



Allocating planetary boundaries to large economies: Distributional consequences of alternative perspectives on distributive fairness



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ARTICLE INFO

Keywords:

Planetary boundaries
MRIO modelling
Environmental footprints
Budget allocation
Equity

ABSTRACT

The planetary boundaries (PBs) framework proposes global quantitative precautionary limits for human perturbation of nine critical Earth system processes. Together they define a global *safe operating space* for human development. Translating the global limits to the national level increases their policy relevance. Such translation essentially divides up the global safe operating space. What is considered fair distribution is a political decision and there is no globally agreed principle that can be applied. Here, we analyse the distributional consequences of alternative perspectives on distributive fairness. We scale the global limits of selected PBs to resource budgets for the EU, US, China and India, using three allocation approaches from the climate change literature. Furthermore, we compare the allocated budgets to 2010 environmental footprints of the four economies, to assess their performance with respect to the selected PBs. The allocation approaches are based on (1) current shares of global environmental pressure ('grandfathering'); (2) 'equal per capita' shares, and (3) 'ability to pay' to reduce environmental pressure. The results show that the four economies are not living within the global safe operating space. Their 2010 environmental footprints are larger than the allocated budgets for all approaches and parameterisations analysed for the PBs for climate change and biogeochemical flows, and, except for India, also for the PB for biosphere integrity. Grandfathering was found to be most favourable for the EU and US for all PBs, and ability to pay as least favourable. For climate change and biogeochemical flows, ability to pay even resulted in negative resource budgets for the two economies. In contrast, for China and India, equal per capita allocation and ability to pay were most favourable. Results were sensitive to the parameterisation. Accounting for future population growth in the equal per capita approach benefits India, with lower budgets for the EU, US and China, while accounting for future economic growth in ability to pay benefits the EU and US, with lower budgets for China and India. Our results underline the need for all four economies to act, while hinting at diverging preferences for specific allocation approaches. The methodology and results may help countries to define policy targets in line with global ambitions, such as those defined by the Sustainable Development Goals (SDGs), accounting for differences in countries' circumstances and capacities. Further attention is required for PB-specific allocation approaches and integration of biophysical and socioeconomic considerations in the allocation.

1. Introduction

Human pressures on the global environment and related environmental impacts have accelerated significantly since 1950 (Steffen et al., 2015a). Almost every component of the Earth system has now been modified as the result of human activity, inspiring some researchers to announce a new geological epoch, naming it the 'Anthropocene' (Crutzen and Stoermer, 2000). Recent global environmental assessments conclude that, without concerted action, current trends will lead to further environmental degradation, posing serious challenges for human well-being and sustainable development (IPCC 2018; IPBES,

2019; UNEP, 2019).

The planetary boundaries (PBs) framework has been proposed as a set of indicators to monitor anthropogenic perturbation of nine critical Earth system processes (Rockström et al., 2009b; Steffen et al., 2015b). The authors further propose precautionary limits, called planetary boundaries (PBs), for each of these indicators based on levels observed during the Holocene. They argue that a Holocene-like state of the Earth system ensures sufficient stability and resilience for ecosystems to support human well-being. Together, the nine PBs define levels of global environmental change in which the environmental risks are considered manageable — i.e. a global *safe operating space* for human

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<https://doi.org/10.1016/j.gloenvcha.2019.102017>

Received 18 May 2019; Received in revised form 7 October 2019; Accepted 20 November 2019

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development. Currently, four PBs are assessed to be transgressed with anthropogenic pressures exceeding the proposed limits (Steffen et al., 2015b).

Since its first publication in 2009, the PBs framework has attracted significant interest from science, business and policy-making. It has been developed further and applied in the scientific literature (Downing et al., 2019), including in improved assessments of individual PB processes (Carpenter and Bennett, 2011; De Vries et al., 2013; Mace et al., 2014), new approaches to address complex interactions and human impacts (Van Vuuren et al., 2016) and translation of the concept to sub-global scales (Häyhä et al., 2016). Furthermore, methodologies have been proposed to make the framework relevant for business (see Sabag Muñoz and Gladek, 2017) and investors (Butz et al., 2018). Finally, the concept has generated interest among EU policymakers (e.g. EU, 2013; BMUB, 2016) and featured prominently in the drafting of the Sustainable Development Goals (SDGs; Lucas et al., 2014; UN, 2015). Recently, it has been proposed that the PBs framework could be used to support the implementation of the SDGs (Hajer et al., 2015) and even to help set global quantitative targets, in line with the more qualitative SDG ambitions (Hoff and Alva, 2017; Lucas et al., 2019).

Although the PBs framework was not designed to be ‘downscaled’ or ‘disaggregated’ to smaller levels (Steffen et al., 2015b), decisions regarding environmental management and resource use are not made on a planetary scale. Therefore, to enable the framework to guide environmental policy-making, its global biophysical information needs to be translated into measures related to human activities at the national level (Häyhä et al., 2016; Dao et al., 2018).

The discussion about allocation of resource rights or reductions of environmental pressures among countries is not new. Common but differentiated responsibilities (CBDR) is a core principle in international environmental law (Pauw et al., 2014). The principle balances the need for all countries to take responsibility for global environmental problems, while recognising the wide differences in countries’ diverse circumstances and capacities. For instance, CBDR is explicitly mentioned in the United Nations Framework Convention on Climate Change (UNFCCC, 1992) and, with respect to environmental issues, was reaffirmed in the 2030 Agenda for Sustainable Development (UN, 2015). For climate change, many proposals for fair and equitable sharing of global emission reduction obligations are presented and discussed in the literature, especially during the first decade of this century (Fleurbay et al., 2014). These so-called allocation approaches are based on divergent equity principles, i.e. general concepts of distributive fairness. In the context of PBs, the discussion on translating global limits to national levels is relatively new, with only a few studies in the scientific literature discussing top-down allocation of PBs to countries (e.g. Fang et al., 2015b; Fanning and O’Neill, 2016; Dao et al., 2018; O’Neill et al., 2018). However, these studies mostly apply one allocation approach per PB, most often based on a country’s share in the global population (equal per capita), and, to date, a systematic analysis of alternative allocation approaches is lacking.

In this paper, we go beyond the existing literature by downscaling selected PBs to the national level, on the basis of different perspectives on distributive fairness. The analysis uses three distinct allocation approaches from the climate change literature (Van den Berg et al., 2019), namely (i) allocation of PBs based on a country’s share in global environmental pressure (grandfathering); (ii) allocation of PBs based on a country’s share in the global population (equal per capita); and (iii) allocation of global transgression of PBs based on a country’s GDP per capita (ability to pay). The allocated budgets should not be confused with targets, but the results can be used to inform discussions about national responsibilities.

For the analysis, the PBs were interpreted as budgets, i.e. the maximum allowable global pressure that can be shared among countries. Applying the three allocation approaches, these budgets were downscaled to the national level, focusing on four large economies (the European

Union (EU),¹ the United States (US), China and India). Together, these four economies accounted for around 40% of the global population (UNDESA, 2019) and 65% of global GDP (World Bank, 2019) in 2019 and 40% to 60% of the global environmental pressures on the selected PBs in 2010 (see Section 3.1). To assess national transgression of the allocated budgets, the downscaled PBs were benchmarked against 2010 national footprints. The year 2010 was the most recent year for which consistent input-output and environmental data was available at the time of research. Footprints consider environmental pressures along the whole supply chain related to national consumption, including imports and excluding exports. Such a perspective provides insights into the countries’ shares in limited natural resource availability and environmental pressures, on a global scale, and is thus relevant for evaluating country performance on global issues (Dao et al., 2018).

The remainder of the article is structured as follows: Section 2 discusses the indicators and global budgets used, as well as the methodologies applied for the calculation of the environmental footprints and the allocation approaches. Section 3 reports the results, including national environmental pressures and allocated budgets, as well as a comparison between the two to discuss country performance on the selected PBs. Section 4 discusses the results in the light of related country-level effort, existing literature and limitations of the analysis. Finally, Section 5 draws some overall conclusions.

2. Methods

The analysis builds on the framework of Häyhä et al. (2016), who argue that translation of PBs to a national level requires addressing their biophysical, socio-economic, and ethical dimensions. The *biophysical dimension* deals with the temporal and spatial scales at which the PB processes take place as well as with the processes, interactions and feedbacks that dominate at those scales. The *socio-economic dimension* addresses differences in natural resource use, emissions and environmental impacts between countries, created by production and consumption patterns and through international trade. Finally, the *ethical dimension* considers the differences in rights, abilities, and responsibilities between countries with respect to resource use, emissions and environmental impacts. In this section, we discuss the three dimensions in the context of our study, including (1) selected PB processes, control variables and global budgets (Section 2.1); (2) countries’ environmental pressures on the selected PB processes (Section 2.2); and (3) ethical considerations and allocation approaches for scaling the global budgets to a national level (Section 2.3).

