Journal of Cleaner Production 448 (2024) 141447

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Measuring the Doughnut: A good life for all is possible within planetary boundaries

Hauke Schlesier [a,*], Malte Schäfer [b], Harald Desing [a]

[a] *Empa - Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland*
[b] *Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, 38106 Braunschweig, Germany*

ARTICLE INFO

Handling Editor: Jing Meng

Keywords:
Safe and just operating space
Sufficiency
Doughnut economics
Decent living standards
Planetary boundaries

ABSTRACT

Humanity is continuing a path towards ecological instability. While resource consumption is unprecedented, significant parts of the human population are still deprived of decent living. The safe and just operating space postulates that it is possible to simultaneously stay within ecological limits and fulfil basic needs. However, evidence that such a state can be achieved given existing population and available technologies is lacking. Here, we attempt to show whether a safe and just space exists by modelling material and energy requirements for satisfying basic needs with various technological scenarios. Environmental impacts of a basket of products representing basic needs satisfaction are measured through life cycle analysis and compared to planetary boundaries for the first time. We find that all planetary boundaries considered can be respected for 8.0 and 10.4 billion people with a probability of 81% and 73% respectively. However, this requires a fossil-free energy system, and an essentially vegan diet as well as no additional cropland conversion. To actually create and enlarge a safe and just operating space, carbon dioxide emissions, biodiversity, Phosphorus and Nitrogen emissions would need to be further reduced, mainly by improved agricultural practices and material circularity.

Significance Statement

The purpose of this study is to find out if humanity can fulfil basic needs for all humans without destabilizing the Earth system. This information is relevant for identifying pathways to futures in which all humans can live good lives without compromising the livelihoods of future generations. Our results show that it is theoretically possible to satisfy the basic needs of 10.4 billion people within ecological limits. However, large-scale transformations in all sectors and dietary changes are necessary to guarantee safe climate conditions.

1. Introduction

Throughout human history, societies existed that sustained themselves over millennia (Suzman, 2020; Gowdy, 1998). In contrast, modern society is appropriating an unprecedented amount of natural resources (Krausmann et al., 2013, 2018; Flörke et al., 2013; Elhacham et al., 2020), altering natural geo-chemical cycles on global scales, and exceeding multiple planetary boundaries (PBs) (Steffen et al., 2015a). Destabilizing Earth system processes threaten the very foundations that have allowed humans to prosper over the last 11 000 years (Rockström et al., 2009b; Steffen et al., 2015b). For example, unabated anthropogenic emission of greenhouse gases subjects future generations to the dangers of self-amplifying global heating—with potentially existential consequences for humankind (Steffen et al., 2018; Lenton et al., 2019; Armstrong McKay et al., 2022; Wunderling et al., 2022).

Despite enormous resource consumption and stocks available in the technosphere (Elhacham et al., 2020), basic needs are not satisfied for all humans (O'Neill et al., 2018). For example, an estimated 720 million people were undernourished in 2020 (Food and Agricultural Organisation, 2021). Multidimensional poverty coexists alongside excessive luxury (Chancel et al., 2021; Oswald et al., 2020). The rich are disproportionately responsible for exceeding PBs (Otto et al., 2019; Wiedmann et al., 2020). Returning to an operating space within PBs is, however, not just a matter of redistribution, but also of reducing overall consumption and transforming the provisioning systems. Kate Raworth postulates the existence of a safe and just operating space for humanity (SJOS), i. e. a society living above satisfying basic needs for all while respecting environmental limits (Raworth, 2012, 2017).

Previous studies analysed whether a particular society achieves social goals for all without exceeding allocated environmental limits. Investigations have been made on regional (Dearing et al., 2014; Cooper and Dearing, 2019), national (Cole et al., 2014; Sayers and

---

* Corresponding author.
E-mail address: hauke.schlesier@empa.ch (H. Schlesier).

https://doi.org/10.1016/j.jclepro.2024.141447
Received 29 March 2023; Received in revised form 22 February 2024; Accepted 23 February 2024

Abbreviations

CO_2	carbon dioxide
DLS	decent living standards
EF	environmental footprint
FF	fossil-free (scenario)
GWP	global warming potential
ISIC	International Standard Industrial Classification of All Economic Activities
LCA	life cycle assessment
LCIA	life cycle impact assessment
LD, HD	low, high demand (scenario)
N	Nitrogen
noLT	no land transformation
P	Phosphorus
P_v	probability of violation
PB	planetary boundaries
SDG	sustainable development goals
SJOS	safe and just operating space
SoS	safe operating space
WB	wooden buildings (scenario)

Trebeck, 2015; Allen et al., 2021; Roy and Pramanick, 2020), continental (Heijungs et al., 2014) and global scales (Randers et al., 2019; O'Neill et al., 2018; Hickel, 2019; Ehrenstein et al., 2020; Conijn et al., 2018; Fanning et al., 2022). Some studies focus on specific social goals – like food supply (Conijn et al., 2018; Gerten et al., 2020; Willett et al., 2019), happiness levels (Ehrenstein et al., 2020), and the gross national product (Heijungs et al., 2014) –, while others account for multiple social objectives (Soergel et al., 2021; Randers et al., 2019; Allen et al., 2021) included in the Sustainable Development Goals (SDGs) (United Nations, 2015). The strength of the SDGs lies in their international acceptance. Yet it is questionable if SDGs are adequately representing social standards for sufficiency as they (i) lack a consistent scale of normalization (Drees et al., 2021), (ii) are not always quantified or quantifiable (Drees et al., 2021), and (iii) have been criticized for containing contradictions between individual goals (Eisenmenger et al., 2020; Alcamo et al., 2020; Menton et al., 2020). Also, outcomes are sensitive to which and how many indicators per goal are selected (Drees et al., 2021).

In a different approach, fulfilling basic needs for all is seen as an enabler for reaching social objectives (Rao and Baer, 2012). Defining material and energy requirements necessary to provide *decent living standards* (DLS) (Rao and Min, 2018; Kikstra et al., 2021; Millward-Hopkins et al., 2020), allows to operationalize the theory of human needs via quantifiable and physical prerequisites for human well-being. However, difficulties arise for needs whose satisfaction is not directly linked to resource inputs (e. g. participation, safety, or mental health). Gough (2020) draws from the DLS approach and conceptualizes *consumption corridors*, another form of the "Doughnut" idea, which are characterized by a lower limit of consumption consistent with need satisfaction and an upper limit to curb excessive consumption incompatible with environmental limits or social norms.

Environmental limits, which should not be transgressed, can be defined in different ways. On a local or regional scale, studies frequently define limits for air, water and soil quality indicators (Dearing et al., 2014; Sayers and Trebeck, 2015) or specific ecosystem features (e. g. fish populations; Cooper and Dearing, 2019). Studies investigating larger scales make use of (allocated) PBs (Randers et al., 2019; Conijn et al., 2018; Sayers and Trebeck, 2015), sometimes in combination with environmental footprints (PB&EF) (O'Neill et al., 2018; Cole et al., 2014; Ehrenstein et al., 2020; Allen et al., 2021; Roy and Pramanick, 2020).

In an analysis of 150 countries, none achieved all SDGs nor stayed within all allocated PBs (O'Neill et al., 2018). Few of these countries could theoretically enter SJOS by reducing inequality within the country and modestly increasing resource consumption (Hickel, 2019). But analysing trends between 1995 and 2015 for 91 of these countries suggests that biophysical limits are being transgressed faster than social goals are achieved (Fanning et al., 2022). When extrapolating these trends until 2050, it becomes apparent that no country is likely to enter SJOS (Fanning et al., 2022). Even under ambitious climate policies, not all targets may be achieved until 2050 (Soergel et al., 2021). Much more ambitious scenarios are necessary to come close to SJOS (Stockholm Resilience Centre, 2018). For example, the *Giant Leap* scenario in the Earth4All model (Dixson-Declève et al., 2022) is claimed to enter SJOS. However, quantitative evidence for this claim is missing.

