Supplementary materials to "Measuring the Doughnut: A good life for all is possible within planetary boundaries"

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S1 Overview

Here, we expand upon the methods and results in our paper. We give data sources, assumptions and calculation. In section S2, we give detailed account on how we arrived at the sufficient material and energy requirements and how we modelled them. In section S3, we show an overview over the scenarios selected. In section S4, we list input parameters used to generate the fossil-free ecoinvent database. In section S5, more details on the defined biophysical limits and LCIA methods are described. Extended results are shown in section S6. Additional data needed for the derivation of the allocation key is shown in section S7. Additional data and code for calculations is linked in section S8.

S2 Decent living requirements and foreground model

The idea that every human is entitled to a certain level of well-being is widespread and manifested in international agreements: The right to an adequate living standard is stated in article 25 of the Universal Declaration of Human Rights [1] as well as in article 11 of the International Covenant on Economic, Social and Cultural Rights [2] and also reflected in the SDGs [3]. The idea of thresholds in human well-being was taken up by researchers and is mirrored in several concepts [4, 5] (e. g. *primary goods*, [6]; *basic goods*, [7]; *universal basic services*, [8]; *decent living standards*, [4, 9]).

In the context of this study, it is important to be familiar with *universal satisfiers* alias *intermediate needs* [10] to define the social objective. Max-Neef [11] lists nine non-hierarchical, interacting, satiable, universal and classifiable needs: subsistence, protection, affection, understanding, participation, idleness, creation, identity and freedom. Doyle and Gough [10] argue that identifying needs on such a high level of abstraction offers no solution to practical issues. They propose eleven universal satisfiers that represent cross-cultural means of satisfying human needs: Nutritional food and water, shelter, non-hazardous working environment, non-hazardous physical environment, health care, education, safe birth control and child-bearing, security in childhood, meaningful relationships, physical and economic security [10].

However, Doyle and Gough [10] provide no material or energy requirements for these universal satisfiers. This gap was filled by Rao, Baer and Min [4, 9], who define requirements (without quantifying all of them), including the dimensions of nutrition, shelter, thermal comfort and cold storage, a clean stove, health, sanitation, education, communication and mobility. More recent research underpinned the DLS approach by identifying a comprehensive list of quantified material and energy requirements [12–15].

Study	Calories needed [$kcal/cap/d$]
Kikstra et al. (2021) [15]	$2000 - 2150$
Millward-Hopkins et al. (2020) [13]	$2000 - 2150$
Willett et al. (2019) [16]	2500
This study	[2000, 2250, 2500]

Table S1: Calories needed in selected literature.

Nutrition

Rao and Min (2018) list calories, proteins and micro-nutrients as well as refrigerator as household requirements for nutrition [4]. Different studies assume slightly different calories needed ranging from 2000 to 2500 $kcal/cap/d$ (see table S1). On this basis, we assume 2000 $kcal/cap/d$ as the LD requirement, 2500 $kcal/cap/d$ as the HD requirement and the mean of 2250 $kcal/cap/d$ as the base scenario.

Obviously, caloric needs can be satisfied by different food. EAT-Lancet Commission focus on diets that are both healthy (considering protein and micro-nutrient needs) and sustainable [17]. In S2, disaggregated food requirement are shown based on the Planetary Health diet of 2500 kcal [17]. We disaggregate grains according to production shares between 2018 and 2022 [18], fruits, legumes and vegetables according to [19] for the year 2013 (fruits) and 2018 to 2020 (legumes, vegetables). Shares of dairy products are based on [20]. We balance shares to 100 % because some food item are not represented in ecoinvent and are therefore dismissed. For the demand scenarios, we scaled the requirements by calories needed. We dismiss coffee and cacao as we consider them luxury food.

Water and hygiene

Rao & Min list access to clean water and to a toilet as requirements for decent living. Millward-Hopkins *et al.* and Kikstra *et al.* state different water needs, 50 and 65 $L/cap/d$ respectively. They both refer to [21], Kikstra et al., however, assumes more water for showering. We base HD and LD requirements on the upper and lower values and define the mean of $58L/cap/d$ as the base scenario requirement. For access to sanitary facilities (toilet) we assume one $7.5kg$ ceramic toilet per household with a life time of 25 years.

Shelter

Buildings offer protection against harmful impacts of wind, moisture, heat, cold and noise and allow for privacy. A shelter requires solid walls and roof and enables access to electricity, water and sanitary [4]. Here, we look at living space and the energy requirements of running that shelter. Rao & Min argue for a minimal living area of 30 m^2 plus 10 m^2 for each person above three household members. A minimal living area reflects the requirement for collectively used rooms like kitchen and bath that do not scale linearly. The lower threshold for existing conditions in Taiwan, Korea, India and China is 10 m^2/cap according to [4]. Millward-Hopkins *et al.* assume 20 m^2 plus 10 m^2/cap for a four member household, resulting in 15 m^2/cap. Kikstra *et al.* assume $10.1 - 14.7\,m^2/cap$. Grubler *et al.* – in a global low energy scenario – assume 30 m^2/cap. To reflect the range stated in the literature, we specify 10 m^2/cap as the LD requirement, 15 m^2/cap as the base requirement and 30 m^2/cap as the HD requirement. Living area is multiplied with a room heights of 2.5 m to derive the living space compatible with ecoinvent building units; the room height of schools and hospitals is assumed to be 3 m. The lifetime of residential buildings and public buildings is assumed to be 80 years.

Energy

Table S3 specifies the direct energy requirements for different dimensions. Note that the energy needed in other dimensions such as water pumping waste disposal, mobility and streets, health care are all considered elsewhere. Here, we only consider only use phase energy for household requirements and schools. To derive energy needed for cooking, we apply the energy intensity of [13] for the three calorie thresholds defined in table S1. For cold storage, we apply the lower intensity for the LD threshold, the upper intensity for the HD threshold and the mean for the base scenario. For heating and cooling, we take the population-weighted average (for countries) of the energy intensity from [13] and calculate the required energy with respected LD, base and HD value for living area (see Shelter). We apply the lower intensity from [13] for warm water energy requirements in the LD case and the highest intensity of 3.2 GJ/cap a from [15] in the HD case. We take the mean for our base scenario. According to [13] schools need 100 to 130 MJ/m^2 of energy per year. We multiply the lower, mean and upper value with 1, 2 and 3 m^2/cap school area required (see Education) to yield the school energy requirement. The LD energy requirements for communication is based on the specification of one phone per household. In

Food (group / item)	Share [%]	Balanced [%]	Share [kg]
Grains			84.7
Wheat	29.16	29.16	24.69
Rice	19.10	19.10	16.17
Corn	43.45	43.45	36.79
Oats	0.09	0.09	0.08
Sorghum	2.35	2.35	1.99
Rye	0.02	0.02	0.01
Barley	5.83	5.83	4.94
Fruits			73.0
Banana	15.77	23.91	22.10
Orange / Tangerine	15.91	24.12	17.61
Apple	12.97	19.66	14.35
Grapes	5.89	8.93	6.52
Plantains	4.20	6.37	
Pineapple	3.81	5.78	4.22
Lime	2.61	3.96	2.89
Lemon	2.08	3.15	
Grapefruit	1.52	2.30	
Dates	1.19	1.80	
Other fruits	34.04		
Legumes			18.3
Bambara beans	0.05	0.19	0.03
Beans, dry	5.47	22.54	4.11
Beans, green	4.69	19.33	3.53
Broad beans, horse beans, dry	1.12	4.61	0.84
Carobs	0.01		
Chick peas	3.12	12.84	2.34
Cow beas, dry	1.74	7.15	1.31
Lentils	1.27		
Peas, dry	2.84	11.69	2.13
Pulses	0.90		
String beans	0.29	1.20	0.22
Vegetables, leguminous	0.32		
Peas, green	3.97	16.37	2.99
Pigeon peas	0.99	4.08	0.74
Lupins	0.24		
Soy bean	69.77		9.1
Vegetables			109.5
Artichokes	0.15		
Asparagus	0.79	1.23	1.34
Cabbages and other brassicas	6.56	10.20	11.17
Carrots and turnips	3.80	5.91	6.47
Cauliflower and broccoli	2.39	3.71	4.06
Chillies and peppers, green	3.36	5.22	5.72
Cucumbers and gherkins	8.22	12.78	14.00
Eggplant	5.17	8.04	8.81
Leeks, other alliaceous vegetables	0.20		
Lettuce and chicory	2.55	3.97	4.35
Mushrooms and truffles	3.90		
Okra	0.94		
Olives	2.17	3.38	3.70
Onions, dry	9.37	14.57	15.95
Onions, shallots, green	0.42		
Pumpkins, squash, gourds	2.56		
Spinach	2.81	4.36	4.78
Tomatoes	17.13	26.63	29.16
Other Vegetables, fresh	27.52		
Dairy products			91.3
Fresh dairy products (milk, yogurt)	92.31	92.31	84.23
Butter, ghee	2.51	2.51	2.29
Cheese	5.18	5.18	4.73
Tubers			18.3
Animal protein			30.6
Beef, lamb, pork			5.1
Chicken & poultry			10.6
Eggs			4.7
Fish			10.2
Nuts			18.3
Fats			14.6
Sugars			11.3

Table S2: Disaggregated food items required for 2500 kcal daily for one year and person.

