

Communicating the environmental impacts of individual actions in the context of Planetary Boundaries[☆]

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ABSTRACT

Human activities, driven by high consumption and rapid development, are pushing environmental degradation beyond the planet's carrying capacities. Changing consumption patterns is a key lever to reduce these environmental pressures to sustainable levels, and this can be quantified using life-cycle assessment (LCA). However, there are misconceptions about the effectiveness of specific actions, and LCA results are typically not contextualized by comparison to environmental carrying capacities, making it difficult to distinguish between “better for the environment” and “good enough for the environment”. This study seeks to address this gap by communicating environmental impacts of lifestyle choices on an absolute scale, using relatable frameworks like that of the Planetary Boundaries. It estimates the footprint of an average person's lifestyle, as well as the impacts of 23 common daily activities, and compares these impacts to an individual's carrying capacity budget for 6 impact categories. Applied to Denmark, the results reveal a significant overshoot of personal environmental budgets across all categories, except for water use, with some activities alone surpassing the full personal budget for impact categories like climate change and resource use. For those major contributing activities, alternative ways of fulfilling them can help realign lifestyles with environmental budgets. Other activities – despite usually perceived as highly impactful – are actually found insignificant. Overall, bringing environmental impacts to sustainable levels through individual actions alone are insufficient to bring environmental impacts to sustainable levels, particularly with the current available technologies. This calls for the need for systemic changes that prioritize sustainable technologies and the adoption of sufficiency-focused lifestyles.

1. Introduction

The influence of human activities on the degradation of Earth system processes is unequivocal. Evidence is now manifold as to the surge in environmental impacts from human activities in the past few decades to levels that exceed global and regional carrying capacities (IPBES, 2019; IPCC, 2023; Almond et al., 2022; Richardson et al., 2023; Steffen et al., 2015a). (Over)consumption in high-income countries is now accompanied by a fast development in lower-income countries, which keeps increasing the global yearly extraction of resources from and emissions to the environment (Wiedmann et al., 2020). At all levels, immediate action is required to lower those environmental impacts to sustainable

levels.

Consumers can make a wide range of choices in their everyday life to lower their environmental impacts. While not sufficient, individual changes in consumption is a fundamental component of the mitigation of human pressures on the environment (Bjørn et al., 2018; Creutzig et al., 2018; O'Rourke and Lollo, 2015). However, individuals have limited knowledge of the environmental impacts of different lifestyles and behaviors, and there are numerous misconceptions on this topic (de Boer et al., 2016). The potential of some actions to reduce impacts are underestimated while others are overestimated (Cologna et al., 2022; Wynes et al., 2020; Wynes and Nicholas, 2017). There is, therefore, a need for comprehensive analysis and communication on the life style

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choices with the largest potential to reduce total personal impacts, as well as what impact reduction to aim for as an individual. This is especially important, as a person's belief in the effectiveness of a given action correlates with the intention to perform this action (Truelove and Parks, 2012), and communication on environmental impacts has the potential to guide their choices (Lupiáñez-Villanueva et al., 2018; Vizzoto et al., 2021).

Life-cycle assessment (LCA) is a standardized tool used to quantify the impacts of products and services (EC-JRC, 2011; Hauschild et al., 2018). In LCA, the mitigation potentials of individual actions are often presented as environmental footprints in physical units, such as kg CO₂-eq for climate change (Cologna et al., 2022; Ivanova et al., 2016, 2020; Jones and Kammen, 2011; Wynes and Nicholas, 2017). This allows for comparing the impact of different lifestyle choices but does not provide any information about the meaning of the numbers given (for example, how bad is 50 kg CO₂-eq for climate change?). Poor communication of LCA results has been found to be an important barrier for decision makers to follow conclusions (Clark and Leeuw, 1999; Galindro et al., 2019). To face this challenge, many practitioners advocate for customizing the results to the audience (Røyne et al., 2019; Vizzoto et al., 2021). They highlight the need to provide the appropriate amount of information, and to complement quantitative results with references values to contextualize the impacts. Finally, when applied to lifestyle choices, impact results mostly focus on climate change only, which can fail to capture the full extent of the environmental impacts of individual actions (Laurent et al., 2012). Opportunities for reducing other environmental impacts may therefore be overlooked, and there is a risk that GHG reduction strategies lead to increases in other environmental impacts. This calls for a new way to display LCA results of individual actions, comparing impacts to benchmarks reflecting sustainable consumption levels in more than a single category. In other areas, such as the food sector, presenting quantitative information as a percentage of reference values (e.g., dietary reference intake values) has proven effective at enabling comparisons between individual choices (“is product A better than product B?”) and at translating abstract scientific quantities to a relatable absolute scale (“is it a lot?”) and has become a widely adopted tool that consumers are now familiar with (Trumbo