Empirical evidence on the non-existence of the SJOS is no proof that the SJOS cannot be achieved, since existing studies do not reflect the potential of more eco-efficient provisioning systems (e. g. 100% renewable energy systems (Breyer et al., 2022)). Studies that consider eco-optimized technologies, however, either lack a multidimensional social objective (Ehrenstein et al., 2020; Conijn et al., 2018; Gerten et al., 2020; Willett et al., 2019), environmental objectives (Millward-Hopkins et al., 2020), or a global scale (Allen et al., 2021). Soergel et al. (2021) consider all of the above aspects, yet they use questioned SDGs as social objectives and a carbon budget consistent with 1.5 °C heating as the climate objective. Although this is reasonable for the short- or medium-term, the question remains if humanity can stay at or below an atmospheric concentration of 350 ppm CO_2 in the long-term, meaning that global net-emissions do not exceed natural CO_2 removal capacities (Myhre et al., 2013; Stein, 1991). Therefore, the question whether or not the "Doughnut" exists remains unanswered, i. e. if it is possible to provide decent living for everyone within ecological limits.

This study aims at filling this research gap by analysing environmental impacts of baskets of products representing DLS under various provisioning system scenarios and considering uncertainties. To do so, we seek to find out if a steady-state SJOS can be achieved and – if yes – to estimate its size. Furthermore, a sufficiency-based allocation key will be derived that mediates between impact categories and resource segments. This can help in finding sustainable resource budgets (as resources are the physical "currency" of our economy (Desing et al., 2020b,a)) based on fulfilled needs.[1] To sum up, this study is the first one attempting to determine whether a "Doughnut" (SJOS) can potentially exist—whether a good life for all is possible. Our understanding of "possible" refers to technical feasibility – i. e. achievable with existing technologies – and does not consider e. g. political or societal obstacles.

A five-step method (Section 2) is developed to estimate the existence of SJOS and derive an sufficiency-based allocation key (Section 3). The implications and limitations are discussed in Section 4; a summary of the findings and outlook to future research provided in Section 5. Details in the procedure as well as additional data, justifications for selected values, and code can be found in the supplementary materials (see Section S1).

2. Method, data and case study

To measure SJOS, we take the following approach: first, we define the social foundation through a basket of products and services representing DLS, upscale the associated environmental impacts with the world population and, finally, compare them to Earth system boundaries, which set limits to maximal impacts compatible with the long-term stability of the Earth system within a Holocene-like state (Rockström et al., 2009a) (the PB framework being one approach of describing them). Per definition, SJOS exists if impacts resulting from

---

[1] Heide et al. attempt to operationalize human need fulfilment for allocation, however relying on social and environmental indicators of "most sustainable countries". This is a questionable approach since none of the countries provides sufficiency for all.

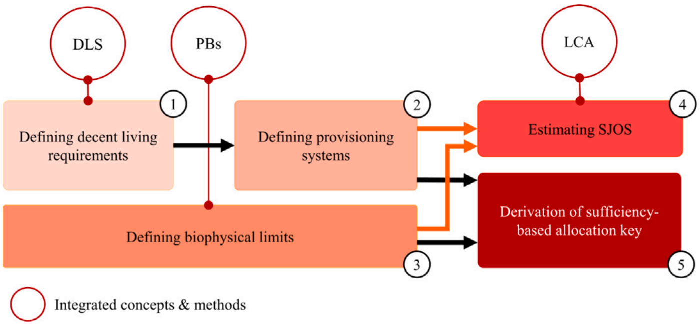

Fig. 1. Overview on the method used in the case study. Numbers correspond to the general method steps described in the text.

providing DLS for a given population do not exceed Earth system boundaries. The distance between fulfilling DLS for all and Earth system boundaries demarcates the "Doughnut" (Raworth, 2012). Finally, impact shares are allocated to resource segments yielding a sufficiency-based allocation key.

The analysis assumes a steady state, i. e. all resource inputs and provisioning systems are constant over time. This represents a post-transformation economy that can be maintained sustainably. Different scenarios for provisioning systems can be considered to test the effect of technological change. Transitions towards such a steady state are not investigated here, as we are interested in measuring the potentials of social – i. e. reducing consumption to sufficiency – and technological change to achieve a possibly sustainable socio-economic system.

The method consists of the following five steps (Fig. 1):

1. Specifying the social foundation by defining sufficiency requirements for an average person and defining the basket of products necessary to fulfil these requirements.
2. Selecting the provisioning systems (e. g. food production, energy infrastructure, transport system) that provide the basket of products for sufficient living. Selection of world population scenarios (UN Department of Economic and Social Affairs, 2022).
3. Selecting environmental objectives: impact categories, Earth system boundaries, and life cycle impact assessment (LCIA) methods.
4. Measuring SJOS: Calculating the impacts of sufficiency (scaled up with the selected population) and benchmarking them against Earth system boundaries.
5. Sufficiency allocation: Allocating Earth system boundaries to resource segments.

Multiple options exist for carrying out the method described above. For example, the social foundation may be defined either by SDGs or decent living standards, and Earth system boundaries can be described either by Planetary Boundaries or limits defined for environmental footprints. In our case study, we translate basic needs into a physical basket of products based on DLS, scale up the environmental impacts on the PBs (using life cycle assessment, LCA), and compare them to PBs using the current and expected peak world population.

2.1. *Decent living requirements*

In the first step, the social foundation – defined in abstract terms such as subsistence, access to education or freedom of speech – needs to be defined. We choose the DLS approach (Rao and Min, 2018), which have already been operationalized to measure decent living energy (Millward-Hopkins et al., 2020; Millward-Hopkins, 2022; Kikstra et al., 2021) and material requirements (Vélez-Henao and Pauliuk, 2023). However, so far they have not been benchmarked against environmental objectives.

The idea that every human is entitled to a certain level of well-being is widespread and manifested in international agreements (United Nations, 1948, 1966, 2015) and is also mirrored in several scientific concepts (e. g. Brand-Correa and Steinberger, 2017; Rawls, 1971; Reinert, 2011; Gough, 2019; Rao and Baer, 2012; Rao and Min, 2018). Basic human needs and capabilities are identified as thresholds for well-being (Max-Neef, 1992; Sen, 1993; Nussbaum, 2000), however, they are too abstract to be applied practically (Doyle and Gough, 1991). Therefore, universal satisfiers that represent cross-cultural means of satisfying human needs were proposed (Doyle and Gough, 1991) (for details on needs and satisfiers, see Section S2). These universal satisfiers have been translated into physical requirements by the *decent living standards* (DLS) (Rao and Baer, 2012; Rao and Min, 2018; Millward-Hopkins et al., 2020; Kikstra et al., 2021). In this study, we build on DLS, expand it where necessary with additional literature (see Section S2), and define a globally representative basket of products able to provide the social foundation. This sufficiency basket is modelled in LCA as the foreground system (Table 1), while the provisioning system supplying this basket is modelled as the background system. As background databases we use ecoinvent v3.8 (Ecoinvent, 2021) and modifications thereof Gómez-Camacho et al. (in preperation) (see Section 2.2). This makes it necessary to express the sufficiency basket in units consistent with ecoinvent.

For nutrition, we follow the detailed recommendations for a planetary healthy diet (Willett et al., 2019) and translate the calories needed per food category into kilogrammes of specific food items which are globally representative and modelled in ecoinvent (see Section S2). Shelter requirements are modelled according to DLS with additional assumptions necessary regarding building life times and room heights. For clothing we add life cycle inventory data for shoes (Gottfridsson and Zhang, 2015). For quantifying physical requirements of health care, hospitals are modelled based on life cycle inventories and functional requirements from Switzerland (Keller et al., 2021; BAG, 2020), which can be seen as globally desirable. Access to schools and communication are modelled following DLS, yet without specifying the number of teachers required, because their number does not relate to a material or energy requirement. Freedom of expression relies on public space large enough to support mass demonstrations. We estimate the required public space that can accommodate largest gatherings in recent history (Ortiz et al., 2022). The modal split for mobility is based on Millward-Hopkins et al. (2020), however, excluding air travel, as it is hard to justify as a universal satisfier, and including scooters in the modal split. For details on data collection and justification for values, see Section S2.