Dimension	Direct energy in use phase		Direct energy in use phase $[MJ/cap/a]$		
	Kikstra et al.	Millward-Hopkins et al.	LD	base	HD
Cooking	$2.2\,GJ/hh/a$	$0.8\,kJ/kcal$	584	657	730
Cold storage	$0.58\,GJ/hh/a$	$0.44\,GJ/hh/a$	88	141	193
Heating / cooling	$[0, 88.3]\,MJ/m^2/a$ (cooling), $[0, 1110.8]\,MJ/m^2/a$ (heating)	$43.8\,MJ/m^2/a$ (global aver.)	438	657	876
Warm water	$[1.1, 3.2]\,GJ/cap/a$	$1017\,MJ/cap/a$ (global aver.)	1017	2109	3200
School	$2.69\,GJ/\$$	$[100, 130]\,MJ/m^2/a$	209	241	272
Communication	$28\,MJ/hh/a$	$28\,MJ/hh/a$	6	16	26
Information	$720\,GJ/TV/a$	$220\,MJ/laptop/a$	44	55	73
Light	-	-	23	47	70
Electricity total	-	-	954	1156	1365
Heat total	-	-	1455	2766	4076

Table S3: Final energy requirements.

the HD scenario we assume a phone for every household member older than 10 years (ca. 93 % in 2050 according to [23]). We assume the mean value for the base scenario. For information purposes, we grant one laptop per household (we prefer a laptop because it includes the functionality of a TV) and apply the energy intensity of $220\,MJ/a$ from [13] and the scenario depended household size. For illumination, we assume that $2500\,lm$ are provided over a period of 4, 6, and $8\,h/d$ in the LD, base, and HD scenario respectively. Further, we assume, that LEDs are used with 30 % efficiency ($105\,lm/W$). We model the lamp requirement by granting 10 new LEDs per year and person with $35\,g$ each.

Harmless working and living conditions

Executing physical human functions requires light, weather protection and good air quality. Buildings need to be equipped in a way that allows working and living in them [4, 13]. Besides illumination, a heating and/or cooling system is required for climate regulation as well as a stove with minimal risk for fire and particulate matter pollution. Additionally, clothing and shoes are universal means for protection against environmental influences [4].

Millward-Hopkins *et al.* assume that illumination of 33 % of the living space for $6\,h$ is acceptable. Referring to [24], they set $125\,lm/m^2$ as the lowest acceptable threshold for illuminance. This results in $15\,000\,lmh/hh/d$ or normalized to one person and year in $1\,368\,750\,lmh/cap/a$ (in the base scenario). We assume $4\,h$ of illumination in the LD and $8\,h$ of illumination in the HD scenario.

For comfort purposes, every household is equipped with one heating or cooling system. Varying heating systems can provide heat, i.a. oil or gas boilers, wood or coal heating, solar thermal and geothermal systems or heat pumps. Oil, gas, or coal heating is based on fossil fuels and is dismissed for widespread use, since it would render climate goals unreachable. Firewood as well as solar thermal and geothermal potentials are geographically constrained. Heat pumps, however, possess the advantage of high efficiency (>250 %) and can also be utilized as cooling systems. Therefore, we assume every household to be equipped with a heat pump ($COP = 2.5$). Rao & Min highlight the importance of clean stoves as domestic particulate matter pollution is the third largest factor for premature deaths [25]. As a consequence, households should have access to modern stoves (gas or electric) to prepare food without danger. Next to Millward-Hopkins *et al.* and Kikstra *et al.*, we follow the idea of one modern stove per household. Clothing is a cross-cultural used element for protection against temperature and humidity. Kikstra *et al.* number the decent amount of new clothes to be $1.3\,kg$ per year in the global South and $2.4\,kg$ per year in the global North. Millward-Hopkins *et al.* take a more conservative stance and assume $4\,kg$ of new clothes per capita every year. We take $1.3\,kg/a$ of clothes as the LD value, $4\,kg/a$ as the HD value and the mean of $2.6\,kg/a$ as the base value. For laundry, we draw on Millward-Hopkins *et al.* and assume $78\,kg$ of washed clothes per year and person and ±25% for LD and HD cases. Kikstra *et al.* quantify the requirement for new shoes to be $0.9\,kg/cap/a$; we resort to this quantification and apply ±50 % to the two demand scenarios.

Health care

It is difficult to define a decent standard of health care, since requirements of medical care depend on i.a. age structures, life styles and the structures of the health care system. Rao & Min focus on minimal health care expenditure that is statistically correlated with life expectancies of 70 to 75 years, resulting in $450 - 700\,\$/cap \cdot a$. Kikstra *et al.* look at correlation between the Healthy Life Expectancy Indicator (HALE) und health care expenditure. They define a decent threshold as the median health care expenditure correlated with a $HALE > 65$ a in efficient countries. The decent health care expenditure results in $1024\,\$/cap/a$. The above approach, however, is lacking a resource reference. Millward-Hopkins *et al.* follow another approach by defining the required area of health care facility per hospital bed. Based on US guidelines, they specify the required area to be $200\,m^2/bed$. To determine per capita demand, [13] simply choose the average bed number per capita. This, however, reflects a status quo and is missing considerations of sufficient levels. This study combines both approaches to benefit from respective advantages: (i) identification of a decent standard following minimally required health care expenditure and (ii) a resource reference trough bed-specific health care facility area. We carry out a regression analyses with 134 countries to link health care expenditure to bed number per capita ($R^2 = 0.44$, see fig. S1).

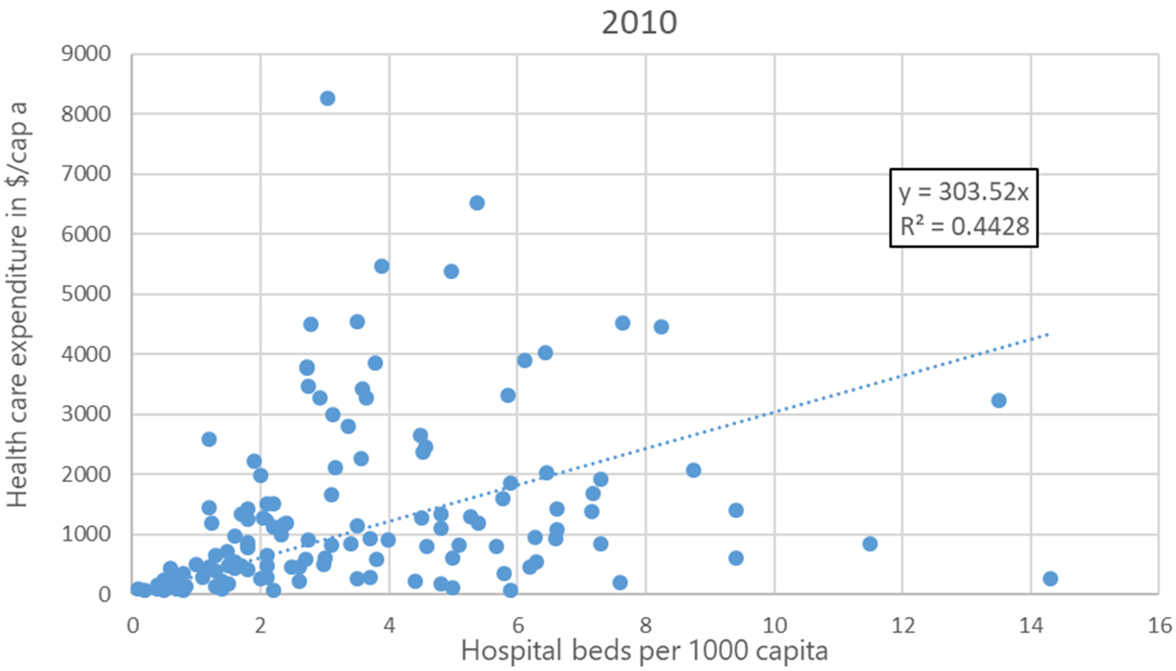

Figure S1: Linear regression of health care expenditure and hospital beds per 1000 capita (data source: [26, 27]