2.1. Selected control variables and global budgets

Roughly two types of PB processes can be distinguished, i.e. systemic processes and aggregated processes (Rockström et al., 2009a). For systemic processes, human activities have a direct impact on Earth system components (e.g. climate change and stratospheric ozone depletion) and global scale thresholds can be identified. For aggregated processes, human activities have an impact on Earth system components on a local or regional scale (e.g. biosphere integrity and biogeochemical flows) without known global scale thresholds. For the first type, there is broad consensus that global coordination is needed for policy responses (see f.i. UNFCCC, 1992) and downscaling is possible. This is not directly obvious for the aggregated processes, although there are reasons why, also here, global coordination and downscaling makes sense (Häyhä et al., 2016). First, scientific understanding is growing that local changes can cascade through the global Earth system, changing physical and biogeochemical feedbacks. Secondly, as a result of international trade, there is a shared responsibility between producers

¹ In the analysis, the EU includes the 27 countries that were a member in 2010 (i.e. excluding Croatia).

and consumers for local environmental degradation. Thirdly, consumption of natural resources and related benefits and environmental impacts are not equally distributed among countries and between groups of people, having implications for the issues of environmental justice, burden sharing, and allocation of scarce resources.

Following the methodology of Dao et al. (2018), four PB processes were selected for analysis: climate change, land-system change (here interpreted as land-use change), biogeochemical flows (including the nitrogen (N) cycle and the phosphorus (P) cycle) and biosphere integrity (here interpreted as biodiversity loss). These are systemic processes or aggregated processes for which a global limit could potentially be identified. Stratospheric ozone depletion was not selected as most ozone-depleting substances are currently phased out. Ocean acidification was not selected, due to its almost one-to-one link with CO₂ emissions, the main driver of global climate change. We are aware that there are still discussions on the PB concept and quantification in the literature. In this paper, we use the proposed limits as they are.

For each selected PB process, a biophysical 'control variable' and a global budget were defined. The PB framework includes a mix of control variables, defined as states of specific PB processes (e.g. atmospheric CO₂ concentration) or as human pressures (e.g. intentional N fixation). Where a control variable defining a state is the closest to the essence of the PB framework, only control variables defining a driver or a pressure can directly be controlled or changed by humans. These are preferred for assessing countries' performances on specific PB processes (Nykqvist et al., 2013). Furthermore, data on national and sectoral levels should be available for the selected control variable to allow benchmarking of allocated PBs against environmental pressures from various perspectives. The selected control variables and related global budgets are thus not necessarily similar to those proposed in the PB framework (Fang et al., 2015a; Dao et al., 2018).

As the biogeochemical flows PB is represented by two cycles (N and P), five control variables are included in the analysis. The PBs, and thereby the budgets, differ in their temporal perspective, i.e. cumulative or annual (Häyhä et al., 2016; Dao et al., 2018). For climate change, the budget is based on the targets in the Paris Agreement (Rogelj et al., 2018). It is a cumulative budget, defining maximum CO₂ emissions that could still be emitted this century, while staying below a 1.5 °C global temperature increase. The global budgets for the other PB processes are based on the global limits from the PB framework. For land-use change and biogeochemical flows, these are annual budgets defining maximum allowable annual cropland use, intentional N fixation and P fertilizer use. For biodiversity loss, the global budget is defined as the total allowable anthropogenic biodiversity loss, using mean species abundance (MSA) as the control variable (see Section 2.1.4). Here, the global budget is a limit on total biodiversity loss that should not be exceeded. The selected control variables and global budgets are summarised in Table 1.

2.1.1. Climate change

The proposed control variables in the PB framework for climate change are atmospheric CO₂ concentration and change in radiative forcing (Steffen et al., 2015b). Global policy targets are expressed in

terms of maximum allowable global temperature increase (UNFCCC, 2015). We based the global budget on the Paris Agreement target, i.e. 'Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' (UNFCCC, 2015). Applying the precautionary principle, as done for quantification of the PBs, the lower limit (maximum 1.5 °C increase) was chosen. As cumulative CO₂ emissions strongly determine the overall warming impact on a century timescale (Meinshausen et al., 2009; Friedlingstein et al., 2014; IPCC, 2014), CO₂ emissions was selected as the control variable. Limiting global temperature increase to 1.5 °C corresponds to a cumulative carbon budget of 860 GtCO₂ from 2011 onwards (Rogelj et al., 2018). Accounting for 290 GtCO₂ emissions emitted globally between 2011 and 2018 (Le Quéré et al., 2018b), a global budget of 570 GtCO₂ from 2018 onwards was used. Under 1.5 °C scenarios, the net contribution of land-use change to cumulative CO₂ emissions over the 2010–2100 period is projected to be close to zero, as emissions are projected to be reduced to zero in the next decade, followed by a period of negative emissions due to reforestation activities (Clarke et al., 2014). Therefore, our analysis focuses only on CO₂ from energy and industry.

As this is a cumulative budget, it cannot directly be benchmarked to annual environmental pressures (here CO₂ emissions), globally or nationally. In the literature, various benchmarking methods have been applied. Nykvist et al. (2013) assumes an equal distribution of the allocated budget between now and 2100, benchmarked to 2010 country footprints. Dao et al. (2018) assumes identical annual per capita budgets between now and 2100, benchmarked to 2010 country footprints. Finally, Fanning and O'Neill (2016) benchmark a cumulative allocated 1850–2100 budgets to cumulative 1850–2100 country footprints. Each method has pros and cons and requires assumptions on the distribution period (in the cited studies, this concerns 2010–2100, 1990–2100 and 1850–2100, respectively), while the third method also requires assumptions on future reduction rates. Furthermore, the second and third methods link well to the equal per capita allocation approach but are less straightforward in combination with other allocation approaches.

Given the focus on alternative allocation approaches, we used the first method. The global CO₂ budget was equally distributed between 2018 and 2100, resulting in an average budget of 7.0 GtCO₂ yr⁻¹ for the remainder of this century. The distribution period chosen is consistent with the time horizon of most mitigation scenarios (IPCC 2018). Using a shorter period, for instance 2018–2050, results in higher annual budgets, as the budget is simply distributed over fewer years, but also requires net zero emissions from 2050 onwards. From the scenario literature, it can be concluded that decarbonisation of the global economy in such a short timeframe with the given carbon budget is not realistic (IPCC 2018).

2.1.2. Land-use change

For land-use change, Rockström et al. (2009b) propose the percentage of global land cover converted to cropland as the control variable, thereby focusing on biodiversity protection and ecosystem functioning. Steffen et al. (2015b) shift the focus towards the

Table 1
Selected PB processes, control variables and global budgets.

Planetary boundary	Control variable	Budget	Unit	Global budget	Global pressure (2010) ²	
Climate change		CO ₂ emissions	Cumulative	GtCO ₂	570 (7.0) ¹	30.6
Biogeochemical flows	N	Intentional N fixation	Annual	Tg N	62	121
	P	P fertiliser use	Annual	Tg P	6.2	16
Land-use change		Cropland use	Annual	Mha	1995	1424
Biodiversity loss		MSA loss	Annual	Million MSA-loss-ha	3724	5327 ³

¹ The number between brackets is the annualised budget.

² See Section 2.2 and Supplementary Material Chapter S2.

³ The MSA footprint indicator is measured as million MSA-loss-ha-yr (see Section 2.2).

biophysical processes in the land system that directly regulate climate (i.e. the exchange of energy, water, and momentum between land surface and the atmosphere), using the area of forested land as percentage of original forest cover. Due to difficulties to link forest loss to its underlying drivers (e.g. consumption of feed, food and timber) in calculating a footprint for this updated control variable, total cropland use was selected as control variable. The global budget ($\leq 15\%$ of global ice-free land surface converted to cropland) was directly derived from Rockström et al. (2009b), corresponding to maximum global cropland use of 1995 Mha.

2.1.3. Biogeochemical flows

For biogeochemical flows for N, Steffen et al. (2015b) focuses on eutrophication of aquatic ecosystems, proposing the control variable intentional N fixation (N fixation in fertiliser and from crop fixation). For biogeochemical flows for P, they focus on freshwater and coastal eutrophication, proposing P flow from fertilisers to erodible soils and P flow from fresh water into the ocean as the respective control variables. Both boundaries act as a global 'valve' limiting the introduction of new reactive N and P to the Earth system, while recognising that regional distribution is critical for impacts. Due to large uncertainties in P flows from fresh water into the ocean² and difficulties with allocating these P flows to countries and sectors in order to calculate a footprint indicator for this control variable, we use the regional-level boundary and related control variable, P fertiliser use. The global budgets (62 TgN yr^{-1} and 6.2 TgP yr^{-1}) were directly taken from Steffen et al. (2015b).