For some universal satisfiers, it is not feasible to define resource requirements. For example, *family and childhood upbringing*, *childhood safety*, *physical security* and *economic security* cannot be directly correlated with physical requirements. We argue that such immaterial satisfiers can be met as long as all other material satisfiers are fulfilled. For example, children's mental health primarily depends on parental affection, which is more likely to be granted if parents do not need to worry about food or shelter. The correlation between poverty and children's development as well as violence (Hsieh and Pugh, 1993; Letourneau et al., 2013; Brooks-Gunn and Duncan, 1997) supports this assumption. Secondly, we argue that having access to the material and energy requirements for a decent life provides economic safety per definition. Therefore, we do not define material and energy requirements for needs concerning family, childhood, physical and economic safety dimensions, and assume that they can be satisfied without further resource inputs (see Section 4 for a discussion).

DLS cannot be defined with ultimate precision. Therefore, we consider a range of possible values (Table 1 and Section S1). Three different scenarios – low demand (LD), base and high demand (HD) – are defined to explore possible deviations in the demand to satisfy basic needs. The base scenario relies on centre or average values stated in the literature (see Section S2); the average household size is assumed to be four

Table 1
Requirements for decent living standards (LD: low demand, HD: high demand). Green: household scale, yellow: community scale, red: national/global scale. μ: mean value (Grubler et al., 2018).

Universal satisfier	Decent living requirements			Per capita		Value from literature
	Nr.	Dimension	Requirements	Value [LD, base, HD]	Unit	
Nutrition	1a	Food	Calories, proteins, micro-nutrients	[2000, 2250, 2500]	kcal/acap	[Millward-Hopkins et al. (2020), μ, Willett et al. (2019)]
	1b	Cold storage	Refrigerator (100 L)	[0.2, 0.25, 0.33]	1/cap	Millward-Hopkins et al. (2020)
	1c	Cooking	Clean stove	[0.2, 0.25, 0.33]	1/cap	Rao and Min (2018)
Water	2	Hygiene	Toilet	[0.2, 0.25, 0.33]	1/cap	Rao and Min (2018)
			Water supply / disposal	[18.25, 21.17, 23.73]	m^3/acap	[Millward-Hopkins et al. (2020), μ, Kikstra et al. (2021)]
Shelter	3a	Building	Solid wall, roof, minimal floor space Electricity, water, sanitary infrastructure	[10, 15, 30]	m^2/cap	[Kikstra et al. (2021), Millward-Hopkins et al. (2020), Grubler et al. (2018)]
	3b	Final energy	Energy infrastructure	[676, 1093, 1512]	kWh/acap	see Table S3
Harmless living, working conditions	4a	Light	Illumination	[73, 137, 243]	klmh/acap	Millward-Hopkins et al. (2020)
	4b	Comfort	Modern heating, cooling system	[0.2, 0.25, 0.33]	1/cap	Rao and Min (2018)
			Clothes	[1.3, 2.6, 4]	kg/acap	[min Kikstra et al. (2021), μ, Millward-Hopkins et al. (2020)]
	4c	Clothing	Laundry	[59, 78, 98]	kg/acap	[-25%, Millward-Hopkins et al. (2020), +25%]
			Shoes	[0.45, 0.9, 1.35]	kg/acap	[−50%, Kikstra et al. (2021), +50%]
Healthcare	5	Healthcare	Area of healthcare facility	[0.25, 0.41, 0.57]	m^2/cap	based on [min Rao and Min (2018), μ, Kikstra et al. (2021)]
Education, information, relationships	6a	School	Equipped schools	[1, 2, 3]	m^2/cap	[−50%, Millward-Hopkins et al. (2020), +50%]
	6b	Access to information	TV / laptop, internet	[0.2, 0.25, 0.33]	1/cap	Millward-Hopkins et al. (2020)
	6c	Communication	Telephone / smartphone ICT infrastructure	[0.2, 0.56, 0.93]	1/cap	[Kikstra et al. (2021), μ, Millward-Hopkins et al. (2020)]
Participation	7a	Freedom of expression and assembly	Public space	[0.28, 0.84, 1.39]	m^2/cap	based on Ortiz et al. (2022)
	7b	Mobility	Motorized transport, infrastructure	[5000, 8527, 15000]	pkm/a	[min Millward-Hopkins et al. (2020), Kikstra et al. (2021), max Millward-Hopkins et al. (2020)]
Family, children upbringing	8		*resource requirement unspecified*	–	–	
Childhood safety	9		*resource requirement unspecified*	–	–	
Physical safety	10		*resource requirement unspecified*	–	–	
Economic safety	11		*resource requirement unspecified*	–	–	

people (which is the mean average household size across 153 analysed countries; United Nations, Department of Economic and Social Affairs, Population Division 2019). The high demand (HD) scenario assumes that more material and energy are needed to provide a decent living standard. Defined HD requirements are oriented on the upper limits specified in the literature, and average household size is three people. In the low demand (LD) scenario, DLS requirements consist of lower values found in the literature, and average household size is specified to be five people. Additionally, the LD scenario assumes an essentially vegan diet (fish consumption remains). Threshold values for these three scenarios are listed in Table 1.

Even though there are regional differences for satisfying basic needs (e. g. varying energy requirements for heating or cooling (Kikstra et al., 2021)), this study is looking at globally representative material and energy requirements only.

We choose two different world population scenarios. The *today* scenario takes population size as of 2023, which is 8 billion, whereas the *peak* scenario refers to the maximum projected population of 10.4 billion (median of projections), which is expected to be reached around the year 2085 (UN Department of Economic and Social Affairs, 2022).

2.2. Provisioning systems

Supply chains provide all necessary inputs for the sufficiency basket (modelled as the foreground system in LCA) and are called provisioning systems, modelled here as LCA background system. Provisioning systems extract natural resources from the environment, transform them into products and useful energy (production systems) (O'Neill et al., 2018; Fanning et al., 2020), but also recover materials at the end of life (recycling systems) and release substances back to the environment (waste disposal and emissions). The same products can be provided by different provisioning systems (e. g. energy from fossil fuels or hydro power). We use two different ecoinvent databases as background systems to model provisioning systems for two levels of eco-efficiency. The ecoinvent 3.8 database (Ecoinvent, 2021) represents a system of conventional energy and transport technologies (e. g. , coal power, gas boiler, internal combustion cars, *etc.*), which mainly runs on fossil fuels (*conventional* provisioning). As fossil emissions are the most pressing environmental concern (Desing et al., 2020a; Desing and Widmer, 2021), we use a fossil-free version of ecoinvent 3.8 (Gómez-Camacho et al., in preperation), where all fossil energy and transport processes are replaced by renewable counterparts (e. g. , photovoltaics, heat pumps, electric vehicles, *etc.*; *fossil-free* provisioning).

Ecoinvent allocates historical expansions of cropland to agricultural processes (Reinhard J., 2017). To better reflect the steady state, we additionally test the effect of halted agricultural land transformation (noLT), i. e. allocated land use changes to agricultural processes are set to zero. Note that land use occupation remains unchanged.

Buildings are modelled in two different scenarios (*concrete/bricks* as modelled in ecoinvent, and *wooden* (Kakkos et al., 2020)), to assess the effect of different building materials, which are the largest material flows by mass today (Krausmann et al., 2018).

Combining three demand scenarios (LD, base, HD), two supply scenarios (*conventional*, *fossil-free*), two building type scenarios (*concrete/brick, wooden*, only in combination with fossil-free low demand), two scenarios with no further (crop)land conversion (*with land transformation, no land transformation*, only in combination with fossil-free low demand), and two population scenarios (*today, peak*), results in 18 investigated scenarios (see fig. S3 for overview).

