Environment International 152 (2021) 106475

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

The role of planetary boundaries in assessing absolute environmental sustainability across scales

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ARTICLE INFO

Handling Editor: Adrian Covaci

Keywords:
Planetary boundaries
Absolute environmental sustainability
Sustainability indicators and assessments
Footprints
Biophysical limits
Environmental policy

ABSTRACT

The idea of revisiting the biophysical limits of human life on planet Earth has gained renewed momentum in the Anthropocene. The planetary boundaries (PBs) framework has emerged as a strong guardrail concept, even though its capacity to inform the development of absolute sustainability assessments and realistic policies remains unclear. In this paper, we present a current synthesis of the development of absolute environmental sustainability (AES) indicators and assessments informed by PBs. We firstly explore how PBs have been considered in AES research at different scales. We then present a critique of how consensus could be reached in standardising and harmonising the share of globally and locally allocated safe operating spaces. We argue that PBs must be linked to human consumption as the main socio-economic driver and that planetary concerns can only be addressed through a holistic perspective that encompasses global tele-connections. Based on our findings, we provide recommendations for the future design of AES indicators and assessments informed by PBs.

1. Introduction

Views divide on how sustainability can and should be assessed with respect to ecological limits and the finiteness of resources on planet Earth (Downing et al., 2020; Hoekstra and Wiedmann, 2014; Steffen et al., 2015b). Weak sustainability assumes that one form of capital (manufactured, human, social and natural) can be substituted for another and a positive overall net outcome can be seen as sustainable even when natural capital stocks are degrading. Strong sustainability, on the other hand, assumes that natural capital stocks are not replaceable, and that human activities must always remain within the carrying capacity of natural capital (Meadows et al., 1972).

The idea of revisiting carrying capacity of natural capital has gained momentum in the scientific community. The most influential has been the planetary boundaries (PBs) framework, originally formulated by Rockström et al. (2009) and updated by Steffen et al. (2015b). It delineates nine absolute biophysical boundaries that guardrail and govern the Earth system in the Anthropocene period (Steffen et al., 2015a). Four boundaries have been already transgressed, namely, climate change, land system change, biogeochemical flows and biosphere integrity. Other sustainability assessment concepts that take into account either biophysical or other limits have been proposed by the academic community. These have been referred to as concepts and frameworks of AES and include the ecological footprint (Wackernagel et al., 2019; Wackernagel and Rees, 1996; Wiedmann and Barrett, 2010), human appropriation of net primary productivity (Haberl et al., 2007; Weinzettel et al., 2019), science-based targets for greenhouse gas emissions (Krabbe et al., 2015) and also the concept of a steady-state economy that aims at limiting the material throughput of economies (Fanning and ONeill, 2016; ONeill, 2015). Traditional assessment methods such as life cycle assessment (Bjørn et al., 2020; Ryberg et al., 2018b) and consumption-based footprint accounting (Fang et al., 2015a; Li et al., 2019; Li et al., 2020b) have also been linked to the PBs framework in order to enable an evaluation of whether or not an entity or activity transgresses boundaries.

Despite these developments in academia, relevant indicator or assessment of absolute sustainability are rarely developed and incorporated into current sustainability policies (OECD, 2015). Current political discourse and practice ignores the discussion of biophysical limits and instead focuses on achieving relative or absolute decoupling, for

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https://doi.org/10.1016/j.envint.2021.106475
Received 28 May 2020; Received in revised form 8 February 2021; Accepted 16 February 2021
Available online 13 March 2021
0160-4120/

instance on decoupling material consumption (Wiedmann et al., 2015) or greenhouse gas emissions (IPCC, 2018) from economic growth. However, by comprehensively reviewing more than 600 decoupling articles, Parrique et al. (2019) find no empirical evidence so far to suggest that a consistent decoupling pattern exists that would meet the following six key criteria: absolute, global, permanent, sufficiently fast, PB-compliant and equitable. The authors conclude that most decoupling observed is relative, and where it has been absolute, this was only temporary, for certain AES indicators, for specific locations and with small rates of mitigation.

In this synthesis of the current literature, we argue for the need and urgency to design AES indicators and assessments as the next major step in sustainability science. The lack of consideration of biophysical limits in current 'decoupling-based sustainability indicators' is distracting and insufficient (Alexander et al., 2018; Jackson and Victor, 2019; Ward et al., 2016). 'Technology optimists' argue that technological advances will increase resource efficiency to such a degree that resource use and environmental impacts can be kept within biophysical limits (Rockström and Klum, 2015; The World in 2050, 2019). Yet, resource efficiency improvements can increase the overall consumption as products and services are made more scalable or accessible at a lower cost, thus in turn influencing consumer behaviour. The rebound effect and Jevons paradox are such examples (Chakravarty et al., 2013; Druckman et al., 2011). The argument that sustainability may be achieved solely by increasing productivity is therefore flawed (Bjørn et al., 2018a; Malik et al., 2016; WRI, 2017). Only by curbing the material throughput and level of economic production and consumption and shifting away from efficiency policies to sufficiency-oriented policies will enable a sustainable future (Wiedmann et al., 2020).

While the PBs framework has been highly influential since first proposed in 2009, there is a lack of discussion on how policies could more widely be informed by PBs and other AES indicators and assessments. There is a need for a more informed understanding of how AES assessments (AESAs) informed by PBs can be rendered operational at global, national, sub-national, city, sector, company and product levels. What progress has been made in defining, harmonising and standardising safe operating space (SOS)? Which AES indicators and assessments informed by the PBs framework have been developed and for what purpose? What are the prerequisites in designing future AES indicators and assessments informed by PBs? These questions have guided our synthesis which complements recent reviews focused on criticisms of the PBs framework (Biermann and Kim, 2020) and PB downscaling approaches (Ryberg et al., 2020).

After outlining the method of this paper in Section 2, we discuss recent research and developments in operationalising the concept of PBs in Section 3.1. In Section 3.2, we analyse how PBs have influenced current sustainability policies. In Section 3.3, we discuss the dichotomy and difficulties arising in the localised SOS allocation and definition process. In Section 3.4 we elaborate on why linking PBs to final consumption is crucially important in achieving global absolute sustainability. We also summarise recent advances in consumption-based footprint indicator development informed by PBs. Based on a discussion of the findings, recommendations on how future AES indicators can better inform sustainability policies are provided in Section 4.

2. Method

Research related to AES indicators and assessments informed by PBs is selected based on existing knowledge of the literature and terms related to the scope of the study. This study categorises prior work that explicitly focuses on PB parameters or constraints. Our aim is to reflect on how PBs have attracted broader attention and have been investigated in academia, government and industry across different scales.

The amount of commentaries and empirical studies on PBs has increased moderately since first proposed in 2009. Downing et al. (2019) and Ryberg et al. (2020) find in their PB literature review that 224 and 196 articles respectively substantially engage, apply and build on the PB concept. Bjørn et al. (2020) identify 45 studies that made use of LCA methods for developing AESA, with many closely linked to the PB concept.