2.1.4. Biodiversity loss

Steffen et al. (2015b) based their selection of control variables on Mace et al. (2014), using both global extinction rate as an indicator of genetic diversity and the Biodiversity Intactness Index (BII) as an indicator of functional diversity. Both are interim control variables, to be used until more appropriate control variables are developed. Here, we selected mean species abundance (MSA) as indicator of functional diversity (Alkemade et al., 2009; Schipper et al., 2016). The MSA is the mean abundance of original species in a disturbed situation relative to their mean abundance in an undisturbed reference situation. The remaining MSA in a certain area is expressed in 'MSA·ha', combining the MSA value of the area (expressed as either a percentage or a value between 0 and 1) and the size of the area. The indicator is similar to the BII, except that MSA does not incorporate increases in abundance from undisturbed to disturbed conditions, i.e., if the abundance of a species is greater in the disturbed conditions than in the reference situation, the abundance of the reference situation is retained. Furthermore, MSA has also been included in footprint calculations providing the relationship between human drivers and the impacts on biodiversity from various pressures (Wilting et al., 2017), which is relevant for the benchmarking. The global budget was based on Steffen et al. (2015b), i.e. maintaining BII at 90% or above. A simulation model was used to translate this BII-based PB into a PB in MSA terms, i.e. maintaining MSA at 72% or above (see Supplementary Material Chapter S1), which is similar to a maximum MSA loss of 28%. Using the same global land area as for land-use change, this corresponds to 3724 million MSA-loss-ha, i.e. an area of 3724 Mha with a remaining MSA value of 0.

2.2. Environmental pressures

Environmental pressures can be considered both from a production- and a consumption-based perspective. In a production-based perspective, environmental pressures are related to domestic production, which includes production for exports (but not imports). A consumption-

based, or footprint, perspective refers to environmental pressures along the whole supply chain related to national consumption, including imports, excluding exports. Production-based indicators are usually published in environmental accounts that are consistent with national (economic) accounts. Footprint indicators are usually calculated with a multi-regional input-output (MRIO) model that relates production and environmental pressures in one region via international trade flows to consumption in other regions (Wiedmann, 2009). The production- and the consumption-based perspectives both include direct environmental pressures from domestic household consumption.

National footprints were calculated using a MRIO model based on input-output data from the World Input-Output Database (WIOD; Timmer et al., 2015) building on Wilting (2014). EXIOBASE version 3 (Stadler et al., 2018) was used to disaggregate the agricultural sector. Production-based environmental data, which were also used in the MRIO model, were based on WIOD and EXIOBASE for CO₂ emissions (climate change), FAO (2017) for cropland use (land-use change) and Bouwman et al. (2017) for intentional N fixation and P fertiliser use (biogeochemical flows). For MSA loss (biodiversity loss), additional data was used, including CH₄ and N₂O emissions from WIOD and EXIOBASE, and non-cropland land use from the GLOBIO model (Alkemade et al., 2009; Schipper et al., 2016), as described in Wilting et al. (2017). The biodiversity footprint is expressed in MSA-loss-ha-yr, reflecting the integration of environmental pressures over space and time. The footprint here combines biodiversity losses due to land-related drivers and the potential future biodiversity losses due to consumption-related greenhouse gas emissions. See Supplementary Material Chapter S2 for further details on the footprint calculations and the data used.

2.3. Equity principles and allocation approaches

Many approaches for fair and equitable sharing of emission reduction obligations are proposed and discussed in the climate change literature. These proposals are based on one or more equity principles, i.e. general concepts of distributive fairness. Equity principles commonly discussed in the literature include (Fleurbaey et al., 2014; Höhne et al., 2014):

- *Sovereignty or acquired rights*: all countries have a right to use the ecological space and current resource use constitutes a 'status quo right'
- *Equality*: all people have equal rights to the ecological space
- *Responsibility*: countries with the largest contribution to the problem should take the largest share in the mitigation action
- *Capability or capacity*: the greater the capacity to act or pay, the greater the share in global mitigation action. The *basic need* principle or *Right to development* can be considered a special expression of the capability principle – the least capable countries could have a less ambitious reduction effort to secure their basic needs
- *Cost effectiveness*: take mitigation action where it is the most cost-effective

Allocation approaches have been used to calculate greenhouse gas emission allowances or emission reduction targets for countries in line with global long-term climate targets (e.g. BASIC experts, 2011; Höhne et al., 2014; Pan et al., 2014, 2017). A distinction can be made between rights-based and duty-based approaches (Den Elzen et al., 2003). Generally, approaches based on the equity principles *sovereignty* and *equality* establish a right to certain levels of resource use or pollution, while approaches based on *responsibility*, *capability* or *cost effectiveness* establish a duty to contribute to mitigation.

In the climate literature, most studies discuss emission allowances in line with global emission pathways (Fleurbaey et al., 2014; Höhne et al., 2014). More recently, the same allocation approaches have been applied to CO₂ budgets, i.e. total cumulative CO₂ emissions

²Recent estimates of global river P export range from 4 TgP yr^{-1} (Beusen et al., 2016) and 9 TgP yr^{-1} (Seitzinger et al., 2010) to 22 TgP yr^{-1} (Steffen et al., 2015b).

Table 2
Allocation approaches used and their parameterisation.

Approach	Equity principle	Parameters	Parameterisation ¹
Grandfathering (GF)	Sovereignty	Environmental accounting approach	Production, consumption
Equal per capita (EPC)	Equality	End year of average population share	2010 , 2030 and 2050
		Population projection	SSP1, SSP2 , SSP3 ³
Ability to pay (AP)	Capability	Environmental accounting approach	Production, consumption
		End year of average GDP share	2010 , 2030 and 2050
		GDP metric	MER, PPP ²
		GDP projection	SSP1, SSP2 , SSP3 ³

¹ Settings in bold are default parameterisations.

² MER = Market Exchange Rate; PPP = Purchasing Power Parity.

³ Population and GDP projections are taken from the Shared Socioeconomic Pathways (SSPs).

that could still be emitted worldwide while staying below specific levels of global mean temperature increase (see e.g. Raupach et al., 2014; Van den Berg et al., 2019). In a budget approach, the remaining CO₂ budget is shared among countries and each country is able to decide their own pathway, given the allocated budget. For this paper, three allocation approaches were selected from the approaches applied by Van den Berg et al. (2019), i.e. grandfathering, equal per capita allocation and ability to pay.

Grandfathering (GF) is a right-based approach based on the sovereignty principle. The approach allocates the global budget based on a country's share in global environmental pressure:

$$pb = \frac{e}{E} \cdot PB \quad (1)$$

where *pb* is the allocated country budget, *PB* the global budget, *e* national environmental pressure and *E* global environmental pressure.

Equal per capita (EPC) allocation is a right-based approach based on the equality principle. The approach allocates the global budget based on a country's share in the global population. This is the most widely used allocation approach in the PB literature. Besides population shares in a given year, allocation can also be based on projected future population shares. The following formula is used for the calculation:

$$pb = \frac{\sum_{t=start}^{t=end} pop_t}{\sum_{t=start}^{t=end} POP_t} \cdot PB \quad (2)$$

where *pop* is the national population in year *t*, *start* is the first year of the cumulation period and *end* is the end year.

Ability to pay (AP) is a duty-based approach based on the capability principle. For this approach, not the global budget, but the global transgression of the PB is distributed among countries, i.e. the difference between the global environmental pressure and the global budget. The approach is only applied to planetary boundaries that are transgressed. It allocates global transgression based on a country's per capita GDP relative to global average per capita GDP. In a first step, relative reductions in national environmental pressures (*pb_r*) are calculated. Countries with per capita GDP levels higher than the global average face relative reductions that are higher than required globally, and the other way around:

$$pb_r = 3 \sqrt{\frac{\sum_{t=start}^{t=end} gdp_t / \sum_{t=start}^{t=end} GDP_t}{\sum_{t=start}^{t=end} pop_t / \sum_{t=start}^{t=end} POP_t} \cdot \frac{(E - PB)}{E}} \quad (3)$$

where *gdp* is national GDP and *GDP* is global GDP. To take into account increasing marginal costs with steeper reductions efforts, the cube root of per capita GDP is used in the calculations (Van den Berg et al., 2019). As this calculation does not guarantee that the sum of allocated reductions (*pb_re*) matches the global transgression, a correction factor (*corr*) is calculated:

$$corr = \frac{\sum_c^N pb_{r \cdot e}}{(E - PB)} \quad (4)$$

where *N* is the total number of countries. In the final step, the national budget is calculated by subtracting the corrected national reduction from environmental pressure:

$$pb = e - \frac{pb_r \cdot e}{corr} \quad (5)$$

The three approaches were implemented in a similar way as by Van den Berg et al. (2019), except that no historical environmental pressures were taken into account for EPC. Furthermore, also no future environmental pressures were considered, meaning that the allocated global transgression for AP were subtracted from the 2010 footprint, also when future GDP developments are accounted for in the allocation.