2.3. Biophysical limits

Calculating SJOS requires the definition of ecological limits, impact categories, confidence levels and life cycle impact assessment (LCIA) methods. Preserving a Holocene-like state is described by ten translated PBs (Steffen et al., 2015b; Desing et al., 2020a) and one additional PB for energy appropriation from the Earth system (Desing et al., 2019). Threshold ranges and distribution types are taken from Ref. Desing et al. (2020a), as a long-term CO_2 boundary is consistent with the steady-state approach of the investigation. This results in eleven impact categories: Direct CO_2 emissions, global warming potential, biodiversity loss, ozone depletion potential, Phosphorus to ocean, Phosphorus to soil, reactive Nitrogen emissions, appropriable land area, appropriable cropland area, blue water consumption and appropriable technical potential of renewable energy. The PB for ocean acidification is disregarded, as it is covered by the threshold for direct CO_2 emissions. PB for green water flows (Wang-Erlandsson et al., 2022), atmospheric aerosol loading (Richardson et al., 2023) and novel entities (Persson et al., 2022) exist, but are excluded from this study due to lack of data and LCIA methods. PB-LCIA are taken from Desing et al. (2020a) (see also Section S5). Threshold ranges for PBs and calculation procedures for indicators are detailed in the SM (S8).

2.4. Measuring the safe and just space

Having defined the social foundation and the ecological ceiling, we derive SJOS by benchmarking the impacts of sufficiency scaled with world population against PBs. A Monte-Carlo simulation (N=1 000) is conducted to determine the probability distribution of the sufficiency basket's impacts. To yield the threshold contribution of the PBs, a second Monte-Carlo simulation is run based on the PB range and distribution type (Desing et al., 2020a). The probability of violation P_v is calculated for each boundary category and the highest value indicates the limiting boundary (see S8 for calculation code). If all P_v are smaller than a defined acceptable probability of violation $P_{v,acceptable}$ (the value of which needs to be decided by society), the "Doughnut" exists. SJOS can be measured as the difference between PBs and the sufficiency basket's impacts leading to $P_v = P_{v,acceptable}$. Violation of one boundary category cannot be compensated by operating space in other categories.

2.5. Sufficiency-based allocation

Absolute sustainability assessments at sub-global scales (e. g. countries, industrial sectors, products) require the allocation of global boundaries to the activities under investigation (Ryberg et al., 2020). The sufficiency basket developed here allows the derivation of a sufficiency-based allocation key, which we exemplify here for allocation to resource segments. The key is derived by allocating impact shares of identified material producing processes to resource segments. The allocation of shares to nine resource segments (chemicals, metals, energy(carriers), minerals, textiles, plant-based agriculture, animal-based agriculture and processed food, wood, and water) is based on the built-in International Standard Industrial Classification of All Economic Activities (ISIC) system (UN, 2008) in ecoinvent. For details on identified processes, contribution analysis, and segment aggregation scheme, see Section S7.

3. Results

In 2011, six out of eleven translated PBs had been violated (Fig. 2) (Desing et al., 2020a). The energy, metal, and chemical sectors contributed most of the climate impacts and were responsible for more than 40% of biodiversity impacts (Fig. 2a, Grandfathering). Reducing consumption to sufficiency levels for all without transforming provisioning systems cuts impacts on all PBs roughly in half (reduction factor of 1.8 to 4.2 for 8 billion and of 1.4 to 3.2 for 10.4 billion people, respectively). Reductions in P to soil and oceans are much larger, because phosphate emissions to soil are not accounted in ecoinvent in contrast to exiobase, which is the data source for global impacts in 2011 (Wood et al., 2015; Desing et al., 2020a). Sufficiency already brings two more boundaries – P to soil and land use – into the safe operating space (see Fig. 2b, base 10.4 bn.). Sufficiency alone is, however, insufficient to navigate into the "Doughnut", as the CO_2, GWP, biodiversity and N boundaries are still transgressed. In a scenario of sufficiency, the agricultural sector grows in relative importance in climate and biodiversity categories (see Fig. 2a, Base). The shift in importance towards the agricultural sector can be explained due to the higher reduction in material footprint (from 11.9 $^{t}/_{a}$ per capita in 2011 to 4.7 $^{t}/_{a}$ per capita in the base scenario) compared to food supply (from average per capita supply of 2870 $^{kcal}/_{d}$ in 2011 United Nations Environment Programme, World Environment Situation Room 2023 down to 2250 $^{kcal}/_{d}$ in the sufficiency case).

As multiple PBs are still transgressed in the sufficiency case, it is inevitable to transform the provisioning systems in addition to reduced consumption. Providing decent living with a fossil-free (FF) energy system, i. e. replacing all fossil energy inputs with renewable energy (Gómez-Camacho et al., in preperation), significantly reduces climate impacts further. It brings GWP impacts below the boundary, CO_2 impacts into the boundary range ($P_{v,CO_2} = [0.51, 0.62]$[2]) and reduces the probability of transgression for biodiversity (down to $P_{v,biodiv} = [0.15, 0.23]$) and N emissions (down to $P_{v,N} = [0.26, 1]$). Even though the fossil-free provisioning systems increase land use, cropland use, P to soil, blue water consumption, and energy demand – due to, for example, increased forestry, solar energy conversion and wood ash disposal via land-farming – impacts remain in the safe zone. Reducing consumption to sufficiency and fully defossilizing the economy is still not enough to navigate into a "Doughnut".

To further reduce impacts, we test low demand scenarios: "FF LD" describes a scenario where sufficiency demand is reduced to the lower end of the estimates for DLS and a vegan diet is introduced alongside a fossil-free provisioning system (FF); the scenario "FF LD WB noLT" additionally changes construction types to wooden buildings (WB) and halts cropland expansion (noLT). Both reduce N emissions and biodiversity loss below the boundary. CO_2 remains the last boundary which is transgressed now with a probability of violation of $P_v = [0.19, 0.27]$. In the wooden building scenarios, CO_2 emissions are decreased due to lower clinker production and higher urea production needed for fibre-boards (urea takes up CO_2 during production). This lowers the CO_2 impact of building provision by 73% compared to concrete/brick buildings (4% of total impact of FF LD WB versus FF LD). Halted cropland expansion further decreases total CO_2 by 27% compared to FF LD WB. The best scenario – i. e. low sufficiency demand provided with fossil-free energy, no cropland expansion and wooden buildings – achieves a decent life within planetary boundaries with 73% probability (population of 10.4 bn). With the current world population of 8 billion, probability for achieving a "Doughnut" would increase to 81%. In the FF LD WB noLT scenario, agriculture is the largest contributor in all impact categories except energy demand (see FF LD WB noLT in Fig. 2a). Note that the contribution of *animal-based agriculture and processed food* is not zero despite vegan diets, because this segment also includes fish and processed products like biopolymers, and plant oil (same division according to ISIC (UN, 2008)).

4. Discussion

This study for the first time measures the technical feasibility of achieving SJOS under consideration of uncertainty by jointly applying DLS, LCA and ESB.