et al., 2001).

In LCA, the normalization step already allows additional insights into impacts score by comparing them to a reference that the decision-makers can better relate to (Dahlbo et al., 2013; Pizzol et al., 2017). An increasing number of scientific articles implement the use of normalization references tied to Planetary Boundaries or other absolute environmental thresholds in what are known as absolute environmental sustainability assessments (AESA) (Bjørn et al., 2020a; Bjørn et al., 2016; Ryberg et al., 2020; Sala et al., 2016). In an AESA, a system's impact scores are compared to a defined environmental budget, i.e., a share of safe operating space (SOS). However, its application to lifestyle choices and individual consumption has been limited so far (Bjørn et al., 2020a).

In this study, we explore how the environmental implications of lifestyle choices can be communicated to individuals using the planetary boundaries as absolute references. We use Denmark as a case study, representing one of the world's wealthiest countries and often regarded as a role model yet noted for its environmental misalignment (Fanning et al., 2021). We provide an estimation of the footprint of an average Danish person, as well as a comparative life-cycle assessment of 23 daily activities in the country, which cover a wide range of activities broadly relevant to the lifestyles of inhabitants in Denmark and other high-income countries. Impacts are compared to an annual impact allowance allocated to each person following an equal-per-capita approach, providing information about the magnitude of environmental impacts from daily activities, as well as the importance of lifestyle choices— or not—in terms of impact savings. We show that this analysis and communication can lead to new insights compared to merely reporting carbon footprints.

2. Methods

2.1. Modeling the yearly consumption of an average person

The overarching methodological approach of the study is presented in Fig. 1. First, the current annual footprint of an average Danish inhabitant is estimated. The calculations of the current footprint rely on a top-down approach, using a global multi-regional input-output