The literature search using the Scopus database proceeded by first narrowing the pool of suitable articles with the following search string:

TITLE-ABS-KEY ("planetary boundar" OR "planetary limit*" OR "safe operating space") AND TITLE-ABS-KEY ("sustainability") AND NOT TITLE-ABS-KEY ("planetary boundary layer"). Years selected 2009–2020.*

This yielded 336 articles. We then manually selected the most relevant ones that address our research questions based on a scan of the full texts and also added other relevant articles that were cited in the initial collection (see Table 2 for grouping criteria). Papers published from 2009, the year of the original PB paper by Rockström et al. (2009), up to 2020 were included.

The main interest of the review is to provide a most up-to-date analysis of conceptual and empirical research on AESAs informed by PBs. We also include commentaries and reviews that discuss the challenges in implementing AESAs informed by PBs, that seek new global and regional PBs, that harmonise operational steps in translating PBs across scales and that evaluate the application of the PB concept in current policies.

3. Results

3.1. Recent research and developments in operationalising the concept of planetary boundaries

Since 2009, there have been continuous efforts to establish absolute biophysical boundaries for a wide range of additional environmental control variables which extend the original PBs framework (Steffen et al., 2015b; Vea et al., 2020) (Table 1). These include food- specific PBs which assume a planetary health dietary pattern that meets nutritional requirement (Conijn et al., 2018; Rockström et al., 2020; Springmann et al., 2018; Willett et al., 2019); livestock PB (Bowles et al., 2019); revised water PBs which consider socio-economic complexities (Bogardi et al., 2013; Falkenmark et al., 2019; Gerten et al., 2013; Gleeson et al., 2020a; Gleeson et al., 2020b; Jaramillo and Destouni, 2015; Zipper et al., 2020); nitrogen flow PB related to food security (de Vries et al., 2013); chemical pollution PB (Diamond et al., 2015); biodiversity PB (Mace et al., 2014; Rounsevell et al., 2020); marine plastic PB (Villarrubia-Gómez et al., 2018); land use PB (Heck et al., 2018; Newbold et al., 2016); marine PB (Nash et al., 2017) and interactions between PBs (Lade et al., 2019).

There have also been many efforts in operationalising PBs at different levels, from global, national, sub-national, city, sector, company to product levels (Table 2). At the global level, Randers et al. (2018) show that the current path of human development will only achieve ten (out of seventeen) SDGs at the expense of pushing eight (out of nine) boundaries out of their safe operating space by 2030. They explore how an integrated mix of policy levers will increase the likelihood of meeting more SDGs while staying within PBs. The report concludes that the scale required for such a transition must be transformational rather than dedicated to conventional policies and funding. O'Neill et al. (2018) estimate the level of biophysical resource use to achieve eleven social goals (for example, high life satisfaction). They conclude that the universal achievement of more social thresholds would come at the cost of transgressing more biophysical boundaries. To meet universal human need satisfaction at current consumption trends, would entail a level of biophysical resource that is two to six times higher than what is sustainable. Researchers also begun to investigate how resources can be utilised to maintain well-being at a decent living standard without overconsumption (Mastrucci et al., 2020). The 'Living Well Within Limits' project is pioneering work that investigates how human need satisfaction can be decoupled from natural resource use (Brand-Correa et al., 2018; Brand-Correa and Steinberger, 2017; Rao

Table 1
A summary of planetary boundary control variables, adapted from Steffen et al. (2015).

Earth-system process	Scale	Control variable	Planetary Boundary (zone of uncertainty)	Current value	References
Climate Change	Global	Atmospheric CO2 concentration	350 ppm CO2 (350–450 ppm)	398.5 ppm CO_2	Rockström et al. (2009); Steffen et al. (2015b)
	Global	Energy imbalance at top-of atmosphere	+1.0 W m^{-2} (+1.0–1.5 W m^{-2})	2.3 W m^{-2} (1.1–3.3 W m^{-2})	Rockström et al. (2009); Steffen et al. (2015b)
Climate change – Food system	Global	Food-related (non-CO_2) GHG emissions	4.3–5.4 Gt CO_2 equivalents per year in 2050	5.2 Gt CO_2 equivalents per year as in 2010	Springmann et al. (2018); Willett et al. (2019)
Freshwater Use	Global	Maximum amount of consumptive blue water use	4,000 km^3/yr (4,000–6,000 km^3/yr)	~2,600 km^3/yr	Rockström et al. (2009); Steffen et al. (2015b)
	Global	Global consumptive anthropogenic freshwater use	~2,800 km^3/yr (1,100–4,500 km^3/yr)	greater than 1,700 km^3/yr	Gerten et al. (2013)
	Basin	Blue water withdrawal as % of mean monthly river flow	Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25–55%); for intermediate flow months: 30% (30–60%); for high-flow months: 55% (55–85%)	Partially exceeded for some basins	Steffen et al. (2015b); Gerten et al. (2020)
	100 large hydrological basins	Suggest human-controlled flow regulation and irrigation alter local freshwater conditions by observation of increased evapotranspiration and decreased temporal runoff variability	Qualitative boundaries proposed, see reference	Global water footprint should be 10,688 ± 979 km^3/yr 17 non-affected 17 basins; 30 moderately affected basins; 53 strongly affected basins	Jaramillo and Destouni (2015)
	N/A	Propose to divide the water planetary boundary into six sub-boundaries, including atmospheric water (Hydroclimate), Atmospheric Water (Hydroecology), frozen water, groundwater, soil moisture, and surface water.	Qualitative boundaries proposed, see reference	N/A	Gleeson et al. (2020a); Gleeson et al. (2020b)
	N/A	Propose to categorise the water planetary boundary into three green water functions (regulatory, productive, moisture feedback) and five blue water functions (supply, carrier, state, productive and regulatory)	Qualitative boundaries proposed, see reference	See reference	Falkenmark et al. (2019)
Freshwater use – Food system	Global	Agricultural consumptive blue water use	780–4000 km^3/yr	1,810 km^3/yr as of 2010	Springmann et al. (2018); Willett et al. (2019)
Nitrogen	Global	Industrial and intentional biological fixation of nitrogen	62 Tg N/yr (62–82 Tg N/yr)	~150 Tg N/yr	de Vries et al. (2013);Steffen et al. (2015b)
Nitrogen-Food system	Global	Nitrogen application for food production	52–130 Tg N	131.8 Tg N as in 2010	Springmann et al. (2018); Willett et al. (2019)
	Global	Nitrogen fertilizer induced surface water nitrogen leaching concentration	1 mg/L N (1–3 mg/L N)	N/A	Gerten et al. (2020)
Phosphorus	Global	Phosphorus flow from freshwater systems into the ocean	11 Tg P/yr (11–100 Tg P/yr)	~22 Tg P/yr	Rockström et al. (2009); Steffen et al. (2015b)
	Regional	Phosphorus flow from fertilizers to erodible soils	6.2 Tg P/yr and applied to erodible (agricultural) soils (6.2–11.2 Tg P/yr)	~14 Tg P/yr	Carpenter and Bennett (2011); Steffen et al. (2015b)
Phosphorus – Food system	Global	Phosphorus application for food production	6–16 Tg P/yr	18 Tg P/yr as of 2010	Springmann et al. (2018);Willett et al. (2019)
Land-system change	Global	% of global land cover converted to cropland	15	11.7	Rockström et al. (2009)
	Global	Area of forested land as % of original forest cover	Global: 75% (75–54%)	62%	Steffen et al. (2015b)
	Biome	Area of forested land as % of potential forest	Tropical: 85% (85–60%) Temperate: 50% (50–30%) Boreal: 85% (85–60%)	N/A	Steffen et al. (2015b); Gerten et al. (2020)
Land-system change – Food system	Global	Cropland use	12.6 million km^2 (10.6–15 million km^2)	12.6 million km^2 as of 2010	Springmann et al. (2018); Willett et al. (2019)
Change in biosphere integrity	Global	Extinction rate (E/MSY)	<10 E/MSY (10–100 E/MSY)	100–1000 E/MSY	Rockström et al. (2009); Steffen et al. (2015b)
	Global	Biodiversity Intactness Index (BII)		84%	