Sufficiency alone is insufficient to create a SJOS for humanity under current or expected population estimates. To return to safe spaces for climate, biodiversity and the nitrogen cycle, large scale transformations of our provisioning systems are necessary. Complete defossilization of the electricity, heat and transport sectors, as well as switching fossil-based industrial feed to bio- and synthetic mass reduces climate and biodiversity impacts significantly. To fulfil basic needs within planetary boundaries with high confidence, demand would need to reduce to the lower estimates for sufficiency (low demand, including an essentially vegan diet), and cropland expansion stopped in addition to a fossil-free provisioning system. In our tested scenarios, the existence of a safe

---

[2] [*today, peak*] population scenario

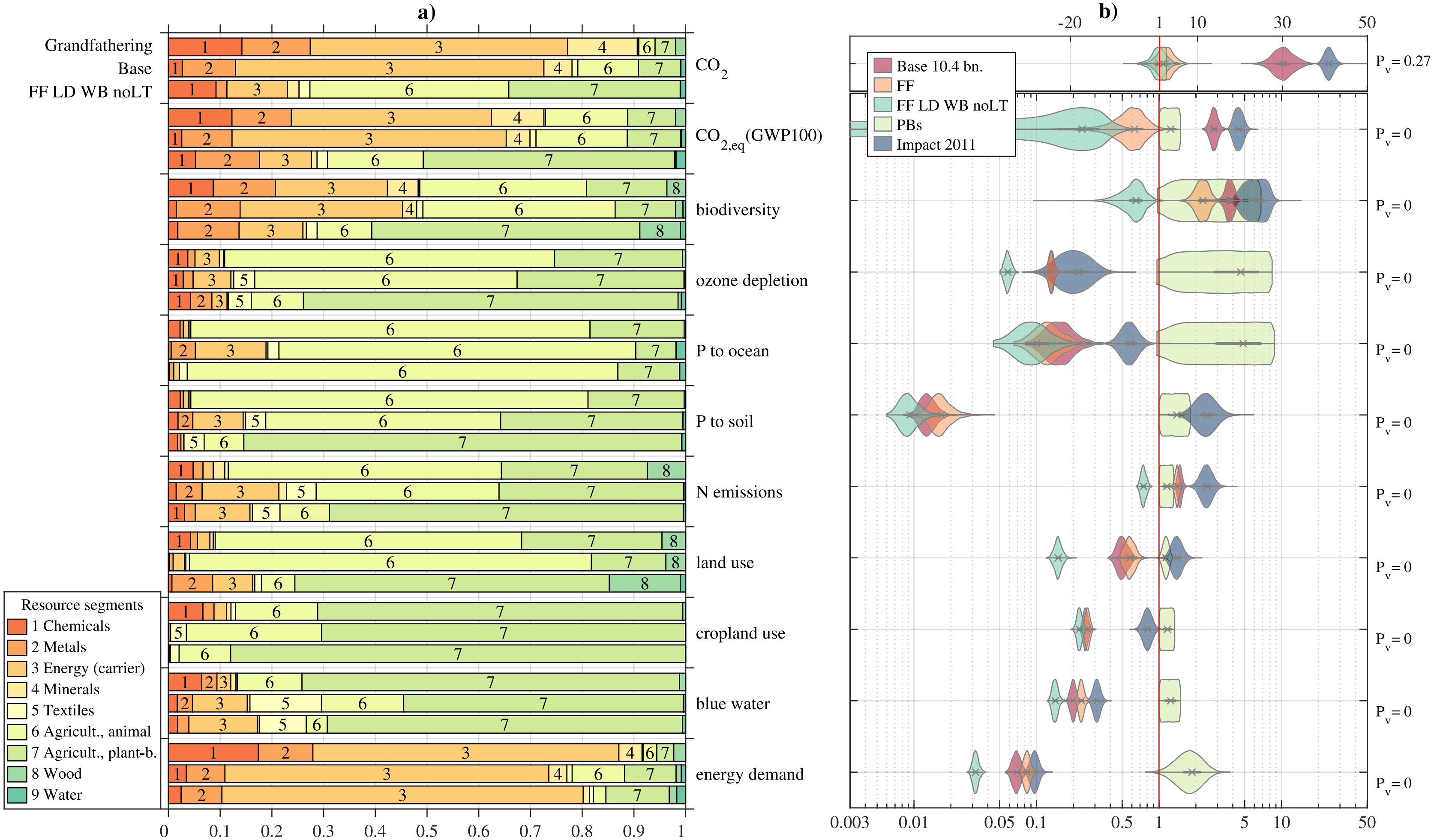

Fig. 2. (a) Share of safe operating space (SoSOS) for nine resource segments measured for three scenarios: Grandfathering for 2011 (from Desing et al. 2020a) Base (base demand scenario, conventional), FF LD WB noLT (low demand scenario, fossil-free, wooden buildings, no land transformation). (b) impact distributions of DLS baskets scaled with a population of 10.4 bn and normalized to the 0.5% quantile of PBs (red line): base demand, conventional; base demand, fossil-free (FF); low demand, fossil-free, wooden buildings, no land transformation (cropland) (FF LD WB noLT); impact in 2011 Desing et al. 2020a. P_v (y-axis, right hand side) describes probability of violating PB in FF LD WB noLT scenario (overlap of impact and PB distribution). Crosses show medians of distributions; bars range from first to third quartile of distributions. The impacts are plotted on a logarithmic scale. An exception are CO$_2$ emissions, which are plotted on a linear scale, because negative net emissions are possible in some scenarios. A limited set of scenarios are depicted in Fig. 2b for clarity; for other scenarios, see Section S6.

and just operating space can only be confirmed once the acceptable probability of violation is defined. As shown in Section 3, the best scenario violates the CO_2 boundary with $P_v = 0.27$ (10.4 bn people). If the acceptable probability is higher (e. g. in the current climate debate, acceptable probabilities to exceed climate targets are set to around 50%; IPCC, 2022; Desing and Widmer, 2021), a safe and just operating space exists for this case. However, if it is lower (e. g. in technical systems – such as aircrafts, power plants, or vaccines – acceptable probabilities of failure are typically $\ll 10^{-4}$ (Desing and Widmer, 2021)), not even basic needs could be fulfilled.

To create and increase SJOS, further improvement options exist, which have not yet been assessed in this study. For example, improving efficiency in provisioning systems by technological and operational advances can decrease impacts generated by the sufficiency basket. The results of this study provide the basis for investigating further improvements and direct development efforts. As more than half of residual CO_2 emissions in the best achieving scenario stem from soil and biomass, the largest potential for further reduction lies in improved agricultural practices (e. g. permaculture, agro-diversity, less food waste, *etc.*). C-absorbing agricultural practices can play an important role in increasing SJOS. More generally, sustainable land use practices need to be investigated, since biodiversity impacts and Nitrogen emissions also need to be reduced. Care needs to be taken regarding burden-shifting induced by changes in agricultural practices when generating trade-offs with biochemical flows, biodiversity, and land use (however, operating space for (crop)land use would exist).

In our background model, we do not assume technological learning (in contrast to Sacchi et al. 2022), following a conservative perspective on future technical capabilities. Thus, we might overestimate the ecological impacts from future provisioning systems. However, to our knowledge other studies do not consider technological learning for agricultural systems either, which according to our results is the most crucial provisioning system for entering SJOS. Thus, it is not likely that learning in regard to energy conversion, industrial processes, *etc.* would affect our results qualitatively.

Another area for further improvements are circular strategies (Desing et al., 2020b; Desing and Blum, 2023). The predominantly linear nature of the current provisioning system has not been changed in this study. Metals, minerals, textiles and chemicals account for 16% of residual CO_2 impacts, which can be reduced by increasing circularity. However, these gains may be offset by depleting stocks of natural resources (e. g. declining ore grade), which increase the efforts for extraction and processing in the future. Ultimately, the complex interactions are dynamic in their very nature, thus analysing them requires modelling the transition into SJOS.

Theoretical evidence that a “Doughnut” state exists is no evidence that it is possible to *transition towards* a “Doughnut” state. The possibility of transitioning is governed by a multitude of factors, including but not limited to (geo)political collaboration and will, social acceptance, energy and material feedback constraints of transitions, tipping elements in the Earth system, the challenge to return to safe CO_2 concentrations (Desing et al., 2022), *etc.*—each of these factors potentially pose a constraint for achieving the “Doughnut”. Investigating transitions into the “Doughnut” using the DLS approach was outside the scope of this study and is a potential area for future research.