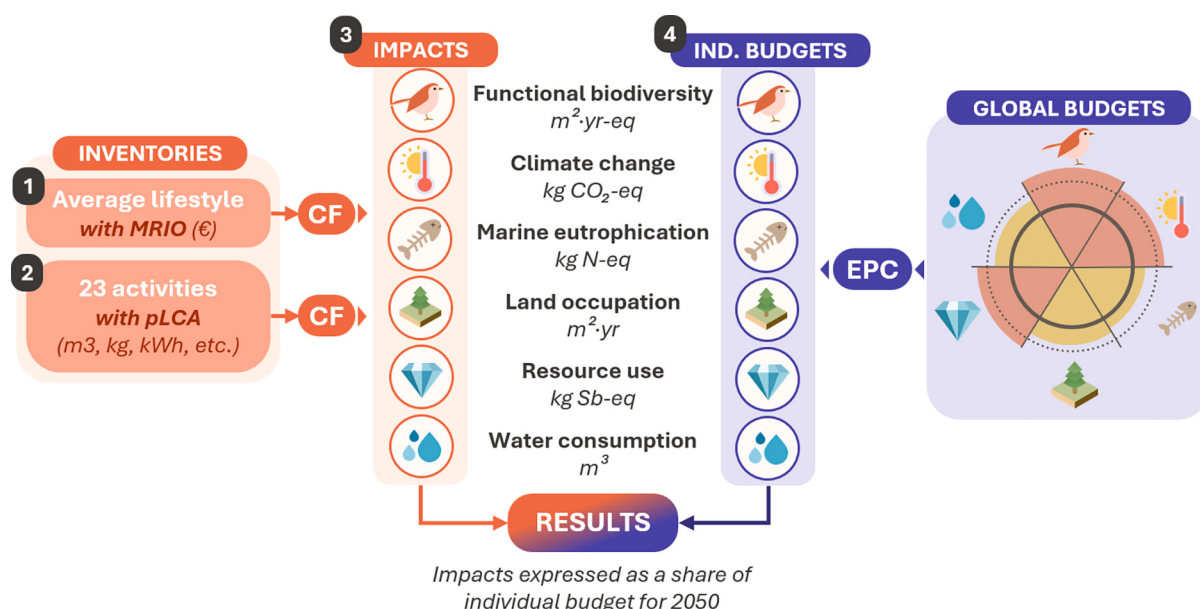


Fig. 1. Overarching methodological approach of the study. The inventories are first built with two different methods. The average lifestyles is made following a top-down approach (with the MRIO database EXIOBASE), while the 23 activities are modeled with process-based life-cycle assessment (or pLCA). In parallel, individual budgets are defined by downscaling global budgets, e.g. the ones defined by the Planetary Boundaries framework, following an equal-per-capita approach (every person gets the same share) for 2050. CF = Characterization factors, turning physical or monetary flows into impacts. EPC = Equal Per Capita, the allocation principle used to downscale from global to individual budgets.

(GMRIO) database. GMRIO databases are based on macroeconomic data at the global or national level. They keep track of the monetary flows between industrial sectors and regions, which can be further translated into impacts with intensity factors (environmental impacts per monetary unit). Among MRIO databases, EXIOBASE has the highest level of sector detail (Tukker et al., 2018) and has long been used to calculate footprints of nations in a various set of environmental indicators, including climate change, water use, land use, marine eutrophication and mineral resource depletion (Beylot et al., 2019; Castellani et al., 2019; Font Vivanco et al., 2017; Giljum et al., 2016; Ivanova et al., 2016, 2017; Ivanova and Wood, 2020; Lutter et al., 2016; Tukker et al., 2016; Vázquez et al., 2023; Wood et al., 2015). The latest version, EXIOBASE 3, was here used to extract the inventory of products and services consumed in Denmark over one year, following a consumption-based approach, in monetary units. This approach includes imported goods consumed in Denmark and excludes exported goods consumed in other world regions for 2019. 2019 was chosen as a reference because it is the most recent year with available data from EXIOBASE that is unaffected by the global economic disruptions linked to COVID-19. The activity of an average person was then calculated by dividing the national inventory by the 2019 population. It was split into five categories representing major groups of basic needs: mobility, housing, general goods consumption (referred to as “consumables” in this study), food, and others (which comprises public spendings), adapting the classification of (Ivanova and Wood, 2020). Details on the calculations, including the mathematical framework used to compute the inventories, are provided in Supplementary Information 1.

2.2. Modeling of the 23 representative activities

A selection of representative activities under the four main categories was made to provide results on specific activities that consumers can identify with. The goal was to capture a wide range of everyday practices for a typical individual living in Denmark. To achieve this, a scientific literature review was conducted to identify activities that either have high environmental impacts, according to existing evidence, or are broadly perceived by consumers as impactful (Cologna et al., 2022; de Boer et al., 2016; De Feo et al., 2022; Hartmann et al., 2021; Ivanova et al., 2020; Poore and Nemecek, 2018; Shi et al., 2016; Thomas et al., 2021; Truelove and Parks, 2012; Wynes et al., 2020; Wynes and Nicholas, 2017). In total, 23 activities were chosen (cf. Table 1). To harmonize the calculation of impacts between the different activities and compare them with absolute thresholds (covered in Section 3.2), the activities were scaled to a typical annual level (see third column of Table 1). For example, the activity “Washing clothes” covers the average number of washing cycles that one person does in one year. This is referred to as the “activity level” in Table 1 (corresponding to the expression “functional unit” in life-cycle assessment).