The outcomes of the different approaches critically depend on their parameterisation (Höhne et al., 2014; Van den Berg et al., 2019). Therefore, to analyse the sensitivity of the three allocation approaches to alternative parameter settings, different parameterisations were analysed (see Table 2). EPC and AP can be based on historical, current or projected future population and GDP, respectively. The PB literature mostly applies EPC using 2010 population shares. For climate change (CO₂ emissions), several studies also include past and/or future population developments in their allocation. Here, we use the year 2010 as the default value, both for EPC and AP, and the periods from 2010 to 2030 and 2010 to 2050, for the sensitivity analysis. As there are large uncertainties in future developments in population and economic development, three distinct projections of population and GDP from the Shared Socioeconomic Pathways (SSPs) are used for the sensitivity analysis (Dellink et al., 2017; KC and Lutz, 2017). The SSP2 scenario, with medium population growth and economic development, was used as the default projection. Alternatively, the SSP1 scenario, with low population growth and high economic development, and the SSP3 scenario, with high population growth and low economic development, were used. Finally, GDP could be measured in market exchange rates (MER) or purchasing power parity (PPP). PPP was used as the default setting.

Besides parameterisation of the allocation approaches, outcomes for GF and AP depend on the way environmental pressures are accounted for, i.e. production-based or consumption-based. Consumption-based environmental pressure (i.e. footprint) was used as the default.

3. Results

In this section, we present and discuss national environmental pressures for the selected PBs and environmental accounting approach (Section 3.1) and the national-level budgets applying the three allocation approaches (Section 3.2). Subsequently, national budgets are used as a benchmark against the national environmental pressures to assess country performance on the selected PBs (Section 3.3).

3.1. National environmental pressures

Overall, except for land-use change, all PBs are transgressed

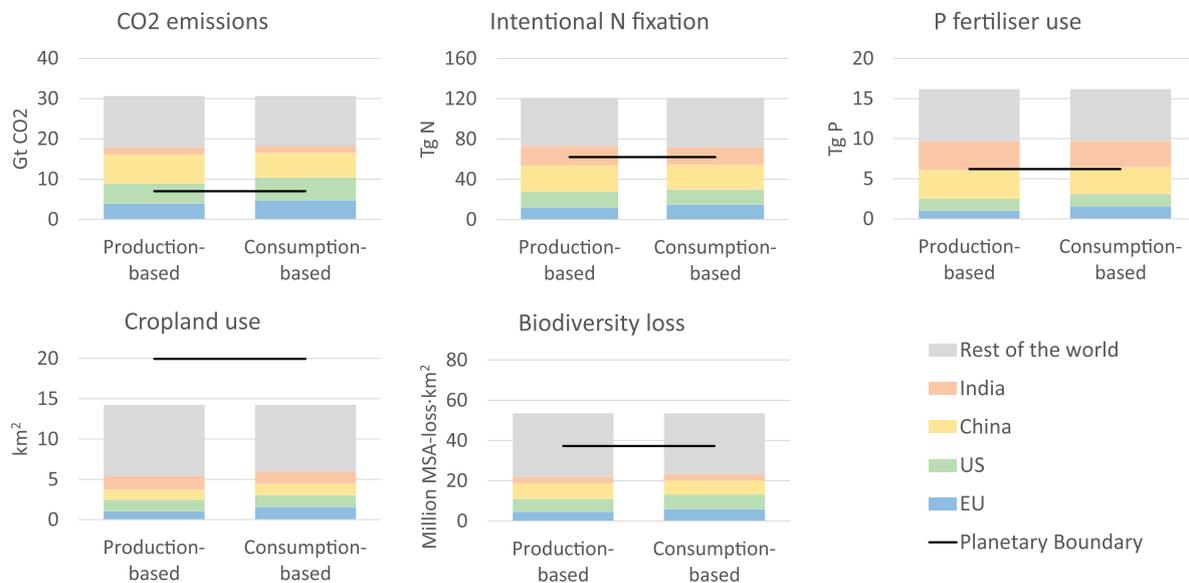


Fig. 1. Environmental pressures from two accounting principles, in 2010.

globally given the selected control variables and budgets, while the shares of the four economies in global environmental pressure differ significantly per control variable. Fig. 1 shows environmental pressures for the four economies, five control variables and the two environmental accounting approach. The selected control variable for climate change, land-use change and biodiversity loss are different than those identified by Steffen et al. (2015b) and thereby provide slightly different results.

For climate change, the planetary boundary of 350 ppm, as defined by Rockström et al. (2009b) and which has already been transgressed, is more stringent than the 1.5 °C target of the Paris Agreement selected here, which still allows around 570 GtCO₂ emissions (Table 1). Under 2018 emission levels of 37.1 GtCO₂ yr⁻¹ (Le Quéré et al., 2018a) this global budget will be exhausted in around 15 years, while the annualised budget (7.0 GtCO₂ yr⁻¹) was transgressed by a factor of 4.4 in 2010. The EU and the US are responsible for relatively large shares of the global CO₂ emissions, i.e. 29% and 34% from a production-based and a consumption-based perspective, respectively. The Chinese share is also large compared to most other PB. But, as the Chinese industry also produces for many developed countries (including the EU and the US), their production-based emissions are higher than their consumption-based emissions, i.e. 24% and 20%, respectively. Finally, the Indian share is relatively small, i.e. around 6% for both accounting approaches.

For land-use change, 2010 cropland use was around 11% of global ice-free land surface, which is significantly below the global budget of 15%. All four economies are responsible for around 10% each of global cropland use from a production-based perspective. Only the EU consumes a large share of its land use abroad, with its consumption-based cropland use being 50% higher than its production-based cropland use.

For biogeochemical flows, both the budgets of intentional N fixation and P fertiliser use are transgressed globally, with a factor of 1.9 and 2.6, respectively. Compared to climate change, the Indian shares on both control variables are relatively large (15% for N and 20% for P for a consumption-base perspective), while especially for P fertiliser use the shares of the EU and the US together is small (19% from a consumption-based perspective). As the EU sources a relatively large share of its agricultural consumption from other parts of the world (see also the discussion of the land-use change PB above), its production-based pressure is much smaller than its consumption-based pressure for both intentional N fixation (10% and 12%, respectively) and P fertilizer use

(6% and 10%, respectively). The Chinese share is around 20% for both control variables, with only a small difference between its production-based and consumption-based pressures.

Finally, the biodiversity loss budget, based on the MSA, is transgressed globally by a factor of 1.4. The consumption-based shares of the EU (11%), the US (13%) and China (13%) are much larger than of India (6%), primarily due to much higher greenhouse gas emission levels of these three economies. Also, for biodiversity loss, the difference between a production-based and a consumption-based perspective is the highest for the EU (9% and 11%, respectively), due to land use abroad.

On per capita basis (see Supplementary Material Chapter S3), the US has the highest environmental pressure on all four planetary boundary processes, with all five control variables above the global average (both production-based and consumption-based). Per capita environmental pressures in the EU are slightly lower, with the consumption-based environmental pressures above the global average and the production-based environmental pressures around or above the global average. For China, per capita environmental pressures for CO₂ emissions, intentional N fixation and P fertiliser use are around the global average (both production-based and consumption-based), while environmental pressures of cropland use and biodiversity loss are significantly below the global average. Finally, India has generally the lowest environmental pressures per capita, with only per capita environmental pressure of P fertiliser use above the global average.

3.2. Allocation results

The three allocation approaches play out differently for the four economies and four PBs. Our results show that grandfathering (GF) is the most favourable approach for the EU and the US (highest allocated budgets), and ability to pay (AP), and sometimes equal per capita (EPC), are most favourable for China and India. Fig. 2 summarises the results of the three allocation approaches in terms of country shares of the global budgets using default parameterisation (see Table 2). Fig. 3 summarises allocated budgets in per capita terms. As EPC allocation is solely based on population shares, the allocated shares are identical for all PBs (Fig. 2) and per capita results are identical for the four economies (Fig. 3). Therefore, EPC is used as a benchmark for comparing allocation approaches.

GF allocates the global budgets based on an economy's 2010 share in global environmental pressure. Of the three allocation approaches,

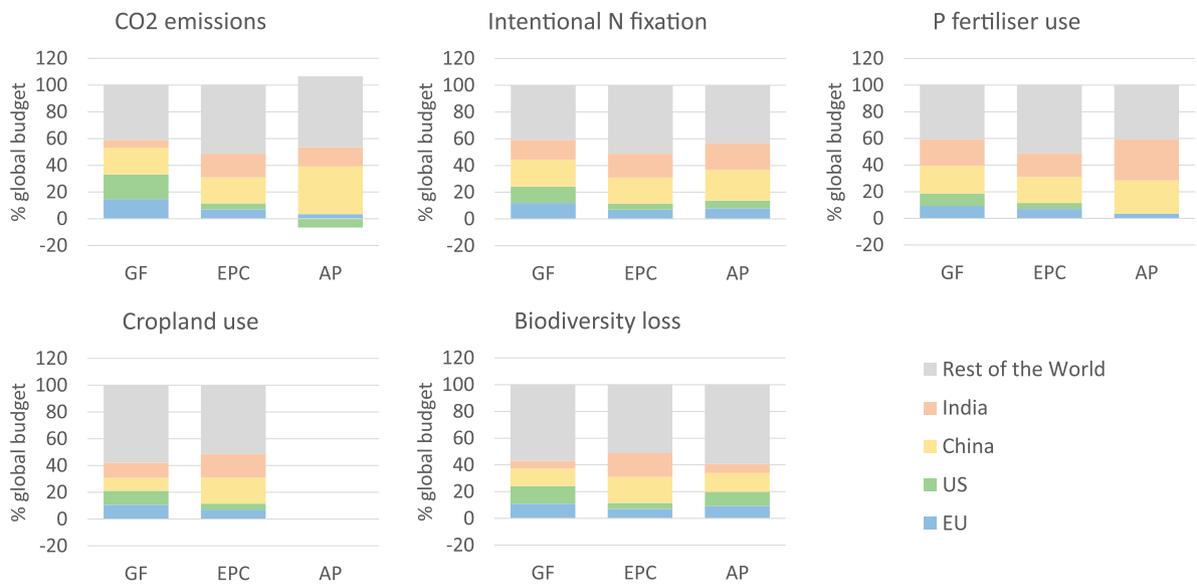


Fig. 2. Country and regional shares for the three allocation approaches under default parameterisation (see Table 2). GF=Grandfathering; EPC=Equal per capita; AP=Ability to pay. AP is only applied to PBs that are already transgressed and is therefore not applied to cropland use.