Applying the minimum health care expenditure of [4] ($450\,\$/cap/a$) and the threshold of [15] ($1024\,\$/cap/a$) to the regression function, gives a range of 1.5 to $3.4\,beds/1000\,cap$ (e.g. New Zealand, Panama, Tunisia are in this range in 2010). Next, we link decent bed numbers to the functional unit of the LCI of [28] (normalized to healthcare services provided by one full-time equivalent for one year [FTE]), who looked at inventories of Swiss hospitals. Using hospital bed and employment data from [29], we specify the conversion factor to $2.3\,FTE/bed$. With the range of decent hospital beds, we can calculate the materials and energy needed based on the inventory data from [28] (see table S4). We assume $1.5\,beds/1000\,cap$ for the LD scenario, $3.4\,beds/1000\,cap$ for the HD scenario and a mean of $2.5\,beds/1000\,cap$ as the base scenario. We dismiss some inventory flows in table S4. Meals including meat are already represented in the nutrition requirements. Coffee is considered a luxury item, not a requirement for need satisfaction. Flows of large medical equipment and crutches are considered negligible small.

Education

Linking decent education to resource use is not trivial. Kikstra *et al.* focus on education expenditure per pupil, yet a resource reference is missing. Millward-Hopkins *et al.* assume that every pupil needs $10\,m^2$. We build upon this quantification. We base population-specific pupil share on the projected age distribution in the year 2050. According to United Nations, Department of Economic and Social Affairs, Population Division 5 to 19 year-olds make up ca. 20 % of the population. This results in a population-specific school area of $2\,m^2/cap$. For our LD scenario, we assume $5\,m^2$ per pupil and $15\,m^2$ per pupil in the HD scenario, leading to $1\,m^2$ and $3\,m^2$ per capita school area respectively. Contrary to Rao & Min who assume nine years of school education, we assume at least twelve years, reflecting some requirements of society for higher education.

Information

	per FTE		per capita	
Flow	Value	Unit	Value	Unit
Electricity	5070	kWh/FTE/a	4.6589	kWh/cap/a
Heat	6157	kWh/FTE/a	5.6578	kWh/cap/a
Served meals	289	1/FTE/a	0.2656	1/cap/a
Meat	16.4	kg/FTE/a	0.0151	kg/cap/a
Coffee	2.28	kg/FTE/a	0.0021	kg/cap/a
Building infrastructure	38	m^2/FTE	0.0349	m^2/cap
Total amount of laundry	0.36	t/FTE/a	0.0003	t/cap/a
Water use, total	41.4	m^3/FTE/a	0.0380	m^3/cap/a
Waste	0.23	t/FTE/a	0.0002	t/cap/a
Bedding	0.57	kg/FTE/a	0.0005	kg/cap/a
Work clothing	1.57	kg/FTE/a	0.0014	kg/cap/a
Housekeeping supplies (selection): Soap	1.88	kg/FTE/a	0.0017	kg/cap/a
Gloves	1900	1/FTE/a	1.7459	1/cap/a
Bandages	111	1/FTE/a	0.1020	1/cap/a
Crutches*	0.64	1/FTE	0.0006	1/cap
Pharmaceuticals	3.46	kg/FTE/a	0.0032	kg/cap/a
Laptop	0.29	1/FTE	0.0003	1/cap
Desktop computer	0.77	1/FTE	0.0007	1/cap
Monitor	1.17	1/FTE	0.0011	1/cap
MRI*	1.06	1/1000 FTE	9.74E-07	1/cap
CT*	1.14	1/1000 FTE	1.05E-06	1/cap
Dialysis machine*	8.99	1/1000 FTE	8.26E-06	1/cap
Paper	17.7	kg/FTE/a	0.0163	kg/cap/a
*excluded				

Table S4: Inventory flows for health care. LCI results from [28] are normalized to a decent bed number of 2.6 beds per 1000 capita. FTE: full-time equivalent.

Rao & Min, Kikstra *et al.* and Millward-Hopkins *et al.* argue for television or a web-enabled device as a requirement for access to information. A laptop combines the monitor element from a TV with access to the internet and is therefore chosen as the satisfier for the information dimension. We set the threshold to one unit per household, resulting in 0.2, 0.25 and 0.33 $units/cap$ in the LD, base and HD scenario respectively.

Relationships and communication

Friendships, family bonds and other relationships are not necessarily associated with material requirements. However, the telephone became a widely used mean of communication and to cultivate relationships. Rao, Min & Mastrucci as well as Millward-Hopkins *et al.* and Kikstra *et al.* list the telephone as a requirement for decent living. Therefore, within this study we assume every person ten years or older to possess a telephone/smartphone (ca. 93 % of the population in 2050, [23]; 0.93/cap) in the HD scenario and one telephone/smartphone per household in the LD scenario (0.2/cap). We take the mean of this range (0.56/cap) as the base value. Additionally, ICT infrastructure (telephone network, internet network) is needed as a collective requirement.

Participation

Freedom of expression and assembly

Rao & Min view adequate and safely accessible public spaces as universal satisfier for freedom of expression and assembly. As we know of no common approach to determine the sufficient requirement of public spaces, we choose an empirical approach. Ortiz *et al.* shows data on the largest protest gatherings in recent history (2006 – 2020) (see fig. S2). The number of protesters can give an estimate on how many people claim their right of assembly and expression simultaneously if we calculate the numbers relative to the national population. Figure S2 shows the population shares present at the largest gathering from 2006 – 2020. We take the 95 % confidence interval to estimate the potential of assembly and assume a crowd density to calculate the public space needed.

The potential of assembly is ∼28 % of the population within a 95 % confidence interval. Note that this is probably an overestimate as some protests took place over days or weeks, meaning that simultaneity is not necessarily given. Nevertheless, we consider this to be a conservative estimate. We further assume crowd densities of 1, 3 and 5 m^2/cap for the LD, base and HD scenario, resulting in 0.28, 0.84 and 1.39 m^2/cap of public space respectively.

Mobility

There is no explicit need for mobility and also no universal satisfier referring to it, however, access to