We modelled material and energy requirements only for need satisfiers correlated to direct physical inputs. This means that no universal physical input is assumed for needs such as childhood security and upbringing, and physical security. We deem this approach legitimate, because (i) emotional needs (e. g. those of children) require social capacities, which are intangible and require no direct material input, (ii) potential satisfiers for physical security can also potentially harm the fulfilment of human needs (e. g. police brutality and war for police and military respectively), which contradicts conditions in the DLS concept (Rao and Min, 2018), and (iii) eligible satisfiers for physical security are not universal (e. g. infrastructure in case of natural disasters, like tsunami protection, earthquake-proof buildings, *etc.*). Identifying universal satisfiers for such needs and illuminating their potential resource requirements is a future task for engineers, anthropologists, social scientists and psychologists.

The requirements for DLS, environmental impacts, and ESB in this study are not regionalized, but defined as globally representative products providing universal satisfiers, globally average impacts, and global boundaries. We argue that a global approach is appropriate, because ESBs are operationalized in previous studies on global scale, many supply chains are global, DLS are defined as universal, and we aimed at selecting globally representative products for the sufficiency basket. Recently, ESBs have been defined on local and regional scale (Rockström et al., 2023; Richardson et al., 2023); however, suitable LCIA methods are lacking. To better reflect regional differences in impacts and carrying capacities, it is first necessary to develop suitable LCIA methods and operationalize regionalized ESBs for LCA. Also, ESBs could change in the future. In our scenarios, we assume a post-transformation society, which has returned to safe climate conditions. Hysteresis, however, could make future Earth systems less resilient, and thus future ESB thresholds might be different from today. Furthermore, data is lacking to regionalize satisfiers for DLS (e.g., mobility needs, living area, clothing, *etc.*) and regional provisioning systems (in ecoinvent, most products are modelled only for some regions, but not all).

Our model likely underestimates Phosphorus impacts, since phosphate flows to soil are not modelled in the ecoinvent 3.8 database. Fertilizer use is a main driver for both P and N flows into the environment. If we assume P emissions to be reduced by the same factor as N emissions, this would result in P to soil emissions within the safe boundary, even though they would be roughly 80 times higher than calculated with ecoinvent. Also, some technology metals like iridium, neodymium, and dysprosium used in electrolysers and wind turbines are not modelled in ecoinvent and their impacts are therefore not accounted for. Furthermore, CO_2 emissions of plastics production (polystyrene, ethylene, and xylene) and end-of-life of plastics are overestimated, since processes are modelled in a blackbox approach in ecoinvent. This is why feed substitution with bio-based or synthetic materials (which might reduce fossil CO_2) requires more detailed modelling of the background system.

A sufficiency-based allocation key between eleven translated PBs and nine resource segments was derived. This allocation key can be applied next to other principles for allocation to arrive at resource or impact budgets for sectors or stakeholders in absolute sustainability assessments (Ryberg et al. 2018, 2020, Hjalsted et al. 2021). Future research can explore this possibility further.

5. Conclusion and future research directions

Today, humanity is neither ensuring decent living for all, nor is it safeguarding the ecological livelihoods for future generations. Previous studies show evidence that progress can be made in aligning minimum living standards for all and long-term ecological stability. However, evidence is lacking that this progress is sufficient to achieve a safe and just operating space (SJOS). Here we show that it is possible to achieve decent living for all with at least 73% confidence with known technologies and under expected population scenarios. This would, however, require the following:

- Providing decent living standards for 10.4 billion people within eleven translated PBs with a high confidence, requires far-reaching dietary changes, minimal consumption and completely defossilized energy systems. This is possible with currently available technologies, however, we cannot find evidence for ecological space for providing luxury.
- The SJOS is limited by the CO_2 boundary, followed by boundaries for biodiversity loss and biogeochemical flows. Defossilizing the economy completely is therefore necessary, but not sufficient for entering the “Doughnut”.

Future research may focus on improving agricultural practices – such as organic farming, permaculture, improved land management –, as it holds the largest potential to further reduce impacts from DLS. This will be particularly relevant for climate, biodiversity and biogeochemical flows. Another potential for improvement is to increase the circularity of material systems (Desing et al., 2020b). Furthermore, provisioning systems, DLS needs, environmental impacts, and Earth system boundaries vary depending on local conditions. As this was excluded here, future research will need to address regional differences to increase significance of our findings for local governance. Overall, these improvements to our study can show if a safe and just operating space above satisfying DLS could possibly exist.

CRediT authorship contribution statement

Hauke Schlesier: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Malte Schäfer:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Harald Desing:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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.

Data availability

A link to a GitHub repository for code is provided.

Acknowledgements

No acknowledgements.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141447.

References

Alcamo, J., Thompson, J., Alexander, A., Antoniades, A., Delabre, I., Dolley, J., Marshall, F., Menton, M., Middleton, J., Scharlemann, J.P., 2020. Analysing interactions among the sustainable development goals: findings and emerging issues from local and global studies. Sustain. Sci. 15 (6), 1561–1572.

Allen, C., Metternicht, G., Wiedmann, T., Pedercini, M., 2021. Modelling national transformations to achieve the SDGs within planetary boundaries in small island developing states. Glob. Sustain. 4.

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science 377 (6611), eabn7950.

BAG, 2020. Kennzahlen der schweizer spitäler 2018 - statistiken zur krankenversicherung. URL https://www.bag.admin.ch/bag/de/home/zahlen-und-statistiken/zahlen-fakten-zu-spitaelern/kennzahlen-der-schweizer-spitaeler.html.

Brand-Correa, L.I., Steinberger, J.K., 2017. A framework for decoupling human need satisfaction from energy use. Ecol. Econ. 141, 43–52.

Breyer, C., Khalili, S., Bogdanov, D., Ram, M., Oyewo, A.S., Aghahosseini, A., Gulagi, A., Solomon, A.A., Keiner, D., Lopez, G., Ostergaard, P.A., Lund, H., Mathiesen, B.V., Jacobson, M.Z., Victoria, M., Teske, S., Pregger, T., Fthenakis, V., Raugei, M., Holttinen, H., Bardi, U., Hoekstra, A., Sovacool, B.K., 2022. On the history and future of 100% renewable energy systems research. IEEE Access 10, 78176–78218. http://dx.doi.org/10.1109/access.2022.3193402.

Brooks-Gunn, J., Duncan, G.J., 1997. The effects of poverty on children. Future Child. 55–71.

Chancel, L., Piketty, T., Saez, E., Zucman, G., et al., 2021. World Inequality Report 2022, World Inequality Lab.

Cole, M.J., Bailey, R.M., New, M.G., 2014. Tracking sustainable development with a national barometer for South Africa using a downscaled "safe and just space" framework. Proc. Natl. Acad. Sci. 111 (42), E4399–E4408.

Conijn, J., Bindraban, P., Schröder, J., Jongschaap, R., 2018. Can our global food system meet food demand within planetary boundaries? Agric. Ecosyst. Environ. 251, 244–256.

Cooper, G.S., Dearing, J.A., 2019. Modelling future safe and just operating spaces in regional social-ecological systems. Sci. Total Environ. 651, 2105–2117. http://dx.doi.org/10.1016/j.scitotenv.2018.10.118.

Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., Carstensen, J., Cole, M.J., Cornell, S.E., Dawson, T.P., Doncaster, C.P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A.W., Nykvist, B., Poppy, G.M., 2014. Safe and just operating spaces for regional social-ecological systems. Global Environ. Change 28, 227–238. http://dx.doi.org/10.1016/j.gloenvcha.2014.06.012.

Desing, H., Blum, N., 2023. On circularity, complexity and (elements of) hope. Circ. Econ. 1 (1), http://dx.doi.org/10.55845/WNHN7338.

Desing, H., Braun, G., Hischier, R., 2020a. Ecological resource availability: a method to estimate resource budgets for a sustainable economy. Glob. Sustain. 3, 1–11. http://dx.doi.org/10.1017/sus.2020.26.

Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K., Hischier, R., 2020b. A circular economy within the planetary boundaries: Towards a resource-based, systemic approach. Resour. Conserv. Recy. 155, http://dx.doi.org/10.1016/j.resconrec.2019.104673.