GF leads to the largest shares for the EU and the US for all PBs, as their per capita footprints are relatively large. This is especially the case for CO₂ emissions, with allocated shares of 15% (EU) and 18% (US), compared to 7% and 5%, respectively, when allocating the global budget on the basis of population shares (EPC). In contrast, for China and India, GF leads to the smallest shares in the global budgets for cropland use (in both countries around 10%) and biodiversity loss (13% and 6%, respectively), and for India also for CO₂ emissions (6%), given

their relatively small per capita footprints. For intentional N fixation and P fertiliser use, China and India's per capita footprints are close to the world average, resulting in allocated budgets close to EPC (19% and 18%, respectively).

AP allocates the global transgression of a PB (difference between global environmental pressures and the global budget), based on an economy's per capita GDP, relative to global average per capita GDP. Thus, the higher a country's per capita GDP, the higher its relative

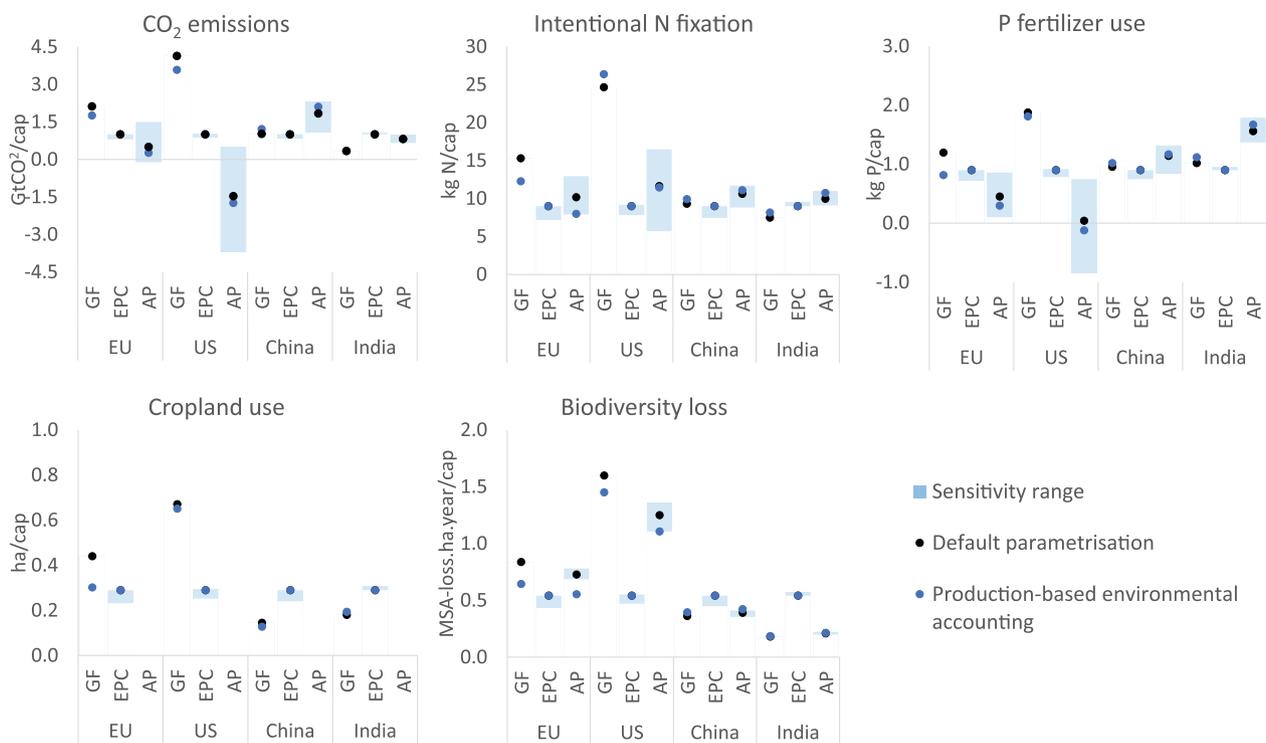


Fig. 3. Allocated budgets for the three allocation approaches under alternative parameterisation (see Table 2). GF=Grandfathering; EPC=Equal per capita; AP=Ability to pay. The 'sensitivity range' includes the results for alternative parameterisations, excluding the alternative environmental accounting approach, i.e. production-based instead of consumption-based, which is shown separately.

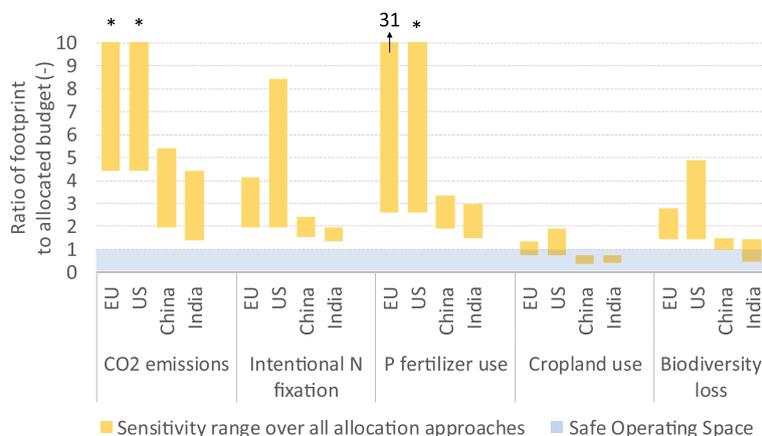


Fig. 4. National transgression (ratio of 2010 footprints over allocated PBs) for the three allocation approaches and alternative parameterisations (excluding environmental accounting approach). Negative AP outcomes are interpreted as an infinite ratio and indicated by an asteriks (*).

reduction (Formula 3) and the smaller its allocated shares. As a result, AP results in low budgets for the EU and the US and high budgets for China and especially India. However, next to per capita GDP levels, allocated budgets also depend on the level of global transgression, as well as current national environmental pressure. Lower levels of global transgression (such as for biodiversity loss and, to a lesser extent, also for intentional N fixation) result in more similar relative reductions between countries. Furthermore, as allocated reductions are subtracted from a country's footprint, large relative reductions can still result in relatively high budgets when its environmental pressure is also high (e.g. in the EU and the US for biodiversity loss). Overall, AP results in relatively small budget shares for the EU for the two PBs with the largest transgression, i.e. CO₂ emissions (4%) and P fertilizer use (4%), and larger shares for China (36% and 25%, respectively). For China, these results stem from relatively large per capita footprints (around the global average), while their 2010 per capita GDP is still relatively low, compared to that of the EU and the US. For the US, AP even results in a negative budget for CO₂ emissions (−7%), as the allocated reduction is larger than their 2010 footprint. Finally, for India, AP results in the highest shares for intentional N fixation (20%) and P fertilizer use (31%).

Next to defaults parameterisation, Fig. 3 also summarises per capita budgets based on alternative parameter settings (see Table 2). Per capita results are used here to ease comparison across economies. For EPC, basing allocation on cumulative future population shares results in lower budgets for the EU, the US and China compared to using default parameterisation, and higher budgets for India. The effect is the largest for EU and China, whose 2010–2050 cumulative population shares are 20% and 17% lower than the 2010 share (see Supplementary Material Chapter S4). Due to the rapid ageing of their population, total population is projected to decrease for these two economies. For the US, the cumulative population shares for the 2010–2050 period are projected at 13%. In contrast, the Indian population is projected to continue to increase, with the total population starting to decrease only after 2065 (after 2050 in SSP1 and after 2100 in SSP3). Furthermore, India's future budget shares are much larger in a world with high population growth (SSP3), then when population growth is low (SSP1). Overall, the results show that, when considering future generations for EPC, India gets a larger share of the global budget than when sharing the budget based on 2010 population shares. Still, compared to default parameterisation, the difference is relatively small, i.e. 6% when basing allocation on 2010–2050 cumulative population shares.