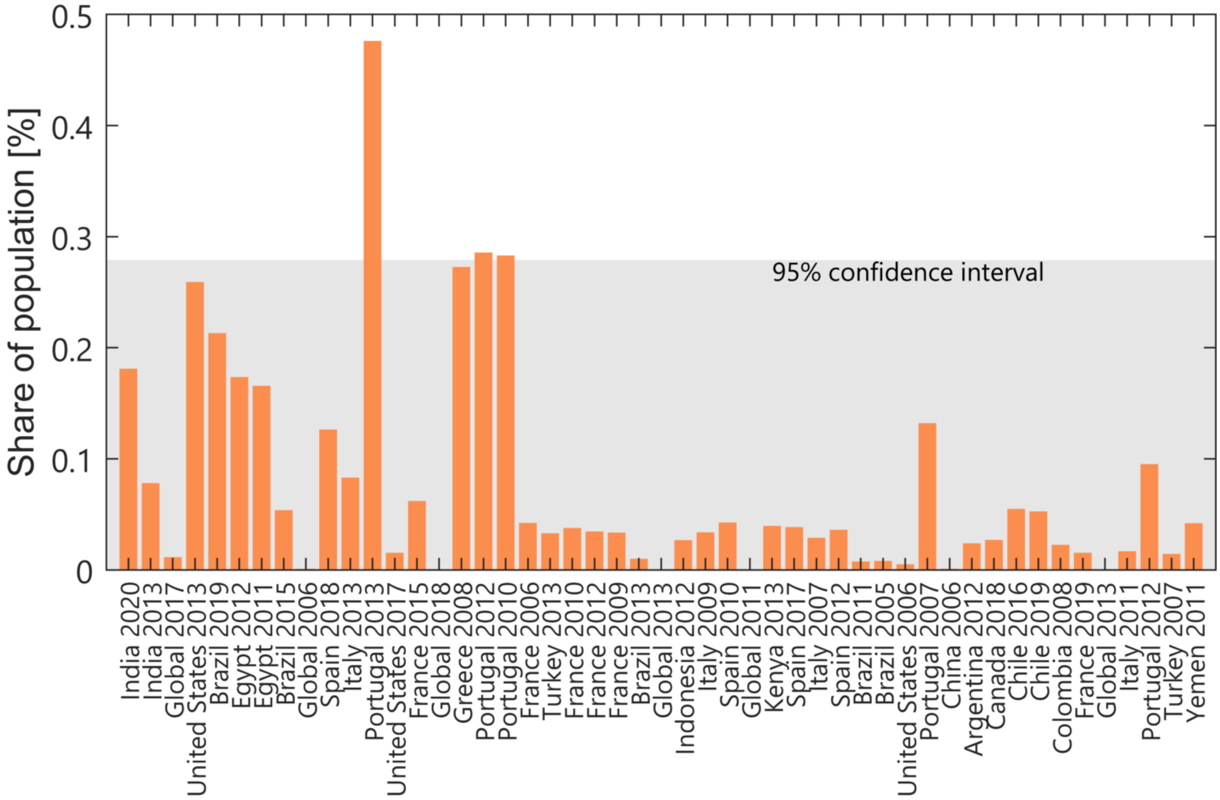

Figure S2: Population share participating in the largest protest gatherings (2006 – 2020) (data soure: [30])

public transport is mentioned as an elements of DLS in [4]. Millward-Hopkins *et al.* and Kikstra *et al.* also define mobility thresholds of motorized transport. We agree in including a mobility dimension as it often is a prerequisite of participation in society, e.g. going to educational or health care facilities, social gatherings, *etc.*

Kikstra *et al.* derive their threshold of 8527 pkm/a from average motorized transport in Japan as it represents a country with low traffic volume and without any significant mobility barriers existing. Millward-Hopkins *et al.* assume a slightly higher value of 10 000 pkm/a (range [5000, 15 000] pkm/a considering urban and rural conditions). They grant 1000 pkm/a of air travel, however, we argue that air travel is not a universal mean of transport, since only a small part of the global population has ever boarded a plane. We go with 8527 pkm/a in the base scenario, yet we reflect the range of mobility requirements by assuming 5000 pkm/a in the LD and 15 000 pkm/a in HD case.

We draw from [15] when selecting the modal split of transport. They again base their modal split on Japan and assume 40% of transport provided by public bus and train respectively. Furthermore, we assume the remaining 20% of transport to be private, splitting it into 15% car and 5% scooter transport. Air travel is excluded.

S3 Scenario development

Figure S3 shows the evolution of our scenario development. We combine different strategies (e. g. sufficiency, defossilization, wooden buildings, no land transformation), demand scenarios (HD, LD, base) and population scenarios (8.0 bn, 10.4 bn people).

S4 Background system

The *premise* package [31] is commonly used to change background databases according to different climate mitigation scenarios generated with IAMs. These generated databases, however, still contain a substantial amount of fossil processes in supply chains, and many processes remain unaltered. We therefore utilize a version of fossil-free ecoinvent database [32], as fossil-free ecoinvent is specifically tailored to substitute fossil processes in supply chains using current technologies (assuming no technological learning) and fits our purpose to analyse a complete defossilization of provisioning systems.

The fossil-free background system is generated via code from [32]. The input parameters for generation are listed in table S5. Please note that we are not allowed to publish the database due to ecoinvent policy. Interested readers can obtain the database modification code upon individual request.

We test an additional scenario with no additional land transformation. As an extension to fossil-free scenarios, we set all "land transformation" exchanges in ecoinvent to zero to be consistent with our steady-state approach, where land occupation would remain constant. Note that the value for land occupation remains unaltered in the database. The code for generating these changes can be found in the Github repository (see S8).

S5 Biophysical limits

We deviate from other studies regarding safe CO_2 emissions. Others look at safe carbon budgets for a limited degree of global heating within a short or medium term time horizon (e.g. [33–35]). We, however, look at annual anthropogenic net-emissions that would not result in any long term CO_2 concentration increase in the atmosphere. This level of emissions is oriented on the amount of CO_2 that is fixated by natural processes such as sedimentation or weathering [36, 37]. It is assumed in our scenario that CO_2 concentrations are at or below safe levels of 350 ppm.

For details on LCIA methods and the code for generating them, visit the associated Github repository (sec. S8). See table S6 for control variable, translated boundary, and LCIA method for respective Earth system processes.

S6 Extended results

In table S7, the probabilities of violation are shown for the investigated scenarios.

In table S8, the median impacts are shown for the scenarios investigated.

Table S5: Input parameters for generating the fossil-free ecoinvent database (ref. [32]).

Variable	***Value***	***Remark***
file path	H:\Schlesier_et_al2022\ecoinvent	file path to ecoinvent database
electricity_location	all markets	string or string list of country codes or "all markets"
lorry_locations		string or string list of country codes or "all markets"
fossil_electricity_reduction_factor	0	0: completely defossilized, 1: completely fossil
phi		share of PV electricity from storage
phi_battery	0,3	battery technology
phi_h2	0	hydrogen storage
phi_pumped	0	pumped hydro storage
nc	5000	number of cycles (batteries)
DD	0,8	discharge depths (batteries)
nu_turnaround	0,75	turnaround efficiency (batteries)
u	0,26	voltage (batteries)
electricity_split		share of substituted electricity
PV	0,9	photovoltaic
Wind onshore	0,02	
Wind offshore	0,03	
Hydro	0	
Geothermal	0,01	
Biomass	0	
Nuclear	0	
Solar	0,04	concentrated solar power
lorry_type_split		share of substituted transport
LTS_BEV	1	battery electric vehicles
LTS_FCEV	0	fuel cell electric
LTS_ICE	0	internal combustion engine
passenger_car_type_split		share of substituted transport
PTS_BEV	1	battery electric vehicles
PTS_FCEV	0	fuel cell electric vehicles
PTS_ICE	0	internal combustion engine
truck_year	2020	
car_year	2020	
rail_fossil_reduction_factor	0	0: electric train only, 1: diesel train only
waterway_fossil_reduction_factor	0	0: synthetic fuels only, 1: fossil fuels only
aircraft_fossil_reduction_factor	0	0: synthetic fuels only, 1: fossil fuels only
synfuel_split		
biogen	0,1	fuels from biomass share
syngen	0,9	synthetic fuels share
Databases to reset	ecoinvent 3.8 cutoff_fossilfree	database name
Databases to compare	ecoinvent 3.8 cutoff, ecoinvent 3.8 cutoff_fossilfree	
heat_production_type_split		weights of heat technologies for substitution
solarthermal	0,15	
heat_pump	0,7	
biomethane	0,05	
biogas	0,05	
wood_chips	0,005	
wooden_logs	0,005	
straw	0,005	
waste	0,005	
electric	0,03	electric resistance

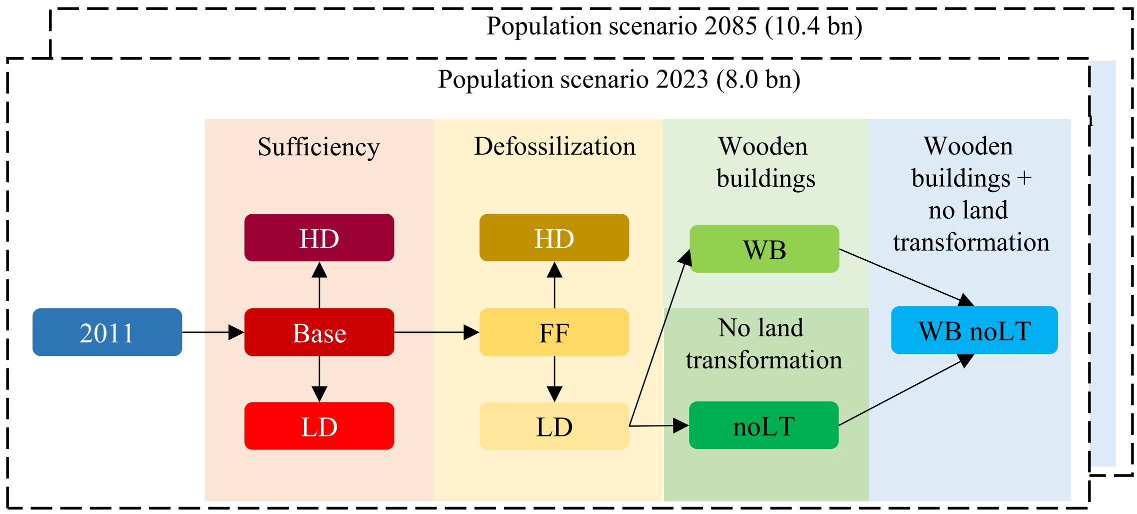

Figure S3: Evolution of scenario development. Arrows indicate that the followed scenario is a combination with the root scenario.