Each activity can be achieved using different options, that were selected to match the most common choices available to consumers in Denmark, many of which could also be relevant to other countries (cf. Table 1). The impacts of the different options are calculated over their entire life cycle. In other words, they represent all the processes needed to fulfill the action. For example, the impacts linked to the “gasoline car” for “commuting to work” do not only include the emissions from the tail pipe, but also impacts from the production and eventual waste management of the car, as well as a share of the road infrastructure.

The modeling was based on the Ecoinvent database (version 3.9.1), which consists of a highly detailed set of processes that compile inventories for commonly used products and services, drawing on a broad collection of average data values from existing scientific literature (Ecoinvent, 2022). Those inventories are lists of all the physical flows of natural resources (such as water or raw materials) and emissions (such as gases and particles) that result from the use of the products and services. They follow a life-cycle perspective, i.e., consider all flows occurring from the extraction of raw materials to the end-of-life of all the

Table 1

The 23 activities covered in the study and their related activity levels and options.

Category	Activity	Activity level for one year	Options
Mobility	Home to work commute	Commuting 22 km/day every working day	Bike, Electric bike, Diesel bus, Electric car, Gasoline car, Motorbike, Train
	Weekend trips	5.3 weekend trips with 2-h journeys	Gasoline car, Electric bike, Plane, Train
	Plane trips	Flying 8706 km	Long-haul flights, short-haul flights, very short-haul flights
	Car usage	27.6 km/day	Diesel car, Electric car, Small electric car, Gasoline car, Small gasoline car
Housing	Type of home	Living 1 year in a new home	Building apartment, Detached house, Semi-detached
	Size of home	Living 1 year in a new home	54 m ² /cap, 38 m ² /cap or 21 m ² /cap
	Electricity supply	1627 kWh of electricity	Average grid, 5 m ² /cap of PV panels, PV self-sufficiency, PV self-sufficiency with battery backup
	Heating system	4867 kWh of heat	Heat pump, district heating, oil boiler, gas boiler
	Heating temperature	4867 kWh of heat	19 °C, 21 °C, 23 °C
Consumables	Lighting	9 bulbs for 2 h/day	Incandescent bulbs, LED bulbs
	Using electronics	Average use of a device	Smartphone, Tablet, TV, Laptop
	Washing clothes	Washing clothes every 5.4 days	30 °C, 40 °C, 60 °C, 90 °C
	Drying laundry	Drying clothes every 5.4 days	Dryer only, Dryer 25 %
	Replacing early	Replacing a device 25 % earlier	Dryer, Washing machine, Refrigerator, TV, Laptop
	Buying clothes	Buying 10.8 kg of clothes	Average consumption, second hand
	Packing groceries	Using grocery bags	Light plastic bag (single use or reused), Plastic shopping net, Paper bag (single use or reused), Cotton bag
	Showering	Taking showers T 10 L/min	Daily 5-min hot, Fewer 5-min hot, Daily 10-min hot, Daily 10-min cold, Daily 20-min hot
	Drinking water	Drinking 2.5 L/day	Tap water, Bottled water (virgin), Bottled water (recycled)
	Type of diet	Average food consumption	Omnivorous diet, Vegan diet, Vegetarian diet
Food	Organic vs. conventional	Average wheat consumption	Conventional wheat, organic wheat
	Fresh vs. frozen	Average vegetables consumption	Fresh carrots/broccolis, Frozen carrots/broccolis
	Milk consumption	117 kg /year	Oat milk, Cow milk
	Food waste	Average food consumption	Average waste, halving food waste

products. The database chosen follows an “attribitional” modeling that aims to “describe the environmentally relevant physical flows to and from a life cycle and its subsystems” (Finnveden et al., 2009). The “cut-off” system model is here used to model the end-of-life. In this model, waste is the producer's responsibility, while recycled products are available to new users “burden-free” (Ecoinvent, 2024). The software OpenLCA (version 2.1.1) was used to build all inventories.

Whenever possible, the processes of the Ecoinvent database were

adapted and modified to improve the technological, geographical, and temporal representativeness of the systems assessed for the Danish context. For example, for the activity “Heating”, the district heating system of Denmark was modeled following the 2020 mix of Danish heating technologies. Details on the modeling of each option of the 23 activities are described in Supplementary Information 1 and 2.