The sensitivity range of AP is a much larger than of EPC (Fig. 3), concluding that this approach is more sensitive to alternative parameterisation. As per capita GDP values converge towards 2100, differences in relative reductions between the four economies decrease

when basing allocation on future cumulative per capita GDP (see Supplementary Material Chapter S4). China's per capita GDP grows fast towards 2030. Under default parameterisation China's relative reduction is below the global average, while using cumulative GDP per capita values results in relative reductions above the global average. India's relative reduction also increases when using future cumulative per capita GDP but remains below the global average for all three socio-economic scenarios. Using alternative GDP projections (SSP1 and SSP3) only results in marginal impacts in relative reductions. However, basing the allocation on per capita GDP in MER terms instead of PPP shows more significant impacts on the allocated budgets, as the former concludes much lower per capita GDP levels for China, and especially India. This alternative GDP metric results in the lowest budgets for the EU and the US for all PBs and for CO₂ emissions even negative budgets for the EU, and higher budgets for China and India.

Finally, basing the allocation on production-based environmental pressure instead of the consumption-based pressures used so far has an impact on both GF and AP (Fig. 3). The impact is the largest for the EU, as the difference between both accounting approaches is the largest, resulting in lower per capita budgets (see Section 3.1). For the US, the difference between the two accounting approaches is relatively small and therefore also the impact on the allocated budgets. The same holds for China and India, although for several PBs these two countries gain slightly by using a production-based perspective, as they are net exporters of environmental pressures for most PBs.

3.3. Country-level performances on selected PBs

Comparing the allocated budgets to 2010 environmental footprints, we find that none of the four economies is fully living within the safe operating space. Fig. 4 summarises national transgression in terms of national environmental footprints over the allocated budgets, using a consumption-based perspective.

Except for land-use change under GF, all allocation approaches (including the full sensitivity range) result in a transgression of the allocated budgets for the EU and the US, with ratios of allocated budgets over environmental footprints, around or above a factor of 2, similar to the global transgression. Dao et al. (2018) classified values above 2 as large and as clearly unsafe. The level of global transgression depends on the allocation approach and especially for CO₂ emissions and P fertilizer the sensitivity ranges are large. Even under the grandfathering approach, which is the most generous for the EU and the US for all PBs, the PB for biogeochemical flows is transgressed by a factor of 2 and for climate change by a factor of 4.4. For the EU, AP based on MER results in a negative budget for CO₂ emissions and thereby in infinite transgression. Excluding this negative budget, the transgression

of CO₂ emissions ranges between a factor of 4.4 for GF and 18.5 for AP, under default parameterisation. For P fertilizer use, we also find a large transgression range (2.6 for GF and up to 31 for AP, based on MER), while for the other control variables, transgression ranges between a factor of 0.7 (no transgression) and 4.1. Result for the US are similar to those for the EU, although we find a much higher upper range for the transgression rates. For climate change, for example, several parameterisations for AP result in negative budgets, and thereby in infinite transgression, for CO₂ emissions and P fertilizer use. For the other control variables, transgression ranges between 0.7 (no transgression) and 8.5.

For China and India, we find that the PB of climate change and biogeochemical flows are transgressed under all allocation approaches and parameterisations, while the allocated budgets are within the safe operating space for cropland use. For India, this is also the case for biodiversity loss under EPC. Transgression of the allocated budgets is mostly below the global average. For China, we find that the allocated budgets for CO₂ emissions and P fertilizer use both transgressed mostly with a factor of 2 or higher, while transgression for biodiversity loss is relatively small, ranging between a factor of 1 (EPC) and 1.5 (AP). For India, we find the lowest transgression and smallest sensitivity ranges. Allocated budgets for CO₂ emissions and P fertilizer use are transgressed by a factor of 1.5 to 4.4, while transgression rates for intentional N fixation and biodiversity loss are below a factor of 1.5.

4. Discussion

The analysis addressed the distributional consequences of alternative allocation approaches for downscaling selected PBs to the national level and compared the results with 2010 national environmental footprints. The analysis provides insights into so-called national fair shares of the global safe operating space, defined by the downscaled PBs given different interpretations of distributive fairness, and related country-level performance on these PBs. Here, we discuss country-level effort related to the different allocation approaches (Section 4.1), discuss the results in the context of the climate change and PB literature (Section 4.2), and discuss limitations of the applied methodology (Section 4.3).

4.1. Country-level effort

Our results clearly show that the normative choices on distributive fairness underlying the three allocation approaches play out differently for the four economies. Table 3 shows country-level reduction percentages between their 2010 environmental footprints and the allocated budgets, using a consumption-based perspective. These reduction percentages provide insights in required country-level effort to move towards the global safe operating space.

Differences in outcomes between the three allocation approaches relate to the underlying equity principle (e.g. sovereignty, equity, capacity), whether and how future population growth and economic developments are considered, and if the approach shares the global resource space (GF and EPC) or a global transgression (AP). Differences in outcomes between the four economies originate from the relative differences in their footprints and from current and future developments

in population and per capita income. Finally, differences in outcomes between the PBs depend on the level of global transgression of the respective PBs and, thus, on the available space for further increases in global environmental pressure, or the required reduction in global pressures.

The three approaches provide diverging perspectives on the principle of common but differentiated responsibilities (CBDR). GF was found most favourable (lowest reduction percentages) for the EU and the US for all PBs analysed, due to their high 2010 footprints, and least favourable for most PBs for China and India. The approach constitutes an equal reduction rate between countries and is thereby not differentiated. AP was found most favourable for biogeochemical flows for China and India under default parameterisation and for China also for climate change. In relative terms, this approach results in higher reduction rates for the EU and the US, allowing more environmental space for China and India. Since 2010, per capita GDP of India and especially China has increased significantly. Updating the calculations with 2019 data when this comes available would thus benefit the EU and US (lower allocated reductions) at the expense of India and especially China, who get higher allocated reductions. Finally, EPC was found most favourable for India and China for land-use change and biodiversity loss, and for India also for climate change. As the outcome of EPC is independent from a country's environmental pressure, it is the only approach that can result in allocated budgets higher than their footprint and thereby allowing for increases in their environmental pressure under specific parameterisation. Accounting for future population growth would benefit India, whose population is projected to increase further, at the expense of the EU, the US and China whose populations are projected to stabilise or even decrease as a result of their aging populations.

For control variables with relatively large global transgression (here CO₂ emissions and P fertilizer use), AP can also lead to negative resource budgets (reductions above 100%) for the EU and the US. Negative CO₂ emissions are common for climate change mitigation, as there is a range of negative emission technologies (e.g. biofuels combined with carbon capture and storage, afforestation and reforestation, direct air capture) and emission trading schemes between countries. Negative resource use or environmental impact is not directly obvious for the other planetary boundaries. For example, certain resources, such as land and N/P fertiliser, remain essential for agricultural production and cannot easily be compensated. However, negative resource use can result from restoration projects or environmental offsetting (i.e. compensation for environmental impacts with equivalent benefits generated elsewhere). Introducing a trading scheme could allow investments in efficiency gains or restoration projects in other countries to counterbalance national environmental pressures.

4.2. Comparison to the literature

Our allocation analysis is inspired by and largely based on the rich climate change literature, in which a broad range of allocation approaches have been analysed. The PB literature includes only a few allocation studies and the amount of approaches used is limited. Of the three approaches used here, only EPC is widely used for downscaling PBs.

Table 3

National reduction effort (percentages difference between 2010 national footprints and allocated budgets) resulting from the different allocation approaches. Negative values represent growth instead of reduction.

	EU (%)	US (%)	China (%)	India (%)	Global (%)
CO ₂ emissions	77 – 101	77 – 120	48 – 81	28 – 77	77
Intentional N fixation	49 – 76	49 – 88	36 – 59	25 – 49	49
P fertiliser use	62 – 97	62 – 117	47 – 70	33 – 66	62
Cropland use	–40 – 26	–40 – 47	–180 – –40	–139 – –40	–40
Biodiversity loss (MSA)	30 – 64	30 – 80	–4 – 32	–122 – 30	30

Overall, for climate change and land-system change, our allocation results for EPC are in line with studies using similar control variables and budgets (Häyhä et al., 2018). Furthermore, our conclusion that the four economies are not living within the safe operating space for climate change and biogeochemical flows is largely in line with the findings of O'Neill et al. (2018). Only for India, our results differ, which stem from large differences in 2010 environmental footprints for intentional N fixation and P fertilizer. Finally, many PB studies struggle with biosphere integrity and therefore omit quantification.

For climate change, much more literature is available. However, most of the literature focuses on pathway allocation and not budget allocation as done here. These results cannot be directly compared, as studies discussing emission-reduction pathways, generally, report emission reductions for a specific year (mostly 2030 or 2050) compared to a benchmark year (mostly 1990 or 2005), while studies that use a budget approach report remaining carbon budgets, with countries deciding themselves how to distribute this over time.