Earth system process	**control variable**	**Translated planetary boundary value [min, max]**	**unit**	**d***	**LCIA method**
Climate change	Direct CO_2 emissions	$[8.25 \cdot 10^{11}, 2.20 \cdot 10^{12}]$	$kg\, CO_2/a$	5	selected LCI results, air, CO2, fossil
	GWP100	$[1.09 \cdot 10^{13}, 1.64 \cdot 10^{13}]$	$kg\, CO_{2eq}/a$	5	IPCC 2013, climate change, GWP 100a
Biodiversity	Potentially disappeared species	$[1.95 \cdot 10^{5}, 1.37 \cdot 10^{6}]$	$species \cdot a/a$	5	biodiversity, species loss, total
Stratospheric ozone	ODP	$[4.24 \cdot 10^{8}, 3.69 \cdot 10^{9}]$	$kg\, ODP_{eq}/a$	5	ozone depletion, including N_2O, average
Biogeochemical flows	P to ocean	$[1.10 \cdot 10^{10}, 1.00 \cdot 10^{11}]$	$kg\, P/a$	5	Phosphorus to ocean, including phosphate, total
	P to soil	$[6.20 \cdot 10^{9}, 1.12 \cdot 10^{10}]$	$kg\, P/a$	5	Phosphorus to soil, including glyphosate, total
	reactive N	$[6.20 \cdot 10^{10}, 8.20 \cdot 10^{10}]$	$kg\, N/a$	5	reactive nitrogen emissions, total, nitrogen total
Land use change	Appropriable land area (all biomes)	$[5.09 \cdot 10^{13}, 6.93 \cdot 10^{13}]$	$m^2 a/a$	1	selected LCI results, resource, land occupation
	Appropriable cropland area	$[1.94 \cdot 10^{13}, 2.61 \cdot 10^{13}]$	$m^2 a/a$	5	cropland use, occupation, total
Freshwater	Blue water consumption	$[4.00 \cdot 10^{12}, 6.00 \cdot 10^{12}]$	m^3/a	5	ReCiPe Midpoint (E) V1.13 no LT, water depletion, WDP
Energy	Appropriable technical potential(ATP)	$[2.26 \cdot 10^{15}, 9.57 \cdot 10^{15}]$	MJ_{el}/a	1	cumulative energy demand, electricity, total

* 1: beta-PERT | 2: triangular | 3: normal | 4: log-normal | 5: rectangular

Table S6: List of translated Planetary Boundaries. Based on [38].

Boundary	**Base 10.4 bn.**	**LD**	**HD**	**FF**	**FF LD**	**FF HD**	**FF LD WB**	**FF LD WB noLUC**	**FF LD noLUC**
					Population 10.4 bn				
CO2	1,000	1,000	1,000	0,622	0,368	0,725	0,355	0,269	0,286
GWP	1,000	0,973	1,000	0,003	0,000	0,038	0,000	0,000	0,000
biodiversity	0,511	0,173	0,730	0,232	0,014	0,339	0,001	0,001	0,002
ozone depletion	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
P to ocean	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
P to soil	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
N emissions	1,000	0,003	1,000	0,998	0,000	1,000	0,000	0,000	0,000
land use	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,000	0,000
cropland use	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
water demand	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
energy demand	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
					Population 8.4 bn				
CO2	1,00	1,00	1,00	0,51	0,27	0,63	0,25	0,19	0,19
GWP	1,00	0,55	1,00	0,00	0,00	0,00	0,00	0,00	0,00
biodiversity	0,35	0,09	0,55	0,15	0,00	0,22	0,00	0,00	0,00
ozone depletion	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P to ocean	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
P to soil	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
N emissions	0,43	0,00	1,00	0,26	0,00	0,97	0,00	0,00	0,00
land use	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
cropland use	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
water demand	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
energy demand	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table S7: Heat map of probability of violations P_v of DLS baskets for 10.4 bn and 8 bn people. Red indicates maximum probability, green lowest.

Boundary	Base	LD	HD	FF	FF LD	FF HD	FF LD WB	FF LD WB noLUC	FF LD noLUC	2011	unit
CO2	2,42E+03	1,47E+03	3,60E+03	1,94E+02	9,98E+01	2,51E+02	1,01E+02	7,17E+01	7,23E+01	3,28E+03	kg CO2/a
GWP	2,97E+03	1,74E+03	4,36E+03	6,62E+02	3,27E+02	8,57E+02	3,02E+02	2,48E+02	2,70E+02	4,71E+03	kg CO2-eq/a
biodiversity	7,36E-05	3,63E-05	1,01E-04	4,42E-05	1,84E-05	5,61E-05	1,58E-05	1,25E-05	1,51E-05	1,24E-04	species.a/a
ozone depletion	5,64E-03	2,80E-03	6,90E-03	5,58E-03	2,75E-03	6,75E-03	2,70E-03	2,47E-03	2,51E-03	9,35E-03	kg ODP-eq/a
P to ocean	1,82E-01	1,43E-01	2,30E-01	1,46E-01	1,16E-01	1,72E-01	1,12E-01	1,11E-01	1,14E-01	6,44E-01	kg P/a
P to soil	7,85E-03	4,96E-03	9,77E-03	1,00E-02	6,61E-03	1,31E-02	6,64E-03	5,54E-03	5,53E-03	1,49E+00	kg P/a
N emissions	8,85E+00	5,27E+00	1,13E+01	8,39E+00	5,02E+00	1,04E+01	4,88E+00	4,46E+00	4,56E+00	1,48E+01	kg N/a
land use	2,56E+03	6,23E+02	2,96E+03	2,94E+03	8,63E+02	3,54E+03	8,65E+02	7,61E+02	7,52E+02	7,14E+03	m^2.a/a
cropland use	4,70E+02	4,19E+02	5,30E+02	4,88E+02	4,31E+02	5,55E+02	4,29E+02	4,20E+02	4,19E+02	1,51E+03	m^2.a/a
water demand	7,70E+01	5,58E+01	9,58E+01	8,97E+01	6,27E+01	1,14E+02	6,19E+01	5,48E+01	5,52E+01	1,20E+02	m^3/a
energy demand	1,72E+04	1,05E+04	2,55E+04	2,10E+04	1,27E+04	3,17E+04	1,22E+04	7,96E+03	8,33E+03	2,42E+04	MJ-el/a

Table S8: Heat map of median impact per capita of DLS baskets. Red indicates highest impact in row, green lowest.

S7 A sufficiency-based allocation key

Contribution analysis

The SoSOS is derived with a contribution analysis (CA) of the LCA results to arrive at a sufficiency-based allocation key (see fig. S8). For that, we identify *primary processes* in the ecoinvent database that produce primary products (metals, food, minerals, chemicals, water, textiles, wood-based products; see github repository, S8). Then, the CA determines the impact and flow shares for each primary process in the supply chain. This is done by looping through the supply chain of the sufficiency basket for a specified depth n (i. e. supply chain levels) until all primary processes are found and impact and flow shares are saved (fig. S8). Then, the CA continues one supply chain level up ($n-1$, $n-2$ and so forth). Since processes in ecoinvent can be nested infinitely, a cut-off criterion for small flows and a maximum supply chain depth needs to be specified to achieve finite calculation times. Due to cut-off, not all impacts and flows can be identified, hence the results are balanced to 1.

Finally, all impact shares are aggregated to yield the SoSOS by assigning the impact of each primary process to a resource segment. We use the built-in International Standard Industrial Classification of All Economic Activities (ISIC) [39] in the ecoinvent database to classify primary processes, which are aggregated to resource segments (table S9). For exceptions for a few primary processes, see the table S10 (e.g. ethylene production is shifted from the segment energy(carriers) to chemicals).

Primary processes

We identified all processes in ecoinvent 3.8 that produce primary products, e. g. chemicals, plastics, metals or metal-oxides, minerals like glass, ceramics, gravel, cement etc., (processed) food, electricity, heat and energy carriers, textiles, wood and wood-based products and water. A list of all names can be found in the Github repository (S8).

Shifts in aggregation to segments

We allocated some products to different resource segments compared to how they be allocated according to table S9 according to the matrix shown in table S10.