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Table 1 (*continued*)

Earth-system process	Scale	Control variable	Planetary Boundary (zone of uncertainty)	Current value	References
			Maintain BII at 90% (90–30%) or above		Steffen et al. (2015b); Gerten et al. (2020)
	Global	Propose to add three metrics, the genetic library of life, levels of functional diversity and biome integrity	Qualitative boundaries proposed, see reference	N/A	Mace et al. (2014)
	Global	Rate of species extinction (number of extinct species per year)	Mean number of described species extinctions to well below 20 per year	See extinction rates across taxa in reference	Rounsevell et al. (2020)
	Global	Biodiversity Intactness Index (BII)	Maintain BII at 90% (90–30%) or above	65% of the terrestrial surface have caused BII to decline beyond 10% with changes most pronounced in grassland biomes and biodiversity hotspots.	Newbold et al. (2016)
Change in biosphere integrity – Food system	Global	Extinction rate due to food production	10 E/MSY (1–80 E/MSY)	100 E/MSY	Willett et al. (2019)
Novel entities Marine Plastic	Global	Propose plastic effect on organisms, on ecosystems and cascading effect on global ecosystem functions	Qualitative boundaries proposed, see reference	N/A	Villarrubia-Gómez et al. (2018)
Marine	Global	Suggest better integration of marine system influence on the PBs framework	Qualitative boundaries proposed, see reference	N/A	Nash et al. (2017)
Chemical pollution	Global	Suggest stepwise progress few well-known chemicals such as POPs, intermediate PBT chemicals, and a few high production volume chemicals with demonstrated toxicity.	N/A	N/A	Diamond et al. (2015)
Atmospheric aerosol loading	Regional	Aerosol Optical Depth (AOD) as a seasonal average over a region	N/A	N/A	Rockström et al. (2009); Steffen et al. (2015b)
Ocean Acidification	Global	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite	≥80% (≥80%– ≥70%)	~84%	Rockström et al. (2009); Steffen et al. (2015b)
Stratospheric ozone Depletion	Global	Stratospheric O3 concentration	<5% reduction from preindustrial level of 290 DU (5%–10%)	Only transgressed over Antarctica	Rockström et al. (2009); Steffen et al. (2015b)

and Min, 2018). The most recent SOS.aquaterra project explores feasible opportunities to meet future global food demand within the PBs of sustainable use of water and land resources (Kummu, 2018). The doughnut economy theory developed by Raworth (2012) delineates a safe and just operating space where basic human needs must be met at the cost of a certain level of resource use (the social foundation) without transgressing the PBs. Recently, this concept has been operationalised at the city level (Thriving Cities Initiative, 2020).

At the country scale, initial research on operationalising PBs to the national level has been initiated by countries who potentially consider PBs as an environmental governance regime, including the EU (Hoff et al., 2014), Switzerland (Dao et al., 2018), Sweden (Nykvist et al., 2013), Netherlands (Lucas and Wilting, 2018), Australian cities (Wiedmann, 2019), South Africa (Cole et al., 2014), Denmark (Bjørn et al., 2018a), New Zealand (Chandrakumar et al., 2020a), Nordic countries (Stoknes and Rockström, 2018) and Arab cities (Hachaichi and Baouni, 2020). Following a PB conference held in Geneva in 2013 and Brussels in 2015, a 'Making the Planetary Boundaries Concept Work' conference was held in Berlin 2017, mainly focusing on how to translate PBs to national policies in practice (BMUB, 2017).

At the sector scale, the energy and power sector has been leading the action in implementing the PBs by far, mostly employing the climate change boundary. The science-based targets have gained momentum in engaging 854 companies to voluntarily align with a well-below 2 °C or 1.5 °C future (SBTi, 2019). In the electricity generation sector, Algunaibet et al. (2019b) model how PBs can be effectively incorporated into US energy mix design, finding one to five PBs are transgressed under different assumptions (Algunaibet et al., 2019a). Child et al. (2018) review sustainability guardrails in global energy transition scenarios and contend that instead of a sole focus on CO_2 emission mitigation, other PBs and ethical choices (e.g. current and future generations' access to modern energy services) shall be fully considered into future energy scenario modelling. Li et al. (2020a) develop absolute scope 3 emission targets pathways that converge to the same level of carbon intensities. As a major driver of PB transgression, the food system has recently attracted significant research attention (Willett et al., 2019). Studies have modelled the options to stay within a range of food-specific PBs, including higher crop and livestock productivity, reductions in food loss and waste, improved water and nutrient management, and shifts towards healthier and more sustainable diets (Conijn et al., 2018; Gerten et al., 2020; Leng and Hall, 2021; Springmann et al., 2018). Other sectors with a recent surge in interest include the built environment (Andersen et al., 2020; Chandrakumar et al., 2020b) and the finance sector (Ding et al., 2020).