One of the few studies that applied a budget approach in the climate change literature is Van den Berg et al. (2019). Their analysis concludes annualised per capita budgets for the EU ranging between -8.6 and 2.9 t CO₂ cap⁻¹ yr⁻¹, based on seven allocation approaches. Based on EPC only, the PB literature concludes per capita budgets ranging between 1.6 and 2.0 t CO₂ cap⁻¹ yr⁻¹ for the EU (Häyhä et al., 2018; O'Neill et al., 2018), while our results for the EU range between -3.9 and 1.4 t CO₂ cap⁻¹ yr⁻¹. The upper bound of our study is lower than the above studies as a result of the more stringent temperature target used (1.5 °C instead of 2.0 °C). Furthermore, our range is much smaller than the range by van den Berg et al. (2019), as we include fewer approaches — notably an approach that resulted in large negative allocation results for the EU, was omitted in our study.

As already said, the climate literature includes more allocation approaches than the three discussed here, also addressing the other equity principles discussed in Section 2.3., i.e. cost effectiveness and responsibility. For PBs other than climate change, estimates of mitigation costs are not available, making allocation based on cost effectiveness not possible for PBs other than climate change. Furthermore, the responsibility principle poses challenges for aggregate processes. When this principle is applied in the climate literature, the allocation approaches generally account for past country emissions, as historical emissions impact future availability (Den Elzen et al., 2005; Pan et al., 2014). For land-use change and biogeochemical flows, the budgets are constant over time. Historical pressures do not impact future availability. This makes the responsibility principle conceptually less relevant for these PB processes. For biodiversity loss this is different, as current biodiversity loss is an accumulation of historical pressures, including land-use change and greenhouse gas emissions. However, there is a lack of data on historical biodiversity loss linked to these pressures and sectors, making it difficult to determine responsibility for these past pressures. Furthermore, most of the historical land-use changes, a root cause of biodiversity loss, are still in effect, while current users can be different than the ones that originally converted the land. All this makes allocation based on the responsibility principle for biodiversity loss very complex.

4.3. Limitations

Our study addresses some key recommendations of Häyhä et al. (2016) for downscaling PBs to the national level, i.e. the inclusion of alternative allocation approaches and taking a consumption-based perspective for assessing country-level performances on the selected PBs. Other issues remain unsolved, including addressing spatial heterogeneity, interrelations between PBs and temporal variability of PB processes.

The analysis was limited by the availability of data, most prominently sectoral data for the calculation of footprint indicators (see Section 2). We therefore had to fall back to the original proposed

control variables for land-system change of (Rockström et al., 2009b) and the regional-level boundary for biogeochemical flows (P cycle). This calls for further research on control variables and/or footprint indicators for the respective PBs.

The control variable used for biosphere integrity (i.e. MSA) was considered a good alternative to the control variable (BII) proposed by Steffen et al. (2015b), as it allows creating a budget for biodiversity loss, is scalable across space, and because a footprint indicator is available. However, the global budget used requires more attention as it was based on a simple regression model with the preliminary BII-based PBs. Furthermore, some researchers propose to focus on sub-global dynamics (Montoya et al., 2018) or put effort in a globally agreed goal, similar to the 1.5 and 2° targets of the Paris Agreement (Mace et al., 2018).

Another limitation relates to the allocation approaches used. All three originate in the climate change literature. No PB-specific approaches were added, such as for example allocation based on territorial land for land-system change or on arable land use for biogeochemical flows (see Fanning and O'Neill, 2016; Häyhä et al., 2018). Furthermore, several approaches were omitted due to conceptual challenges and missing data (see also Section 4.2). Finally, a top-down allocation approach was applied, while a multi-scale systemic approach, as proposed by Steffen and Stafford Smith (2013) and Häyhä et al. (2016), might be more appropriate for the aggregated PB processes. Further analysis should thus broaden the set of allocation approaches and explore ways to better link the equity dimension to the socio-economic and the biophysical dimension.

5. Conclusions

In this paper, we translated selected PBs to national resource budgets for the EU, the US, China and India. The analysis focused on distributional consequences of alternative allocation approaches from the climate change literature based on different perspectives on distributive fairness. Furthermore, the allocated resource budgets were compared to national footprints, to assess country performance on the selected PBs. Overall, the results suggest that none of the four economies is living within the global safe operating space as defined by the four PBs analysed.

The analysis finds a range of allocated budgets for the four economies. Outcomes depend on the allocation approach used, national environmental footprints and the level of global transgression of the respective control variable. Translation of PBs to countries essentially divides up the global safe operating space: approaches that are favourable for one country, i.e. allowing higher environmental pressures, inevitably are less favourable for other countries. Both EPC and AP resulted in reduction efforts (percentage difference between environmental footprints and allocated budgets) larger than the global average for the EU and the US and lower for China and India. For budgets with relatively large global transgression (CO₂ emissions and P fertilizer use), AP even resulted in negative resource budgets for the EU and the US. Results were also sensitive to the parameterisation of the approaches. Accounting for future population growth in EPC benefits India (higher allocated budgets) at the expense of the EU, the US and China (lower allocated budgets). In contrast, accounting for future economic growth in AP benefits the EU and the US at the expense of China and, to a lesser extent, also India.

Our results hint at diverging country preferences for specific allocation approaches and parameterisation. In the end, what is considered fair is a political decision and there is no globally agreed principle that can be used. However, insights into country-level consequences of alternative allocation approaches for national resource budgets can help countries to assess their performances on global environmental challenges. Furthermore, such insights can help countries to define national policy targets in line with global ambitions, such as those defined by the SDG. The methodology and results presented here can serve as a

starting point.

Global climate change negotiations have proven that scientific knowledge is invaluable for incorporating global environmental challenges into national policymaking. To determine national fair shares of the global safe operating space, the climate change literature on fair and equitable allocation is of specific added value. Further attention is required for PB-specific allocation approaches and integrating biophysical and socio-economic considerations in the allocation approaches, including spatial heterogeneity, interrelations between PB processes and temporal dynamics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Olav-Jan van Gerwen and Marcel Kok (both PBL Netherlands Environmental Assessment Agency) for their valuable input and fruitful discussions throughout this research and Tiina Häyhä (Stockholm Resilience Centre) and Holger Hoff (Stockholm Environment Institute) for their comments on earlier versions of this study. Furthermore, we thank three anonymous reviewers for their valuable comments on an earlier draft of this manuscript. The research was supported by the Dutch ministry of Foreign Trade and Development Cooperation. Detlef van Vuuren acknowledges the contribution of the EU funded PICASSO project (ERC programme) under contract 819566.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2019.102017.