Quality of contribution analysis

Two parameters are needed for the contribution analysis (see fig. S8): (i) the maximum supply chain depth and (ii) the flow amount cutoff-criterion. We selected 40 as maximum supply chain depth and <0.0001 as cutoff, which results in acceptable calculation time for the percentage of impact shares found. See table S11 for the percentage of impact shares found. Sensitivity analysis showed, that more depths (e. g. level of 50) and smaller cut-off did not result in significantly more shares found.

S8 Github repository

The following data can be obtained in the Github repository of this study:
https://github.com/empa-tsl/measuring_the_doughnut

- The code to import the foreground system and calculate the impact of the baskets and the contribution analysis, as well as auxiliary data.
- Characterization factors of LCIA methods and the code to generate these.
- Raw impact data of Monte-Carlo runs for each scenario.
- List of all primary processes.
- Figure generator code including calculation of probability of violation.

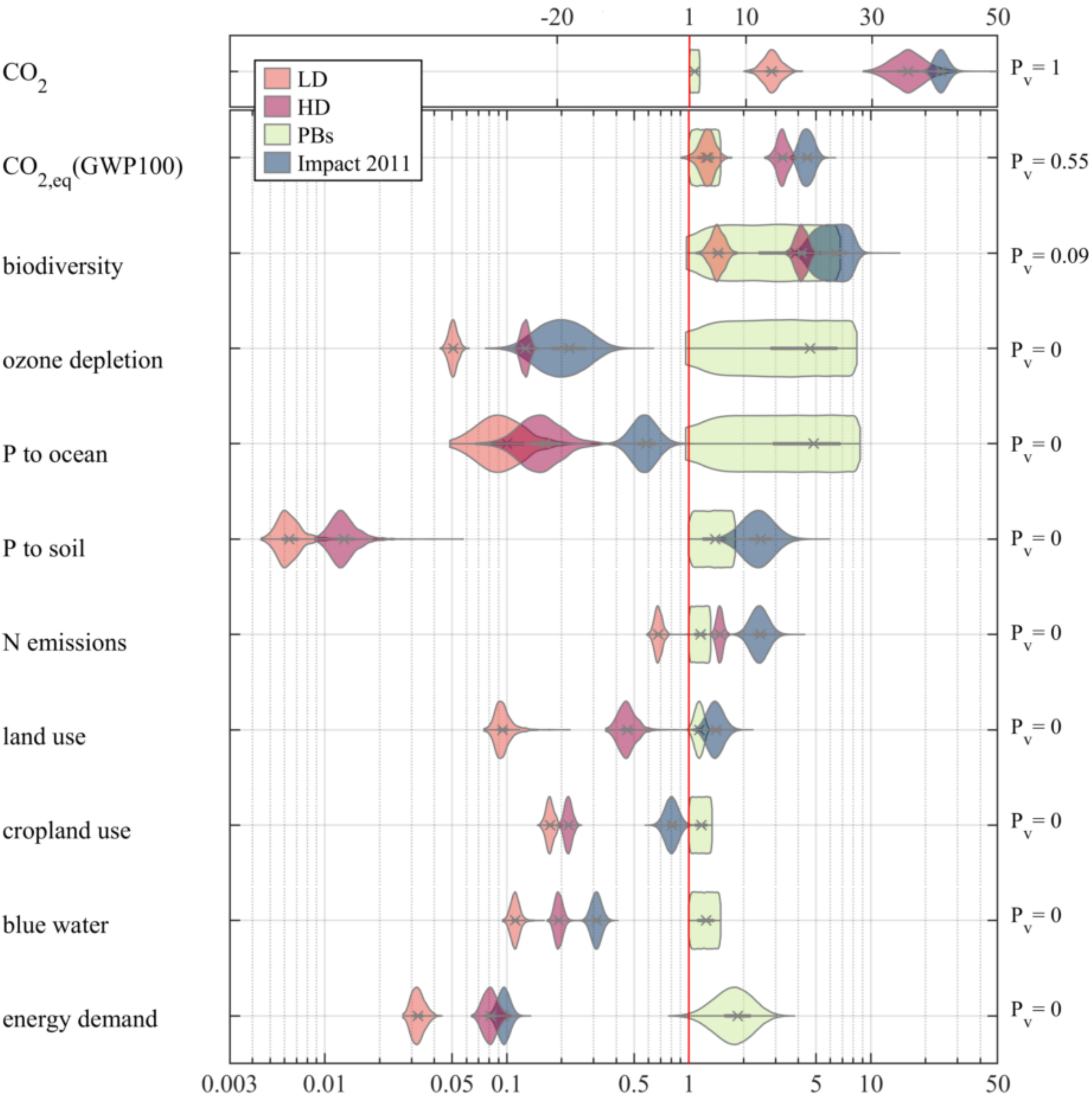

Figure S4: Impacts of DLS baskets benchmarked against PBs (8.0 bn people, conventional provisioning systems). For explanation, see caption of fig. 2. P_v is shown for base, low demand scenario (LD).

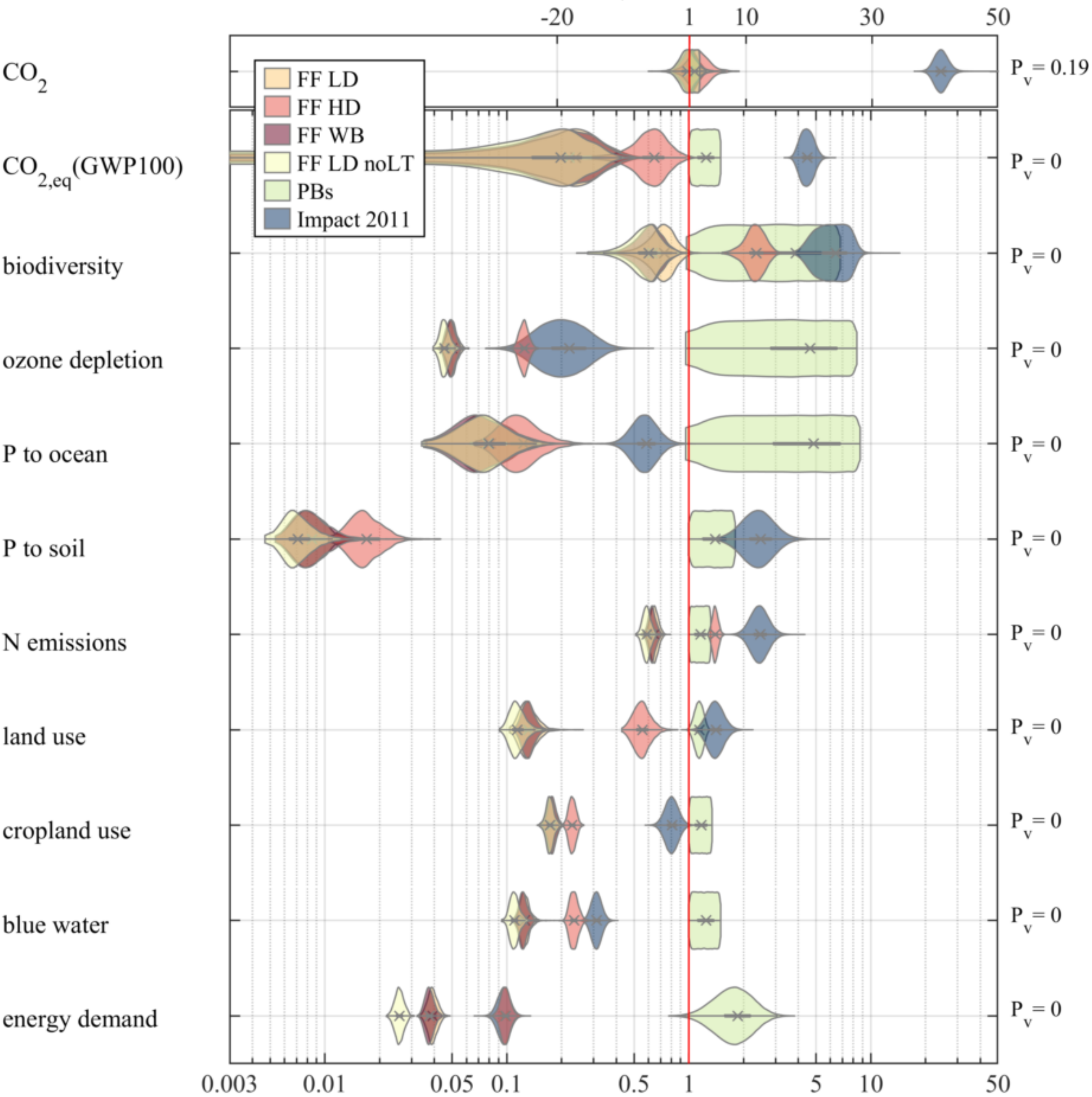

Figure S5: Impacts of DLS baskets benchmarked against PBs (8.0 bn people, fossil-free provisioning systems). For explanation, see caption of fig. 2. P_v is shown for fossil-free, low demand, no land transformation (FF LD noLT) scenario.