At the corporate level, there is an emerging interest in assessing the absolute performance of their operations due to shareholder and investor pressure (Muñoz and Gladek., 2017). The Kering Group along with the University of Cambridge Institute for Sustainability advocate that corporations should proactively restore local environmental functioning by respecting local boundaries, rather than assessing their fair share allocation of the global boundaries (CISL, 2019). L'Oréal explore how PB-based weighting factors can be used as a decisive prioritising rule (Vargas-Gonzalez et al., 2019). Alpro sets context-specific water boundaries with WWF (Alpro, 2018). Mars adopts the PB-aligned egalitarian downscaled absolute boundaries for their greenhouse gas (GHG) emissions, water use and land use under a 'Healthy Planet' blueprint (WWF, 2017). Unilever explores the challenges of applying PBs as a basis for assessing their land use, biodiversity and water-related impacts with universities (Clift et al., 2017). In the investment field, almost none of the sustainability ratings methodologies adequately rate absolute

Table 2
Recent influential studies that have shaped absolute environmental sustainability science informed by the planetary boundaries.

Field or research program	Contribution(s)	References
3.1. Recent research and developments in operationalising the concept of planetary boundaries		
Improved definition of PBs	Establish and extend absolute biophysical thresholds for a wide range of additional environmental indicators ('control variables')	See Table 1.
PBs operationalization research across scales	Global: Decouple universal human need satisfaction from material use and consumption demands	Randers et al. (2018); O'Neill et al. (2018); Mastrucci et al. (2020); Brand-Correa et al. (2018); Brand-Correa and Steinberger (2017); Kummu (2018)
	National and city: Derive fair share of national and city SOS	EU (Hoff et al., 2014); Sweden (Nykvist et al., 2013); South Africa (Cole et al., 2014); Denmark (Bjørn et al., 2018a); Switzerland (Dao et al., 2018); Nordic countries (Stoknes and Rockström, 2018); Netherlands (Lucas and Wilting, 2018); Australian cities (Wiedmann, 2019); New Zealand (Chandrakumar et al., 2020a); Arab cities (Hachaichi and Baouni, 2020)
	Sector: Energy sector-led research; emerging food sector research	Energy (Algunaibet et al., 2019a, b; Child et al., 2018; Li et al., 2020a); Food (Conijn et al., 2018; Gerten et al., 2020; Leng and Hall, 2021; Springmann et al., 2018; Willett et al., 2019); Finance (Ding et al., 2020) Buildings (Andersen et al., 2020; Chandrakumar et al., 2020b)
	Company and product: Voluntary alignment with self-determined SOS	WWF (2017); Clift et al. (2017); Alpro (2018); CISL (2019); Vargas-Gonzalez et al. (2019);
3.2. Towards a consensus on allocating global SOS to the local level		
Existing SOS downscaling* methodology	Either employs a strict top-down allocation of global SOSs or seeks to establish a delineation of local boundaries from the bottom-up; Comparison between the two methodologies	Top-down methodology (Chandrakumar et al., 2020a; Dao et al., 2015; Dao et al., 2018; Fang et al., 2015b; Hoff et al., 2014; Lucas et al., 2020; Nykvist et al., 2013) Bottom-up methodology (Cole et al., 2014; Dearing et al., 2014; McLaughlin, 2018; Teah et al., 2016)
Harmonising and standardising the SOS to the local level	Mainstream the global SOS downscaling and local boundary defining steps and make them generalisable and scalable	Häyhä et al. (2016); van Vuuren et al. (2016); Häyhä (2018); Hossain et al. (2017); Muñoz and Gladek. (2017); SEI (2017); SEI (2018); Bjørn et al. (2018b); Hossain and Ifejika Speranza (2020); Ryberg et al. (2020); Vea Hjalsted et al. (2020); Zipper et al. (2020)
3.3. The consumption-based perspective is essential for AESA research		
Prevailing socio-metabolic methods that allow for AESA from a consumption-based perspective	To reveal how PBs are exceeded by consumption elsewhere and how responsibility should be shared, emphasise on inequality	Conceptual links between footprints and PBs (Fang, 2021; Hoekstra and Wiedmann, 2014; Laurent and Owsianiak, 2017; Li et al., 2019, 2020a) LCA (Algunaibet et al., 2019b; Bjørn et al., 2020; Bjørn and Hauschild, 2015; Bjørn et al., 2016; Doka, 2015; Ryberg et al., 2018a; Ryberg et al., 2016; Ryberg et al., 2018b; Sørup et al., 2020; Uusitalo et al., 2019; Vargas-Gonzalez et al., 2019); MRIO (Li et al., 2019, 2020a; Li et al., 2020b)
3.4. Presence of PBs in current international and national policies		
Absence of PBs in SDGs narrative	To raise questions regarding the absence of humanity's demands of the biosphere in SDGs goals.	Dong and Hauschild (2017); Bengtsson et al. (2018); Chandrakumar and McLaren (2018); Sachs et al. (2020); Barrett et al. (2020);
Absence of PBs in existing policies	To raise concerns regarding the concept of absolute sustainability has not yet influenced the framing of most national policies	EU (2013); UNEP, 2019; WEF, 2020; EEA, 2020
4.1. Standardising AESA metrics informed by biophysical limits		
Socio-metabolic modelling approaches and PBs	Better link human drivers and biophysical limits; humanity's prospective consumption demands to be brought down to sustainable levels	IRP (2019); Wiedmann and Lenzen (2018); Haberl et al. (2019); Wiedmann et al. (2020); UNEP (2020)
Social-ecological modelling approaches and PBs	Explore socio-ecological drivers interactions and feedbacks on PBs	Dearing et al. (2014); Hossain et al. (2017); Cooper and Dearing (2019); Hossain and Ifejika Speranza (2020)
Circular economy and PBs	Recognise that scaling indicators (in absolute terms) is equally	Haas et al. (2020); pDesing et al. (2020)

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Table 2 (*continued*)

Field or research program	Contribution(s)	References
	important as recycling indicators (in percentage terms)	
Comparison of PBs with other AES frameworks	Differences between PBs and other AES frameworks; critical appraisal of future implications of PBs compared to its predecessor	Downing et al. (2019); Downing et al. (2020); Biermann and Kim (2020)
4.2. Defining appropriate local boundaries		
Institutional governance design in defining local boundaries	Highlights importance of institutional design in shaping the governance of PBs; Translating global SOSs to local scales require standardised and tiered operational steps	Biermann (2012); Galaz et al. (2012); Sala et al. (2015); Sterner et al. (2019); Lade et al. (2019); Biermann and Kim (2020); Downing et al. (2020); Downing et al. (2019); Engström et al. (2020);
4.3. Designing AES indicators that encompass both biophysical limits and human well-being		
Future AES indicator and assessment design	Mainstream environmental policies based on resource efficiency gains should be supplanted by policies that focus on sufficiency, i.e. that caps consumption in the pursuit of achieving high human development	Randers et al. (2018); Parrique et al. (2019); Wiedmann (2020)
Social foundations within PBs	Focus on achieving social provisioning services and decent living standards within PBs; ethical allocations approaches to operationalise the PBs	Raworth (2017); Brand-Correa and Steinberger (2017); Rao and Min (2018); Fanning et al. (2020); UNDP (2020); Barrett et al. (2020); Thriving Cities Initiative (2020); Ensor and Hoddy (2020);

corporate sustainability performance (Butz et al., 2018). For instance, Rekker et al. (2019) and Burnside (2019) conclude that all nine prevailing sustainability rating schemes fail to assess the gap between current performance and the absolute target of 2 °C.

