social, economic, environmental, and institutional dynamics, the approach we discussed in this paper can inform the development of biophysically grounded and socio-economically responsible, fair and just national shares of the global challenges.

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