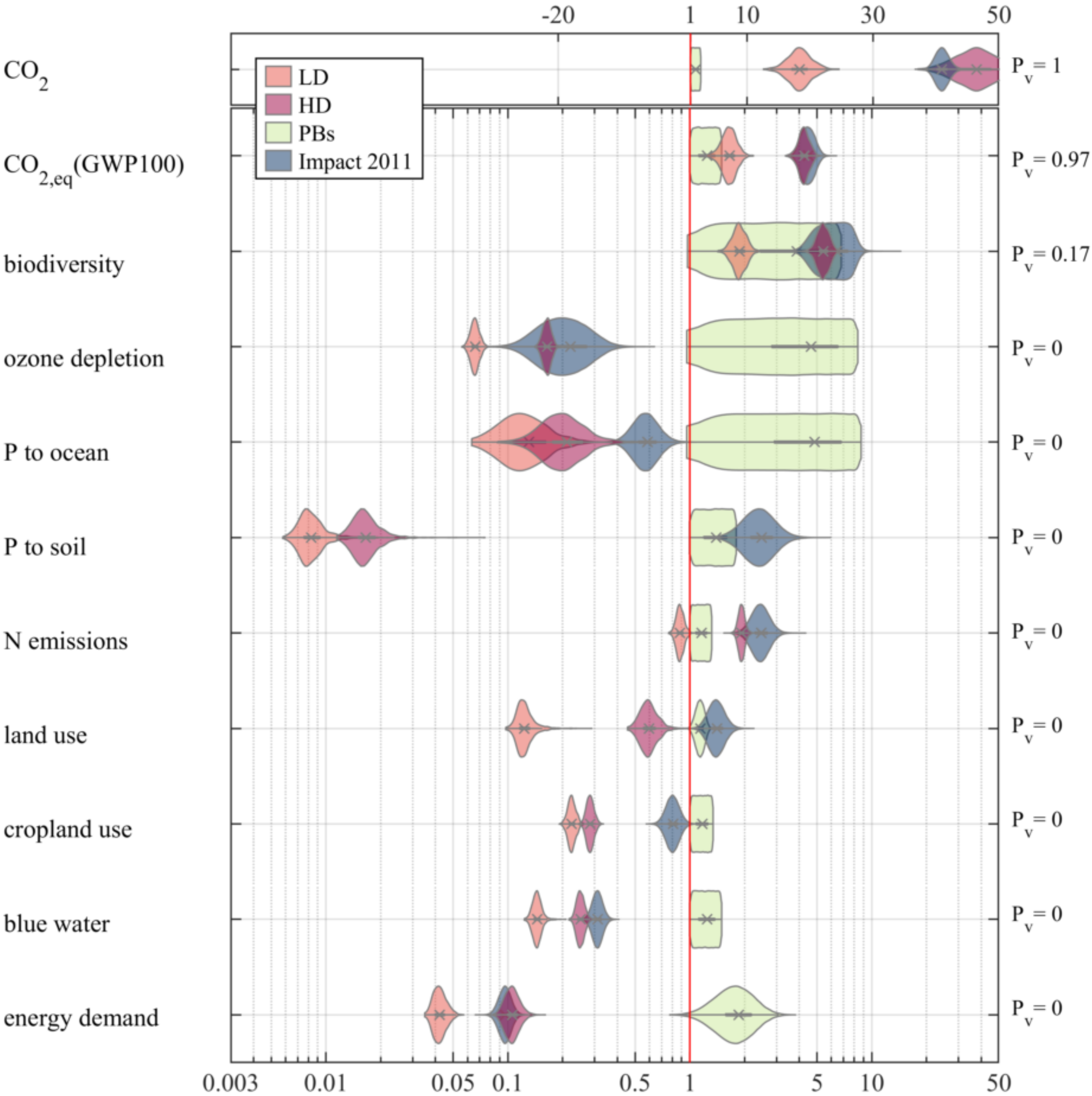

Figure S6: Impacts of DLS baskets benchmarked against PBs (10.4 bn people, conventional provisioning systems). For explanation, see caption of fig. 2. P_v is shown for base, low demand scenario (LD).

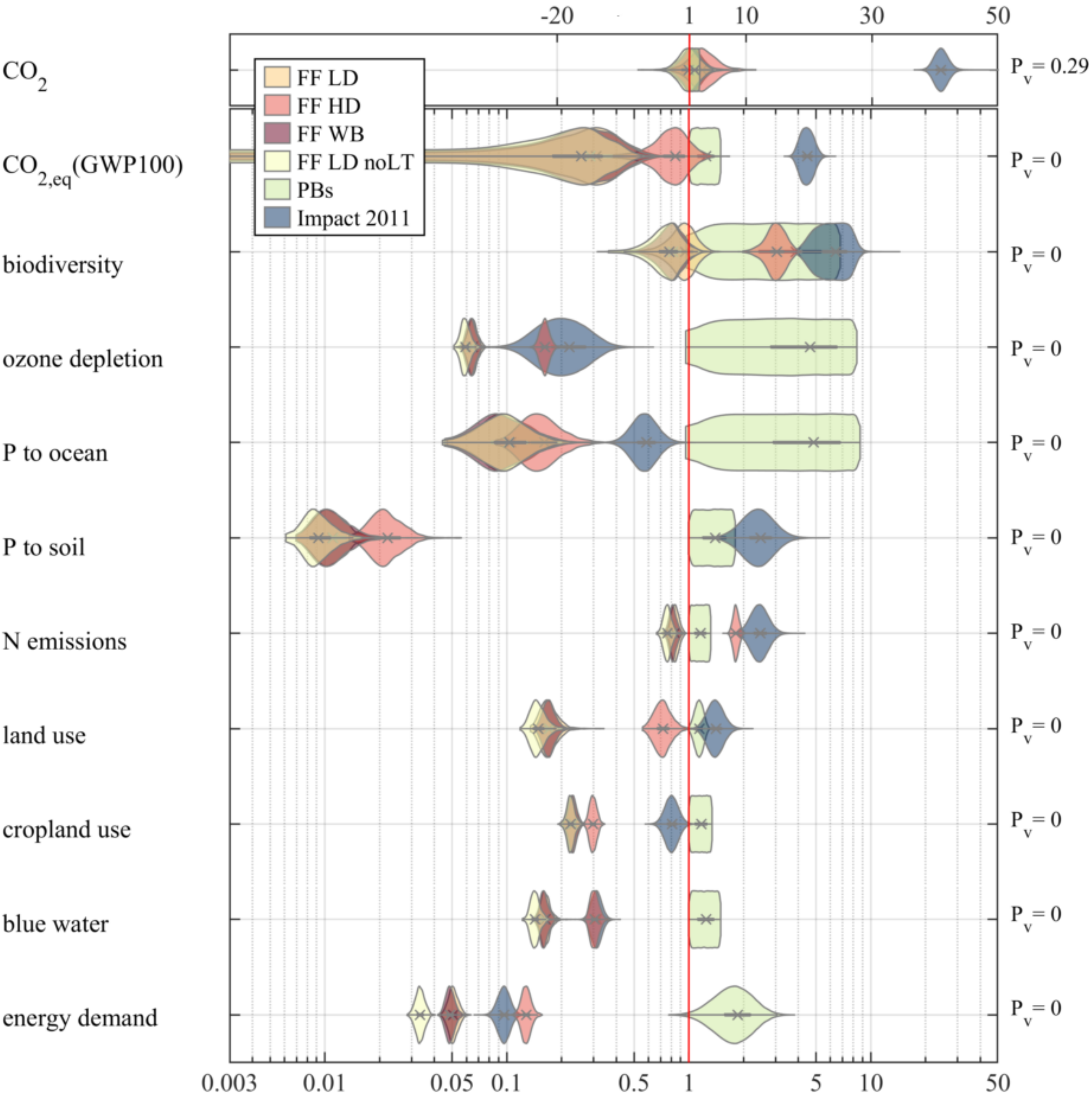

Figure S7: Impacts of DLS baskets benchmarked against PBs (10.4 bn people, fossil-free provisioning systems). For explanation, see caption of fig. 2. P_v is shown for fossil-free, low demand, no land transformation (FF LD noLT) scenario.