3.2. Towards a consensus on allocating global SOS to the local level

Implementation of PB studies either employs a strict top-down allocation of global SOSs or seeks to establish a delineation of local boundaries from the bottom-up (WWF, 2017) (Table 2). The former approach considers normative choices, while the latter argues that respecting local environmental and resource constraints are a prerequisite for reducing the aggregated effects on the global PBs. Most national studies employ the principle of equal shares (Fang et al., 2015b; Hoff et al., 2014; Nykvist et al., 2013), or equal per capita shares compatible with intergenerational equity (Dao et al., 2015; Dao et al., 2018) when downscaling PBs. A summary of top-down PB downscaling methods is provided by Ryberg et al. (2020). Some scholars also employ bottom-up approaches that do not relate directly to global limits on the premise that respecting local boundaries such as observed local environmental boundaries (Cole et al., 2014; Dearing et al., 2014; McLaughlin, 2018) and local perception of environmental risks (Teah et al., 2016) should be seen as the priority. Emerging PB studies begin to properly integrate and tackle distributive fairness inquiries at national levels (Lucas et al., 2020) and sector levels (Chandrakumar et al., 2019). Most aforementioned studies conclude that PBs are transgressed to a certain extent, for certain control variables.

To mainstream the operational steps and make them generalisable and scalable, studies emerge in the field of harmonising and standardising the PB-operational process. Häyhä et al. (2016) and Häyhä et al. (2018) develop general PB operational frameworks that address the biophysical, socio-economic and ethical dimensions of PBs. Hossain et al. (2017) and Hossain and Ifejika Speranza (2020) emphasise the importance of integrating social wellbeing into the SOS at regional social-ecological system (SES) scales. They argue that an understanding of SES dynamics (e.g. feedbacks, nonlinearity) and SES governance (e.g. integrating stakeholders' visions) are essential. Bjørn et al. (2018b) propose six steps for any given AESA project, (1) setting system boundaries using a production-based (PBA) or consumption-based approach (CBA); (2) defining specific environmental sustainability objective; (3) quantification of SOS; (4) quantification of pressure; (5) principle for allocating SOS; (6) aggregation of pressure to SOS. The One Planet Approach developed by Muñoz and Gladek. (2017) adds two more steps: 'adding the underlying system process' and 'mapping the relevant system dynamics'.

In terms of defining local boundaries, Ryberg et al. (2020) propose a framework to understand the underlying distributive choice theories, including target, currency, pattern, geographical scope, temporal scope, clauses, and constraints. Vea Hjalsted et al. (2020) propose an initial SOS downscaling to individuals followed by an upscaling approach to extend individual SOS at organisational levels, similar to the proposal by CISL (2019). This SOS allocation process can be achieved by using consumption expenditure or eco-efficiency data, and has the merit of reflecting individual priority given to a product or sector. Zipper et al. (2020) propose a decision tree to harmonise the top-down global SOS fair share approach and the bottom-up local boundary deviation approach. They illustrate their framework using the freshwater control variable and argue that, in accordance with the precautionary principle, the lowest boundary should be prioritised among a set of global and local boundaries identified, regardless of how the boundaries are derived. There is no consensus on the standardisation of distributing the global SOS and harmonisation of AESA steps.

3.3. The consumption-based perspective is essential for AESA research

In a world of trade, countries sustain their development with goods and services provided by distant global hinterlands. A mere focus on reducing and decoupling domestic resource use therefore constitutes a limited perspective on the question of what is equitable and sufficient at the planetary scale (Hoekstra and Wiedmann, 2014). The environmental impacts and societal consequences associated with a country's consumption should no longer be defined by national boundaries, but by the extent of its global impacts (O'Rourke, 2014; Ramaswami et al., 2016). Considering the magnitude of international trade and its potential to create significant spillovers (Liu et al., 2015) or efficiencies (Davis et al., 2017; Janssens et al., 2020; Porkka et al., 2017), a failure to incorporate outsourcing through trade into the PBs framework would potentially result in significant assessment bias.

On the one hand, global trade of resource-intensive commodities may create significant environmental impacts which can be highly spatially concentrated (Teixidó-Figueras et al., 2016). Some developing economies continue to deliver primary materials to high-income countries while experiencing few improvements in their domestic material living standards (Schandl et al., 2018). Meanwhile, developed economies are often high-consuming societies that have not been able to moderate their high levels of consumption (Wiedmann et al., 2020; Wiedmann et al., 2015). For instance, the material footprint in high-income countries, on a per-capita basis, is 1.6 higher than the upper-middle income group, and 13 times the level of the low-income groups (IRP, 2019).

Decision-makers need to understand the extent of appropriation of natural resources and how trade can be conducted in a sustainable and equitable manner (Häyhä et al., 2016). On the other hand, in a globalised world, natural capital flows between economies with a varying degree of resource endowment. Imports of goods and services can be a central strategy for nations to obtain locally scarce resources and can therefore avoid the transgression of local resource use or pollution limits while boosting climate change adaptation and food security and sustaining domestic economies (Davis et al., 2017; Janssens et al., 2020; Li et al., 2019; Porkka et al., 2017). Research has shown that in the context of food, trade has a high resource saving potential, especially in the case of water, although this may vary across specific trade links and different local socio–economic contexts (Dalin et al., 2014).

A consumption-based perspective that accounts for these global teleconnections is therefore a key prerequisite in AESA research. The question of 'how PBs are exceeded by consumption elsewhere and how responsibility should be shared' need to be explicitly incorporated into any assessment. In general, these types of questions are well addressed by research on socio-economic metabolism, which studies the society-nature relationships and focusses on directly linking the biophysical processes and socio-economic drivers (Haberl et al., 2019). Of the major socio-metabolic methods at hand, those that explicitly quantify or allocate environmental pressures or impacts are most relevant for PB research (Häyhä et al., 2016). In the following, we focus on the two prevailing methods that allow for AESA from a consumption-based perspective, namely Life Cycle Assessment (LCA) and environmentally extended input-output analysis (EE-IOA).

Approaches based on life cycle assessment

Life cycle assessment (LCA), coupled with assigned share of environmental carrying capacity, allows for the AES assessments at product or company levels. Initial steps in this direction were taken by assigning carrying capacity to regional impact categories as a form of regionalised normalisation (Bjørn et al., 2020; Bjørn and Hauschild, 2015; Bjørn et al., 2016; Ryberg et al., 2016; Ryberg et al., 2018b). A typical LCA AESA involves four steps: assessing environmental impact of a specific entity, quantifying the carrying capacity as inspired by or derived from the PBs framework, assigning the carrying capacity to the entity, and determining the exceedance of the assigned carrying capacity.