Desing, H., Gerber, A., Hischier, R., Wäger, P., Widmer, R., 2022. The 3-machines energy transition model: Exploring the energy frontiers for restoring a habitable climate. Earth's Future 10 (10), e2022EF002875.

Desing, H., Widmer, R., 2021. Reducing climate risks with fast and complete energy transitions: applying the precautionary principle to the Paris agreement. Environ. Res. Lett. 16 (12), http://dx.doi.org/10.1088/1748-9326/ac36f9.

Desing, H., Widmer, R., Beloin-Saint-Pierre, D., Hischier, R., Wäger, P., 2019. Powering a sustainable and circular economy—An engineering approach to estimating renewable energy potentials within earth system boundaries. Energies 12 (24), 1–18. http://dx.doi.org/10.3390/en12244723.

Dixson-Declève, S., Gaffney, O., Ghosh, Y., Rockström, J., Stoknes, P., Randers, J., 2022. Earth for all – a survival guide to humanity. URL https://www.clubofrome.org/publication/earth4all-book/.

Doyle, I., Gough, L., 1991. A Theory of Human Need. Guilford Press, New York.

Drees, L., Luetkemeier, R., Kerber, H., 2021. Necessary or oversimplification? On the strengths and limitations of current assessments to integrate social dimensions in planetary boundaries. Ecol. Indic. 129, 108009.

Ecoinvent, 2021. Ecoinvent v3.8. Report, Ecoinvent, URL https://www.ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-8/3.

Ehrenstein, M., Calvo-Serrano, R., Galán-Martín, Á., Pozo, C., Zurano-Cervelló, P., Guillén-Gosálbez, G., 2020. Operating within planetary boundaries without compromising well-being? a data envelopment analysis approach. J. Clean. Prod. 270, http://dx.doi.org/10.1016/j.jclepro.2020.121833.

Eisenmenger, N., Pichler, M., Krenmayr, N., Noll, D., Plank, B., Schalmann, E., Wandl, M.-T., Gingrich, S., 2020. The sustainable development goals prioritize economic growth over sustainable resource use: a critical reflection on the SDGs from a socio-ecological perspective. Sustain. Sci. 15 (4), 1101–1110.

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M., Milo, R., 2020. Global human-made mass exceeds all living biomass. Nature 588 (7838), 442–444.

Fanning, A.L., O'Neill, D.W., Büchs, M., 2020. Provisioning systems for a good life within planetary boundaries. Global Environ. Change 64, 102135.

Fanning, A.L., O'Neill, D.W., Hickel, J., Roux, N., 2022. The social shortfall and ecological overshoot of nations. Nat. Sustain. 5 (1), 26–36.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F., Alcamo, J., 2013. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environ. Change 23 (1), 144–156.

Food and Agricultural Organisation, 2021. The state of food security and nutrition in the world, 2021. transforming food systems for food security, improved nutrition and affordabel healthy diets for all. report, FAO.

Gerten, D., Heck, V., Jägermeyr, J., Bodirsky, B.L., Fetzer, I., Jalava, M., Kummu, M., Lucht, W., Rockström, J., Schaphoff, S., Schellnhuber, H.J., 2020. Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat. Sustain. http://dx.doi.org/10.1038/s41893-019-0465-1.

Gómez-Camacho, C.E., Schlesier, H., Hischier, R., Desing, H., Fossil-free ecoinvent (FFEI 3.8 V1.0): a benchmark for defossilised scenarios in future-oriented life cycle assessments (in preperation).

Gottfridsson, M., Zhang, Y., 2015. Environmental impacts of shoe consumption, combining product flow analysis with an LCA model for Sweden.

Gough, I., 2019. Universal basic services: A theoretical and moral framework. Polit. Q. 90 (3), 534–542.

Gough, I., 2020. Defining floors and ceilings: the contribution of human needs theory. Sustain.: Sci. Pract. Policy 16 (1), 208–219.

Gowdy, J., 1998. Limited Wants, Unlimited Means: A Reader on Hunter-Gatherer Economics and the Environment. Island Press.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat. Energy 3 (6), 515–527. http://dx.doi.org/10.1038/s41560-018-0172-6.

Heide, M., Hauschild, M.Z., Ryberg, M., 2023. Reflecting the importance of human needs fulfilment in absolute sustainability assessments: Development of a sharing principle. J. Ind. Ecol..

Heijungs, R., De Koning, A., Guinée, J.B., 2014. Maximizing affluence within the planetary boundaries. Int. J. Life Cycle Assess. 19 (6), 1331–1335.

Hickel, J., 2019. Is it possible to achieve a good life for all within planetary boundaries? Third World Q. 40 (1), 18–35.

Hjalsted, A.W., Laurent, A., Andersen, M.M., Olsen, K.H., Ryberg, M., Hauschild, M., 2021. Sharing the safe operating space: Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. J. Ind. Ecol. 25 (1), 6–19.

Hsieh, C.-C., Pugh, M.D., 1993. Poverty, income inequality, and violent crime: a meta-analysis of recent aggregate data studies. Crim. Justice Rev. 18 (2), 182–202.

IPCC, 2022. Climate change 2022 - impacts, adaption and vulerability. Report, IPCC.

Kakkos, E., Heisel, F., Hebel, D.E., Hischier, R., 2020. Towards urban mining—estimating the potential environmental benefits by applying an alternative construction practice. a case study from Switzerland. Sustainability 12 (12), 5041.

Keller, R.L., Muir, K., Roth, F., Jattke, M., Stucki, M., 2021. From bandages to buildings: Identifying the environmental hotspots of hospitals. J. Clean. Prod. 319, 128479.

Kikstra, J.S., Mastrucci, A., Min, J., Riahi, K., Rao, N.D., 2021. Decent living gaps and energy needs around the world. Environ. Res. Lett. 16 (9), http://dx.doi.org/10.1088/1748-9326/ac1c27.

Krausmann, F., Erb, K.H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. USA 110 (25), 10324–10329. http://dx.doi.org/10.1073/pnas.1211349110.

Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, D., 2018. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. Global Environ. Change 52, 131–140. http://dx.doi.org/10.1016/j.gloenvcha.2018.07.003.

Lenton, T.M., Rockstrom, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., Schellnhuber, H.J., 2019. Climate tipping points - too risky to bet against. Nature 575 (7784), 592–595. http://dx.doi.org/10.1038/d41586-019-03595-0.

Letourneau, N.L., Duffett-Leger, L., Levac, L., Watson, B., Young-Morris, C., 2013. Socioeconomic status and child development: A meta-analysis. J. Emotional Behav. Disorders 21 (3), 211–224.

Max-Neef, M., 1992. Development and human needs. In: Ekins, P., Max-Neef, M. (Eds.), Real-Life Economics: Understanding Wealth Creation. Routledge, London, pp. 197–213, URL www.max-neef.cl/download/Max-neef_Human_Scale_development.pdf.

Menton, M., Larrea, C., Latorre, S., Martinez-Alier, J., Peck, M., Temper, L., Walter, M., 2020. Environmental justice and the SDGs: from synergies to gaps and contradictions. Sustain. Sci. 15 (6), 1621–1636.

Millward-Hopkins, J., 2022. The energy requirements of providing universal decent living in a 'fairly' unequal world. http://dx.doi.org/10.21203/rs.3.rs-1145498/v1.

Millward-Hopkins, J., Steinberger, J.K., Rao, N.D., Oswald, Y., 2020. Providing decent living with minimum energy: A global scenario. Global Environ. Change 65, http://dx.doi.org/10.1016/j.gloenvcha.2020.102168.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Climate Change 2013: The Physical Science Basis. Cambridge Unversity Press, Cambridge.

Nussbaum, M.C., 2000. Women and Human Development: The Capabilities Approach. Vol. 3, Cambridge University Press.

O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1 (2), 88–95. http://dx.doi.org/10.1038/s41893-018-0021-4.

Ortiz, I., Burke, S., Berrada, M., Saenz Cortés, H., 2022. An analysis of world protests 2006–2020. In: World Protests. Springer, pp. 13–81.