Nr.	Segment	Code	ISIC rev. 4 division
1	Chemicals	20	Manufacture of chemicals and chemical products
2	Metals	07	Mining of metal ores
		24	Manufacture of basic metals
3	Energy(carriers)	05	Mining of coal and lignite
		06	Extraction of crude petroleum and natural gas
		19	Manufacture of coke and refined petroleum products
		D	Electricity, gas, steam and air conditioning supply
		49	Land transport and transport via pipelines
4	Minerals	B	Other mining and quarrying
		23	Manufacture of other non-metallic mineral products
5	Textiles	13	Manufacture of textiles
6	Agriculture, animal	10	Manufacture of food products
		02	Fishing and aquaculture
7	Agriculture, plant based	01	Crop and animal production, hunting and related service activities
8	Wood	16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
		02	Forestry and logging
		17	Manufacture of paper and paper products
9	Water	36	Water collection, treatment and supply

Table S9: Assignment of ISIC divisions to resource segments.

type	products	Chemicals	Metals	Energy(carriers)	Minerals	Textiles	Agrisector, animals	Agrisector, plants	Wood	Water
product	benzene	1	0	-1	0	0	0	0	0	0
product	sulfur	1	0	-1	0	0	0	0	0	0
product	ethylene	1	0	-1	0	0	0	0	0	0
product	hexane	1	0	-1	0	0	0	0	0	0
product	hydrogen, liquid	1	0	-1	0	0	0	0	0	0
product	methylcyclopentane	1	0	-1	0	0	0	0	0	0
product	naphtha	1	0	-1	0	0	0	0	0	0
product	paraffin	1	0	-1	0	0	0	0	0	0
product	propylene	1	0	-1	0	0	0	0	0	0
product	white spirit	1	0	-1	0	0	0	0	0	0
product	cattle for slaughtering, live weight	0	0	0	0	0	1	-1	0	0
product	cow milk	0	0	0	0	0	1	-1	0	0
product	chicken for slaughtering, live weight	0	0	0	0	0	1	-1	0	0
product	red meat, live weight	0	0	0	0	0	1	-1	0	0
product	sheep for slaughtering, live weight	0	0	0	0	0	1	-1	0	0
product	sheep fleece in the grease	0	0	0	0	1	0	-1	0	0
class	0161:Support activities for crop production	0	0	0	0	0	0	-1	0	1
product	irrigation	0	0	0	0	0	0	-1	0	1
product	hydrogen, gaseous	1	0	-1	0	0	0	0	0	0
product	algae cultivation | algae broth production	0	0	0	0	0	-1	1	0	0
product	algae harvesting for dry algae production	0	0	0	0	0	-1	1	0	0
product	algae harvesting| dry algae production	0	0	0	0	0	-1	1	0	0
product	1,1-dimethylcyclopentane	1	0	-1	0	0	0	0	0	0
product	2,3-dimethylbutan	1	0	-1	0	0	0	0	0	0
product	2-methylpentane	1	0	-1	0	0	0	0	0	0
product	heptane	1	0	-1	0	0	0	0	0	0
product	pitch	0	0	-1	1	0	0	0	0	0
product	bagasse, from sweet sorghum	-1	0	0	0	0	0	1	0	0
product	bagasse, from sugarcane	0	0	0	0	0	-1	1	0	0

Table S10: Shift matrix of products; 1 indicates the segment to which the product is allocated to, -1 is the segment it is allocated from.

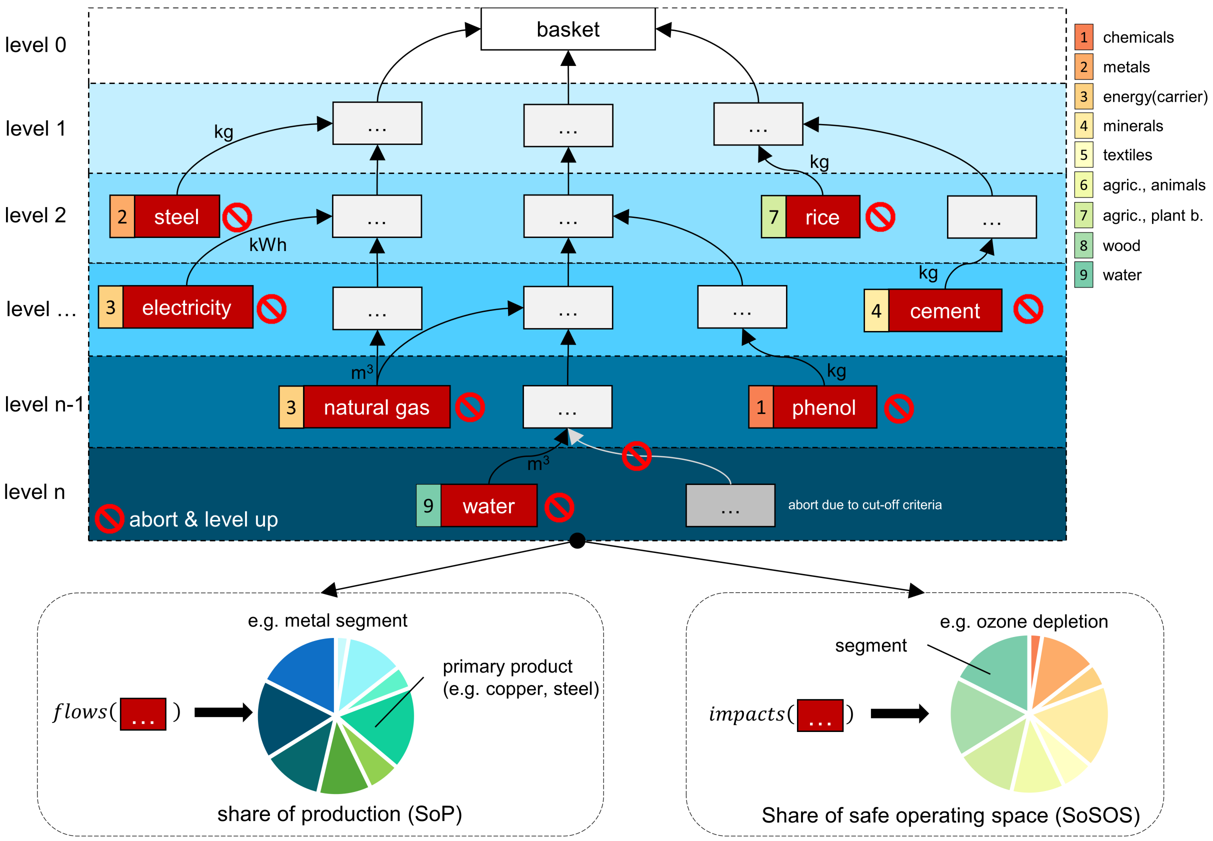

Figure S8: Concept of contribution analysis to determine the share of production (SoP) and the share of safe operating space (SoSOS). The algorithm loops through the supply chain of the sufficiency basket to identify flows of primary products and calculates their relative impact.

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impact category	Base	FF	FF LD WB noLT
CO2	83,5%	87,6%	93,4%
GWP	84,2%	84,9%	79,0%
BIO	89,6%	93,7%	91,2%
ODP	93,7%	94,1%	89,6%
P2O	98,6%	98,2%	99,1%
P2S	94,8%	95,0%	93,1%
RNE	92,8%	95,0%	95,6%
LO	98,4%	97,9%	96,3%
CU	99,9%	99,8%	100,0%
WD	95,6%	94,7%	95,5%
CED	97,8%	96,1%	97,9%

Table S11: Percentage of shares found in scenarios for impact category (SoSOS of scenarios are shown in 2a). FF = fossil-free; FF LD WB noLT = fossil-free, low demand, wooden buildings, no land use change. GWP = Global Warming Potential; BIO = Biodiversity loss; ODP = Ozone Depletion Potential; P2O = Phosphorous to ocean; P2S = Phosphorous to soil; RNE = reactive nitrogen emissions; LUC = land use change; CU = cropland use; WD = water demand; CED = Cumulative Energy Demand (see S6 for LCIA methods)