There is an increasing trend that LCA practitioners are incorporating PBs through various stages of life cycle assessment. PBs are used as constraints in the life cycle inventory analysis (Algunaibet et al., 2019b). PBs are also used in life cycle impact assessment as characterisation factors (CFs). For instance, Ryberg et al. (2018b) introduce PB-informed characterisation models for fifteen impact categories in their PB-Life Cycle Impact Assessment (LCIA) method. In their proposed framework CFs encompass *'the average change in distance between current and preferred environmental state per unit change in elementary flow.'* Ryberg et al. (2018a) further describe the advantages of including the time perspective into the elementary flow into LCIA (i.e. *mass per year*), compared to Doka (2015) and Bjørn and Hauschild (2015). PBs are also used as weighting factors in the weighting step (Vargas-Gonzalez et al., 2019) and as normalisation references in the normalisation step (Sørup et al., 2020; Uusitalo et al., 2019).

Approaches based on EE-IOA

EE-IOA can be used to link the planetary biophysical resource flows and environment impacts with the monetary exchange of goods and services via global supply chains (Miller and Blair, 2009). The ability of environmental-economic accounting to reflect physical and economic interdependencies is essential. Global multi-region input–output models allow for the connections to be made between the location of environment impacts and the consumption of goods and services in the world, enabled by global supply chains (Dietzenbacher et al., 2013; Wiedmann and Lenzen, 2018). The explicit and complete depiction of inter-industry (production-trade-consumption) linkages avoid sectoral or spatial cut-offs compared to 'coefficient approaches' (Feng et al., 2011; Kanemoto et al., 2012).

Footprint results derived by EE-IOA have been moderately adopted by PB practitioners to assess the level of PB transgression. For instance, environmental footprint results can be used to directly compare with downscaled PBs (Fang, 2021; Lucas et al., 2020; O'Neill et al., 2018). Li et al. (2020b) further illustrate how PB exceedances can be measured by developing exceedance and surplus footprints. The merits of integrating PBs with footprints are threefold. First, benchmarking footprints against PBs turns them into a metric of absolute sustainability, shifting the focus towards the degree of PB exceedance (Laurent and Owsianiak, 2017; Li et al., 2019). Second, through their intrinsic link between production and consumption, PB-benchmarked footprints can contribute to reconciling trade-offs between global and local sustainability goals, helping to formulate global environment governance agendas (Muñoz and Gladek., 2017; Zipper et al., 2020). And third, if footprints can be benchmarked against localised PBs, then the consumption-based responsibility attribution reflects location-specific and not only aggregate impacts along the supply chain (Li et al., 2019).

3.4. Presence of PBs in current international and national policies

PBs provide a strong narrative and metaphor for international cooperation and communication but whether it can motivate realistic policy design remains a major challenge (Biermann, 2012; Biermann and Kim, 2020). Probably the most common strength of the PBs concept is that it serves as a guardrail rather than a pathway for society (Galaz et al., 2012).

PBs and SDGs

Unlike the widely agreed UN 2030 SDG agenda, there is no political consensus that the PBs are the biophysical limits that we should not transgress globally (except climate change boundary) (Griggs et al., 2013). This is because decisions regarding environmental management are made at global, national, sub-national, city, sector, company and product scale. The current SDG 12 Sustainable Production and Consumption lacks a clear sub-goal agreement to curb overconsumption. Existing goals only focus on relative resource use decoupling indicators and suggest resource use efficiency enhancements, while ignoring human well-being decoupling completely (Bengtsson et al., 2018; Dong and Hauschild, 2017).

Governments are unclear about the discrete strategies of how to operationalise the PBs agenda and how PBs can help to deliver SDGs. Achieving all 17 SDGs and 169 targets whilst remaining within all PBs seems like an overwhelming if not impossible task (Bleischwitz et al., 2018). Suggestions to hierarchically organise the SDGs in a way that prioritises those related to "staying within planetary boundaries" (Costanza et al., 2014b), have also proved challenging to implement (Biermann and Kim, 2020). In most studies of future development pathways biophysical boundaries are absent from the scenario narratives and driving forces, for instance, in the Shared Socioeconomic Pathways (Riahi et al., 2017), the iSDG model (Allen et al., 2019) and the integrated land system model (Gao and Bryan, 2017). Until now, only Randers et al. (2018) assess the extent of transformational requirement to achieve SDGs within all PBs in 2050 through an integrated global system model (the Earth3 model).

PBs in current policies

To date, the concept of absolute sustainability has not yet influenced the framing of most national policies with the exception of only a few national and supra-national governments. The EU's 7th Environment Action Programme to 2020 (Living well within the limits of our planet) explicitly respects the biophysical limits in their 2050 vision as *'In 2050, we live well, within the planet's ecological limits…Our low-carbon growth has long been decoupled from resource use…further research into planetary boundaries…'* (EU, 2013). The European environment — state and outlook 2020 explicitly places current Europe's consumption into a global context and recognises its responsibility associated with its high consumption outside its territory (EEA, 2020). Based on three European PB studies, the report also features a standalone sub-chapter in its scene setting: 'Is Europe living within the limits of the planet?'. It reaches the conclusion that *'Europe has achieved high levels of human development ('living well') but at the expense of overshooting its share of global SOS for several PBs, even under generous assumptions of assigned shares'*. In

Germany, PBs are framed as absolute guardrails in Germany‘s Integrated Environment Programme and Germany‘s National Sustainability Strategy (BMUB, 2017).

In most global sustainability transition and environmental governance outlook reports, the observations of ambition to living within PBs are brief and do not specify policy levers to enable transformative transitions. For instance, the UN Environment’s sixth Global Environment Outlook concentrates on ‘*Providing a decent life and well-being…by 2050, without further compromising the ecological limits of our planet and its benefits…*’ but does not explicitly state the pathway to implementation (UNEP, 2019). In the World Economic Forum Global Risks Report 2020, the only PB the report thoroughly discusses is the climate change boundary, where it says ‘*The near-term consequences of climate change add up to a ‘planetary emerge*ncy’…’ (WEF, 2020).

Taking Australia as an example, the State of the Environment Report, which thoroughly reviews the state of the Australian environment in 2016 (Jackson, 2017), biophysical limits are described in one phrase ‘*achieving long-term sustainability requires that the use of the environment is kept within biophysical limits…*’ (Hatfield-Dodds et al., 2015). Proponents of Australian relative resource use decoupling achievements argue that GHG emissions, energy consumption and water use show a lower increase rate than its Gross Value Added from 1996 to 2014 (Jackson, 2017). Schandl et al. (2016) further prove that using the same models as employed in the National Outlook, dematerialisation and decarbonisation can be achieved for 13 world’s major economies, including Australia, through well-designed policies. Allen et al. (2019) nest Australian national SDG scenarios within the global Shared Socioeconomic Pathways and conclude a ‘Sustainability Transition’ scenario will deliver 70% SDG targets achievement by 2030, though none of the 52 targets and 97 indicators they model considers biophysical limits.