Oswald, Y., Owen, A., Steinberger, J.K., 2020. Large inequality in international and intranational energy footprints between income groups and across consumption categories. Nat. Energy 5 (3), 231–239.

Otto, I.M., Kim, K.M., Dubrovsky, N., Lucht, W., 2019. Shift the focus from the super-poor to the super-rich. Nature Clim. Change 9 (2), 82–84. http://dx.doi.org/10.1038/s41558-019-0402-3.

Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L., Fantke, P., Hassellov, M., MacLeod, M., Ryberg, M.W., Sogaard Jorgensen, P., Villarrubia-Gomez, P., Wang, Z., Hauschild, M.Z., 2022. Outside the safe operating space of the planetary boundary for novel entities. Environ. Sci. Technol. 56 (3), 1510–1521. http://dx.doi.org/10.1021/acs.est.1c04158.

Randers, J., et al., 2019. Achieving the 17 sustainable development goals within 9 planetary boundaries. Glob. Sustain. 2, http://dx.doi.org/10.1017/sus.2019.22.

Rao, N.D., Baer, P., 2012. "Decent living" emissions: A conceptual framework. Sustainability 4 (4), 656–681. http://dx.doi.org/10.3390/su4040656.

Rao, N.D., Min, J., 2018. Decent living standards: Material prerequisites for human wellbeing. Soc. Ind. Res. 138 (1), 225–244. http://dx.doi.org/10.1007/s11205-017-1650-0.

Rawls, J., 1971. A theory of justice.

Raworth, K., 2012. A safe and just space for humanity: Can we live within the doughnut. Oxfam Policy Pract.: Clim. Change Resilience 8 (1), 1–26, URL https://www.ingentaconnect.com/content/oxpp/oppccr/2012/00000008/00000001/art00001.

Raworth, K., 2017. A Doughnut for the Anthropocene: humanity's compass in the 21st century. Lancet Planet. Health 1 (2).

Reinert, K.A., 2011. No small hope: The basic goods imperative. Rev. Soc. Econ. 69 (1), 55–76.

Reinhard J., G.S., 2017. Consideration of land use change in ecoinvent version 3.3: Method, implementation and illustration. White paper. Report, ecoinvent Association, Zürich, Switzerland.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., et al., 2023. Earth beyond six of nine planetary boundaries. Sci. Adv. 9 (37), eadh2458.

Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S.E., et al., 2023. Safe and just earth system boundaries. Nature 1–10.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009a. A safe operating space for humanity. Nature 461 (7263), 472–475. http://dx.doi.org/10.1038/461472a.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schnellhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V., Hansen, J., Brian, W., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009b. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. 14 (2), 1–33.

Roy, A., Pramanick, K., 2020. Safe and just operating space for India. In: Handbook of Modern Environmental Materials Management. Springer, Nature Switzerland AG, http://dx.doi.org/10.1007/978-3-319-58538-3_210-1.

Ryberg, M.W., Andersen, M.M., Owsianiak, M.a., Hauschild, M.Z., 2020. Downscaling the planetary boundaries in absolute environmental sustainability assessments – a review. J. Clean. Prod. 276, http://dx.doi.org/10.1016/j.jclepro.2020.123287.

Ryberg, M.W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., Hauschild, M.Z., 2018. How to bring absolute sustainability into decision-making: An industry case study using a planetary boundary-based methodology. Sci. Total Environ. 634, 1406–1416. http://dx.doi.org/10.1016/j.scitotenv.2018.04.075.

Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew. Sustain. Energy Rev. 160, 112311. http://dx.doi.org/10.1016/j.rser.2022.112311, http://dx.doi.org/10.1016/j.rser.2022.112311.

Sayers, M., Trebeck, K., 2015. The UK Doughnut: A Framework for Environmental Sustainability and Social Justice. Oxfam GB.

Sen, A., 1993. Capability and well-being. Qual. Life 30, 270–293.

Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., Hofmann, M., Bauer, N., Bertram, C., Bodirsky, B.L., Leimbach, M., Leininger, J., Levesque, A., Luderer, G., Pehl, M., Wingens, C., Baumstark, L., Beier, F., Dietrich, J.P., Humpenöder, F., von Jeetze, P., Klein, D., Koch, J., Pietzcker, R., Strefler, J., Lotze-Campen, H., Popp, A., 2021. A sustainable development pathway for climate action within the UN 2030 agenda. Nature Clim. Change 11 (8), 656–664. http://dx.doi.org/10.1038/s41558-021-01098-3.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C., 2015a. The trajectory of the anthropocene: The great acceleration. Anthropocene Rev. 2 (1), 81–98. http://dx.doi.org/10.1177/2053019614564785.

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015b. Sustainability. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855. http://dx.doi.org/10.1126/science.1259855.

Steffen, W., Rockstrom, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the earth system in the anthropocene. Proc. Natl. Acad. Sci. USA 115 (33), 8252–8259. http://dx.doi.org/10.1073/pnas.1810141115.

Stein, R., 1991. Accumulation of Organic Carbon in Marine Sediments. In: Lecture Notes in Earth Sciences, Springer.

Stockholm Resilience Centre, 2018. Transformation is feasible - how to achieve the sustainable development goals within planetary boundaries. URL https://www.stockholmresilience.org/publications/publications/2018-10-17-transformation-is-feasible---how-to-achieve-the-sustainable--development-goals-within-planetary-boundaries.html.

Suzman, J., 2020. Work: A History of How We Spend Our Time. Bloomsbury Publishing.

UN, 2008. International standard industrial classification of all economic activities - revision 4. Report ST/ESA/STAT/SER.M/4/Rev.4, UN Department of Economic and Social Affairs, URL https://unstats.un.org/unsd/publication/seriesM/seriesm_4rev4e.pdf.

UN Department of Economic and Social Affairs, 2022. World population prospects 2019: Highlights. Data, United Nations, URL https://population.un.org/wpp/.

United Nations, 1948. Universal Declaration of Human Rights.

United Nations, 1966. International Covenant on Economic, Social and Cultural Rights. URL https://www.refworld.org/docid/3ae6b36c0.html.

United Nations, 2015. Sustainable development goals. Dev. Cooperation 42, 4.

United Nations, Department of Economic and Social Affairs, Population Division, 2019. Patterns and trends in household size and composition: Evidence from a United Nations dataset. Report ST/ESA/SER.A/433), URL https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/files/documents/2020/Jan/un_2019_household_size_and_composition.pdf.

United Nations Environment Programme, World Environment Situation Room, 2023. GOAL 12: Responsible consumption and production. Indicator 12.2.1. Website, United Nations Environment Programme, URL https://wesr.unep.org/article/indicator-1221.

Vélez-Henao, J.A., Pauliuk, S., 2023. Material requirements of decent living standards. Environ. Sci. Technol..

Wang-Erlandsson, L., Tobian, A., van der Ent, R.J., Fetzer, I., te Wierik, S., Porkka, M., Staal, A., Jaramillo, F., Dahlmann, H., Singh, C., et al., 2022. A planetary boundary for green water. Nat. Rev. Earth Environ. 1–13.

Wiedmann, T., Lenzen, M., Keysser, L.T., Steinberger, J.K., 2020. Scientists' warning on affluence. Nature Commun. 11 (1), 3107. http://dx.doi.org/10.1038/s41467-020-16941-y.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492. http://dx.doi.org/10.1016/s0140-6736(18)31788-4.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., De Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Schmidt, J., Merciai, S., Tukker, A., 2015. Global sustainability accounting—Developing EXIOBASE for multi-regional footprint analysis. Sustainability 7, 138–163. http://dx.doi.org/10.3390/su7010138.

Wunderling, N., Winkelmann, R., Rockström, J., Loriani, S., Armstrong McKay, D.I., Ritchie, P.D., Sakschewski, B., Donges, J.F., 2022. Global warming overshoots increase risks of climate tipping cascades in a network model. Nature Clim. Change 1–8.