References

- Alkemade, R., Van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., et al., 2009. GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. *Ecosystems* 12 (3), 374–390.
- BASIC experts. (2011). Equitable access to sustainable development: contribution to the body of scientific knowledge. BASIC expert group, Beijing, Brasilia, Cape Town and Mumbai.
- Beusen, A.H.W., Bouwman, A.F., Van Beek, L.P.H., Mogollón, J.M., Middelburg, J.J., 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences* 13 (8), 2441–2451.
- BMUB. (2016). Shaping Ecological Transformation - Integrated Environmental programme 2030. Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), Berlin.
- Bouwman, A.F., Beusen, A.H.W., Lassaletta, L., Van Apeldoorn, D.F., Van Grinsven, H.J.M., et al., 2017. Lessons from temporal and spatial patterns in global use of n and p fertilizer on cropland. *Sci. Rep.* 7, 40366.
- Butz, C., Liechti, J., Bodin, J., Cornell, S.E., 2018. Towards defining an environmental investment universe within planetary boundaries. *Sustain. Sci.* 13 (4), 1031–1044.
- Carpenter, S.R., Bennett, E.M., 2011. Reconsideration of the planetary boundary for phosphorus. *Environ. Res. Lett.* 6 (1), 014009.
- Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., et al., 2014. Assessing transformation pathways. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y. (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, New York.
- Crutzen, P.J., Stoermer, E.F., 2000. The anthropocene. *IGBP Global Change Newsl.* 41, 17–18.
- Dao, H., Peduzzi, P., Friot, D., 2018. National environmental limits and footprints based on the planetary boundaries framework: the case of Switzerland. *Global Environ. Change* 52, 49–57.
- De Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. *Curr. Opin. Environ. Sustain.* 5 (3), 392–402.
- Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the shared socioeconomic pathways. *Global Environ. Change* 42, 200–214.
- Den Elzen, M.G.J., Berk, M.M., Lucas, P.L., Eickhout, B., van Vuuren, D.P., 2003. Exploring climate regimes for differentiation of commitments to achieve the EU climate target. National Institute for Public Health and the Environment (RIVM), Bilthoven.
- Den Elzen, M.G.J., Schaeffer, M., Lucas, P.L., 2005. Differentiating future commitments on the basis of countries' relative historical responsibility for climate change: uncertainties in the 'Brazilian Proposal' in the context of a policy implementation. *Climatic Change* 71 (3), 277–301.
- Downing, A.S., Bhowmik, A., Collste, D., Cornell, S.E., Donges, J., et al., 2019. Matching scope, purpose and uses of planetary boundaries science. *Environ. Res. Lett.* 14 (7), 073005.
- EU. (2013). Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. Official Journal of the European Union L 354/171, Brussels.
- Fang, K., Heijungs, R., De Snoo, G.R., 2015a. Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint-boundary environmental sustainability assessment framework. *Ecol. Econ.* 114, 218–226.
- Fang, K., Heijungs, R., Duan, Z., de Snoo, G., 2015b. The environmental sustainability of nations: benchmarking the carbon, water and land footprints against allocated planetary boundaries. *Sustainability* 7 (8), 11285.
- Fanning, A.L., O'Neill, D.W., 2016. Tracking resource use relative to planetary boundaries in a steady-state framework: a case study of Canada and Spain. *Ecol. Indic.* 69, 836–849.
- FAO. (2017). FAOSTAT, food and agriculture organization of the United Nations, Rome; last accessed October, 10, 2017. Food and Agriculture Organization of the United Nations, Rome, <http://faostat3.fao.org/faostat-gateway/go/to/home/E>.
- Fleurbaey, M., Kartha, S., Bolwig, S., Chee, Y.L., Chen, Y., et al., 2014. Sustainable development and equity. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y. (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, New York.
- Friedlingstein, P., Andrew, R.M., Rogelj, J., Peters, G.P., Canadell, J.G., et al., 2014. Persistent growth of CO₂ emissions and implications for reaching climate targets. *Nat. Geosci.* 7 (10), 709–715.
- Hajer, M., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., et al., 2015. Beyond cockpitism: four insights to enhance the transformative potential of the sustainable development goals. *Sustainability* 7 (2), 1651–1660.
- Häyhä, T., Cornell, S., Hoff, H., Lucas, P.L., Van Vuuren, D.P., 2018. Operationalizing the concept of a safe operating space at the EU level – first steps and explorations. Stockholm Resilience Centre Technical Report, prepared in collaboration with Stockholm Environment Institute (SEI) and PBL Netherlands Environmental Assessment Agency. Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden.
- Häyhä, T., Lucas, P.L., Van Vuuren, D.P., Cornell, S.E., Hoff, H., 2016. From planetary boundaries to national fair shares of the global safe operating space — how can the scales be bridged? *Global Environ. Change* 40, 60–72.
- Hoff H. and Alva I.L. (2017). How the planetary boundaries framework can support national implementation of the 2030 agenda. SEI Policy Brief. Stockholm Environment Institute (SEI) and TMG Think Tank for Sustainability, Stockholm.
- Höhne, N., Den Elzen, M., Escalante, D., 2014. Regional ghg reduction targets based on effort sharing: a comparison of studies. *Clim. Policy* 14 (1), 122–147.
- IPBES, 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichi, K., Liu, J., Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razaque, J., Reyers, B., Roy Chowdhury, R., Shin, Y.J., Vissers-Hamakers, I.J., Willis, K.J., Zayas, C.N. (Eds.), *IPBES secretariat, Bonn*.
- IPCC, 2014. *Climate Change 2014: Synthesis Report. Intergovernmental Panel On Climate Change (IPCC)*. Geneva, Switzerland.
- KC, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100. *Global Environ. Change* 42, 181–192.
- Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Hauck, J., et al., 2018a. Global Carbon Budget 2018. *Earth Syst. Sci. Data* 10 (4), 2141–2194.
- Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Pongratz, J., et al., 2018b. Global Carbon Budget 2017. *Earth Syst. Sci. Data* 10 (1), 405–448.
- Lucas, P.L., Kok, M.T.J., Nilsson, M., Alkemade, R., 2014. Integrating biodiversity and ecosystem services in the Post-2015 development agenda: goal structure, target areas and means of implementation. *Sustainability* 6 (1), 193–216.
- Mace, G.M., Reyers, B., Alkemade, R., Biggs, R., Chapin, F.S., et al., 2014. Approaches to defining a planetary boundary for biodiversity. *Global Environ. Change* 28, 289–297.
- Lucas, P.L., van Vuuren, D.P., Elder, M., 2019. Chapter 20: A Long-Term vision for 2050. In: Ekins, P., Gupta, J., Boileau, P. (Eds.), *Global Environmental Outlook - GEO6: Healthy Planet, Healthy People*. UN Environment, Nairobi.
- Mace, G.M., Barrett, M., Burgess, N.D., Cornell, S.E., Freeman, R., et al., 2018. Aiming higher to bend the curve of biodiversity loss. *Nat. Sustain.* 1 (9), 448–451.
- Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., et al., 2009. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* 458 (7242), 1158–1162.
- Montoya, J.M., Donohue, I., Pimm, S.L., 2018. Planetary boundaries for biodiversity: implausible science, pernicious policies. *Trends Ecol. Evol. (Amst.)* 33 (2), 71–73.
- Nykvist, B., Å., Persson, Moberg, F., Persson, L., Cornell, S., et al., 2013. National environmental performance on planetary boundaries. Stockholm Environment Institute (SEI), Stockholm A study for the Swedish Environmental Protection Agency. Report

- 6576.
- O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. *Nature Sustain.* 1 (2), 88–95.
- Pan, X., Teng, F., Ha, Y., Wang, G., 2014. Equitable access to sustainable development: based on the comparative study of carbon emission rights allocation schemes. *Appl. Energy* 130, 632–640.
- Pan, X., Den Elzen, M., Höhne, N., Teng, F., Wang, L., 2017. Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environ. Sci. Policy* 74, 49–56.
- IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), In press.
- Pauw P., Bauer S., Richerzhagen C., Brandt C. and Schmole H. (2014). Different perspectives on differentiated responsibilities. A State-of-the-Art Review of the Notion of Common but Differentiated Responsibilities German Development Institute, Bonn.
- Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., et al., 2014. Sharing a quota on cumulative carbon emissions. *Nat. Clim. Change* 4, 873.
- Rockström, J., Steffen, W., Noone, K., Å., Persson, Chapin, F.S., et al., 2009a. Planetary boundaries: exploring the safe operating space for humanity. *Ecol. Soc.* 14 (2), 32.
- Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., et al., 2009b. A safe operating space for humanity. *Nature* 461 (7263), 472–475.
- Rogelj J., Shindell D., Jiang K., Fifita S., Forster P., et al. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development, in: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., et al. (Eds.), *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, In press.
- Sabag Muñoz O. and Gladek E. (2017). *One planet approach - Methodology Mapping and pathways Forward*. Metabolic, Amsterdam.
- Schipper, A., Bakkenes, M., Meijer, J., Alkemade, R., Huijbregts, M., 2016. The Globio Model. PBL Netherlands Environmental Assessment Agency, The Hague A technical description of version 3.5.
- Seitzinger, S.P., Mayorga, E., Bouwman, A.F., Kroeze, C., Beusen, A.H.W., et al., 2010. Global river nutrient export: a scenario analysis of past and future trends. *Global Biogeochem. Cycl.* 24 (4).
- Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., et al., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. *J. Ind. Ecol.* 22 (3), 502–515.
- Steffen, W., Stafford Smith, M., 2013. Planetary boundaries, equity and global sustainability: why wealthy countries could benefit from more equity. *Curr. Opin. Environ. Sustain.* 5 (3), 403–408.
- Steffen, W., Broadgate, W., Deutsch, B., Gaffney, O., Ludwig, C., 2015a. The trajectory of the anthropocene: the great acceleration. *Anthrop. Rev.* 2 (1), 81–98.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., et al., 2015b. Planetary boundaries: guiding human development on a changing planet. *Science* 347 (6223).
- Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G.J., 2015. An illustrated user guide to the world input–output database: the case of global automotive production. *Rev. Int. Econ.* 23 (3), 575–605.
- UN. (2015). *Transforming our world: the 2030 agenda for sustainable development*. United Nations, New York.
- UNDESA, 2019. *World population prospects 2019* Population Division, New York.
- UNEP, 2019. *Global Environment Outlook - GEO6: Healthy Planet, Healthy People*. United Nations Environment Programme, Nairobi.
- UNFCCC, 1992. *United Nations Framework Convention on Climate Change*. United Nations, New York.
- UNFCCC, 2015. *Paris Agreement*. United Nations Framework Convention on Climate Change, Paris.
- Van den Berg, N.J., van Soest, H.L., Hof, A.F., den Elzen, M.G.J., van Vuuren, D.P., et al., 2019. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change*.
- Van Vuuren, D.P., Lucas, P.L., Häyhä, T., Cornell, S.E., Stafford-Smith, M., 2016. Horses for courses: analytical tools to explore planetary boundaries. *Earth Syst. Dynam.* 7 (1), 267–279.
- Wiedmann, T., 2009. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol. Econ.* 69 (2), 211–222.
- Wilting, H.C., 2014. Carbon and land footprint time series of the Netherlands – integrating data from the GTAP and WIOD databases. In: *Proceedings of the 22th International Input-Output Conference*, Lisbon.
- Wilting, H.C., Schipper, A.M., Bakkenes, M., Meijer, J.R., Huijbregts, M.A.J., 2017. Quantifying biodiversity losses due to human consumption: a global-scale footprint analysis. *Environ. Sci. Technol.* 51 (6), 3298–3306.
- World Bank, 2019. *GDP (current US\$)*. The World Bank Group.