4. Recommendations

Based on the findings of our literature review, we make three sets of recommendations to advance AES indicators and assessments informed by PBs (Fig. 1).

4.1. Standardising AESA metrics informed by biophysical limits

Future research should continue to seek consensus in standardising AES indicators and assessment methodologies across all scales. This would require scientists from environmental, economic, social and engineering sciences to employ absolute sustainability thinking and to better link human drivers and biophysical limits (Haberl et al., 2019; van Vuuren et al., 2016). Supply-side solutions that achieve increases in productivity can play a significant role in reducing pressure on planetary boundaries but the urgency and great mitigation potential of demand-side solutions to equitably downscale consumption demands, is reported by a number of researchers (IRP, 2019; UNEP, 2020; Wiedmann et al., 2020). A much debated question is whether the ‘degrowing’ of wealthy economies will experience a loss in wellbeing (Barrett et al., 2020). Another question is whether a civilisational shift to an ecocentric world could possibly be envisaged under capitalism and current market economies (Wiedmann, 2020). Recognising there are many unanswered questions about the implication of demand-side solutions on PBs and AESA research, socio-metabolic and dynamic system modelling have been and are increasingly been employed to model driver interactions and feedbacks in a finite socio-ecological system (Cooper and Dearing, 2019; Randers et al., 2018). Scholars of circular economy also begin to provide some explanation as to why a socio-metabolic perspective is essential to PBs research. Haas et al. (2020) find a growing global socioeconomic metabolism that transgress PBs in the past century (i.e. annual inputs and outputs of non-circular primary materials exceed the limited source and sink capacities of the earth system). Elhacham et al. (2020) find global human-made mass exceeds all living biomass in the year 2020. These initial results are suggestive that the use of scale indicators (in absolute terms) should receive critical attention in a finite world (compare to the recycling rate in percentage terms).

Recent socio-metabolic model development would enable greater capacity in developing consumption-based AES indicators and assessments. For instance, in the EE-IOA discipline, sub-national and city EE-IO model advances feature timely and geographically explicit assessment of the driving forces of local and displaced impacts (Geschke and Hadjikakou, 2017; Lenzen et al., 2017). The ongoing development of spatially extended economic accounts based on remote sensing (Moran et al., 2020) provides further promise in terms of PB research. Scenario-based EE-IOA offers future macro-level estimates and feedbacks of demand-side policy measures, such as changes in production recipes, resource productivity improvement, shifts in intermediate and final demand, mitigation modelling from household consumption and lifestyle behaviour, and rebound effects (Donati et al., 2020; Hardt et al., 2021; Ivanova et al., 2020; Wiebe et al., 2019; Wood et al., 2018a).

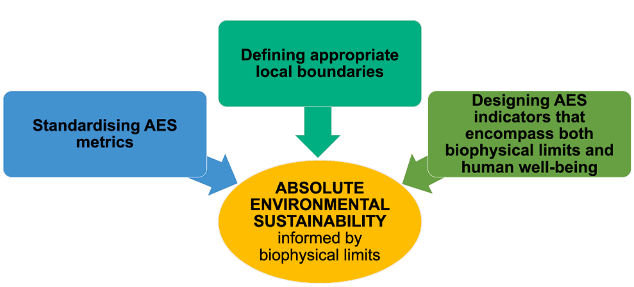

Fig. 1. Key recommendations and research pathways for designing absolute environment sustainability indicators and assessments informed by PBs.

4.2. Defining appropriate local boundaries

The reference value that any sustainability indicator is compared to is of vital importance in an AESA (Little et al., 2016; Sala et al., 2015). We argue that the ability of AESAs to reconcile trade-offs between multi-scalar environmental sustainability boundaries is essential (Heck et al., 2018; Li et al., 2019). Ideally, AESAs should comply with local sustainability requirements while aligning with global biophysical limits. As the PBs were not initially proposed to account for local, national or regional boundaries, PB operationalisation studies should seek context-specific local boundaries that are most relevant to the local circumstances, while at the same time observing global boundaries. This likely requires the concurrent employment of both bottom-up and top-down approaches.

Defining and implementing context-specific local boundaries requires technological innovation and an effective monitoring and governance system (e.g. pricing of transgressing PBs (Engström et al., 2020)), all of which are driven by ambitious institutional innovation (Sala et al., 2015). Scientists, producers and civil society cannot unilaterally determine a local boundary due to competing interests and only a joint cohort of professionals and practitioners can implement this agenda. State actors may be best placed to design, allocate and govern appropriate local boundaries. Government can create short-term resource trading schemes, taxes, subsidies and long-term market-based approaches with corrective redistribution systems that factor in technology policies and socio-ecological interactions (Sterner et al., 2019).

In seeking appropriate local boundaries, we propose that translating global SOSs to local scales require standardised and tiered operational steps, i.e. the local boundaries should contain three dimensions, biophysical, social and political. First, improved biophysical control variables that govern the Earth system and should be quantified and the robustness over some existing PBs should be evaluated (e.g. terrestrial net primary production (Running, 2012), nutritional food (Rockström et al., 2020; Willett et al., 2019), biodiversity and water (Heistermann, 2017; Rockström et al., 2018)). The biophysical definition of a local boundary must respect Earth system dynamics and recognise that biophysical boundaries cannot be substituted. Taking the water control variable as an example, local biophysical needs include ecological requirements of the water basin and intra-annual variability of rivers, whereas higher-level biophysical needs include regional and global water cycle stability and water tipping points (Abbott et al., 2019; Falkenmark et al., 2019).

A local boundary-defining process will not only look at environmental issues within the context of the biophysical needs, but also at competing socio-economic interests from citizens, companies, society, and the health of ecological systems in general. A social local boundary can be defined by regional or national commitment based on public perception on the impact of particular PBs on people's livelihoods as different communities may prioritise different use of their local boundary share (Teah et al., 2016). Ethical and normative criteria play a decisive role in defining in what can be regarded a fair and just share of safe, local operating space (Downing et al., 2020). Ethical implications relate to questions of fairness, inequality, (historic) responsibility, capacity to act, right to development, and anticipated future requirements (SEI, 2017, 2018). Normative criteria include a country's share in global population, land area, economic output, resource efficiency, historical share of resource use (grandfathering), emissions and environmental impacts, etc (van den Berg et al., 2020). Applying these criteria should follow widely accepted rules and standards based on consensus (Ensor and Hoddy, 2020).

As the third dimension, a political dimension should be included to account for future socio-ecological dynamics. This is because of the lagged or hysteretic environmental feedbacks of excessive resource use on ecosystem resilience and human well-being (health, food and income) (Dearing et al., 2014). Each specific policy goal should be evaluated in terms of future environmental responses and outcomes. A local boundary is dynamic and evolves over time. For instance, the science-based targets use company market share and company growth projections to adjust their emission pathways (Krabbe et al., 2015). Furthermore, due to the geographical separation of production and consumption, wider beneficiaries of resource-intensive commodities trade (metal (Watari et al., 2021)) and full society cost of pollution exceedances should be quantified and made visible across borders (Li et al., 2019). As van Vuuren et al. (2016) contend in their PB review, instead of always pursuing complex fully integrated models, a PB-related target research question should be analysed by an appropriate type of model. Future research should focus on deriving local boundaries at all spatial and temporal scales, national, sub-national, as well as for individual businesses and products (Bjørn and Hauschild, 2015).

4.3. Designing AES indicators that encompass both biophysical limits and human well-being

We find that the ambition to live within PBs is rarely mentioned in existing policies and the integration of PBs into mainstream environmental policies remain underexplored. In AES indicator and assessment design, we argue that two components should be explicitly formulated and integrated i.e. respecting the biophysical limits and improving human wellbeing. The challenge now for sustainability scientists is clear: How can humanity transition to a world where human well-being is pursued while negative impacts to the planet are kept within acceptable limits? Biophysical limits must be strictly respected as the pre-requisite in almost, if not all environmental, social and economic policy design (Griggs et al., 2013) (Table 2). In this regard, the doughnut economy theory explicitly recognise PBs as the Earth's life support system and the social foundation indicators (e.g. skill sets, healthcare) as the ultimate measure for sustainable development (Raworth, 2017; Thriving Cities Initiative, 2020). Also, the biosphere economy theory considers tipping points and threshold effects in ecological systems (Crépin and Folke., 2015).

On the other end of the wellbeing-PBs spectrum, it is human welfare and well-being (i.e. the outcome) that must be ultimately quantified rather than the means to reach the outcome, e.g. economic throughput (Ryberg et al., 2020). The beyond-GDP discourse is re-gaining momentum and well-being depends on how healthy all types of capitals are (produced, human and natural capital) (Bateman and Mace, 2020; Contestabile, 2020; Costanza et al., 2014a). Genuine progress indicator (Kubiszewski et al., 2013), the Inclusive Wealth Index (UNEP, 2018) and the Better Life Index (OECD, 2020) are examples for appropriate measures of societal progress. The 'Living Well Within Limits' project has a designed focus on analysing decent living standards and social provisioning services, with the aim to decouple basic human needs satisfaction from irreducible material use (e.g. energy services) (Brand-Correa and Steinberger, 2017; Rao and Min, 2018).

Sustainability targets adopted in current international policies fail to formulate biophysical limits as a complementary prerequisite to increasing equality in human welfare (Table S1) (Sachs et al., 2020). A major barrier is the perception that developing policy that prioritises meeting PBs could impede progress on social and economic goals, especially dominant in the developing world (Biermann and Kim, 2020). A major contributor to this fallacy is the fact that relative resource use decoupling indicators (OECD, 2015) tend to rely on economic throughput and resource efficiency gains as proxies for development. A separation of economic-growth targets from sustainability metrics has long been advocated (Editorial Nature, 2020; Jackson and Victor, 2019; Raworth, 2017; UNDP, 2020). Absolute decoupling (fewer resources are used over time regardless of economic growth) does not measure human wellbeing or biophysical limits directly but has similar goal orientations (Stoknes and Rockström, 2018; Wood et al., 2018b). Human well-being decoupling does measure the service provided or satisfaction of human need per unit of resource use IRP (2019), but fails to account for biophysical limits. We argue that mainstream environmental policies based on resource efficiency gains should be supplanted by policies that focus on sufficiency, i.e. that caps consumption in the pursuit of achieving high human development (Parrique et al., 2019; Wiedmann et al., 2020).

Future AES indicators and assessments but also the implementation of existing commitments (e.g. SDGs) need to embed PB concerns (Randers et al., 2018). In achieving this planetary concern, distinct challenges remain in devising sustainable pathways for countries at different stages of socio-economic development (Sterner et al., 2019). We agree with Biermann and Kim (2020)'s critique that the impact of PBs on national policy processes does not extend much beyond the Global North and that political stakeholders from the Global South should be fairly represented. Recent modelling by the International Resource Panel suggests that the growth rates of resource use in emerging economies must be balanced by absolute reductions in developed economies, based on the consensus that developing economies have the rights to reach the prosperity of developed economies (IRP, 2019). We argue that developed economies with high consumption-based SOS should prioritise curbing resource consumption while allowing developing economies with low consumption-based SOS to improve their sustainable societal wellbeing.

In the short-term, precautionary and stringent absolute sustainability thinking (technological mandates and performance-safe standards) may help to prioritise certain policy instruments to avoid lagged environmental feedbacks of excessive resource use and stress (Dearing et al., 2014). For instance, rights-based policy instruments such as capped tradable quotas may be favourable over price-based tools (e.g. taxes and subsidies) (Meyer and Newman, 2018). In the long-term, policy coherence is needed between environmental policies and through time. These are policies with a time horizon of 10–30 years therefore time-bound benchmarks derived from these transformational policy pathways are critical in offering clarity for businesses and other stakeholders (Steffen et al., 2018).

5. Conclusion

A failure to encompass absolute biophysical limits in international and national policies would be a missed opportunity for humans to thrive in a finite world. Much of the problem is a lack of consensus in standardising AES measurement metrics and defining appropriate local boundaries. The success of the PB concept in motivating policy-making processes and behaviour change is reliant on a common knowledge and understanding of underlying Earth system science dynamics and socio-economic complexities. Although the original PBs were not designed to be downscaled, efforts in translating the global environmental limits to smaller scales can potentially open up the policy window of AESAs and increase the likelihood of their implementation.

Rapid and transformational changes to our economies and societies are necessary to ensure sustainable pathways of human development in the Anthropocene (Ripple et al., 2017; Steffen et al., 2015a). To this end, sustainable and equitable appropriation of natural capital within bio-physical limits is essential to preserve human well-being. We believe planetary boundaries can accelerate the uptake of environmental limits in international and national environmental policy design. We support the need for the development of metrics that track planetary wellbeing and biophysical resource use boundaries as the first step towards implementation of absolute decoupling and transformational transitions of social norms (sustainable per capita consumption life style) over broad scales (Steffen et al., 2018). In the post-COVID-19 recovery phase and as humanity goes through the recalibration of SDG processes, staying within PBs will strongly depend on a successful bottom-up implementation from individuals, corporate, cities and countries.

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.

Acknowledgements

The authors are grateful to anonymous reviewers for their very helpful comments.

Funding

This research was supported by the Australian Research Council [grant number DP190102277], and the National Natural Science Foundation of China [grant number 72074193, 71704157].

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106475.

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