2.3. Calculation of environmental impacts

After modeling the systems representing the inventory of flows (also referred to as life-cycle inventories or LCI), those were translated into environmental impacts. The choice of the impact categories was inspired by the Planetary Boundaries (PB) framework, originally developed by Rockström et al. (2009) and successively updated by Steffen et al. (2015b) and Richardson et al. (2023). Although renowned and widely used, the PB framework is not straightforward to implement in LCA (Ryberg et al., 2016). For example, the PB framework uses control variables that differ from the conventional impact indicators of LCA, while it disregards impact categories that are not linked to the stability of the Earth system, such as abiotic resource depletion (Dong and Hauschild, 2017; Ryberg et al., 2016). Despite these challenges, this study includes most of the categories of the PB framework that are currently exceeded (Richardson et al., 2023). The category of novel entities, which is challenging to quantify (Persson et al., 2022), was excluded from this study. Conversely, a category for mineral resources, not covered in the PB framework, was added. In total, the study assesses impacts across six environmental categories: Functional biodiversity, Climate change, Marine eutrophication, Land occupation, Resource use, and Water consumption.

Translating inventories into impacts follows different characterization models for the average lifestyle (using GMRIO) and the 23 activities (using pLCA). For the average lifestyle, the inventory of elementary flows is given in monetary units and characterization factors adapted from Beylot et al. (2019) were used. For pLCA, the inventory is expressed in physical units (e.g., kg or m³), and different impact assessment methods were used, but primarily the method developed by the EC-JRC, EF3.1, when possible. Between the two approaches, the level of detail varies; with, for example, a higher number of elementary flows included in pLCA. Eventually, the indicators used sometimes differ from the latest PB framework iteration to make them usable both using GMRIO and pLCA. For water consumption for example, the indicator from the previous iteration of the PB framework (Steffen et al., 2015b), i.e., the volume of blue water consumed (in m³) was used. For climate change, impacts were expressed as greenhouse gas emissions (in kg CO₂-eq) rather than CO₂ concentration changes (ppm) or radiative forcing (W/m²), used in the PB framework. For functional biodiversity, a new indicator, based on the approach of Galán-Martín et al. (2021), was introduced (equivalent functional biodiversity area loss). In most cases, this also enhanced the clarity of results for effective communication with non-experts.

The impact categories, indicators, and characterization models used in the study as well as their respective sources are provided in Table 2. Additional information about the methodological choices made is provided in Supplementary Information 1, while the full list of characterization factors is given in Supplementary Information 2 and 3.

2.4. Individual annual environmental budgets

The individual environmental budgets are determined on a per capita, per year basis, enabling direct comparison with activities also assessed on an annual scale. The reference year taken is 2050, providing consumers with a projection of how their lifestyles would need to evolve in the coming 25 years. Those individual environmental budgets were then used as normalization references to express the impacts of lifestyles and activities.

To establish these budgets, PBs adapted for LCA were first identified.

Table 2
Impact categories, their corresponding indicators, characterization models and adapted Planetary Boundaries (PBs). Additional information about the methodological choices made is provided in Supplementary Information 1. The full list of characterization factors is given in Supplementary Information 2 and 3.

Impact category		Functional Biodiversity	Climate Change	Marine Eutrophication	Land Occupation	Resource Use	Water Consumption
Impacts characterization	Indicator	Equivalent functional biodiversity area loss	Greenhouse gas emissions	Nutrients reaching marine end compartment	Change of land cover and land use intensification	Abiotic resource depletion (ADP ultimate reserves)	Blue water consumption
	Unit	m ² -yr-eq	kg CO ₂ -eq	kg N-eq	m ² -yr	kg Sb-eq	m ³
	Average lifestyle (GMRIO)						
	23 activities (pLCA)	Galán-Martín et al. (2021); Hanafiah et al. (2012) 10 % permissible loss of the Biodiversity Intactness Index (BII)	EF3.1 (EC-JRC, 2022) 2 degrees of warming by 2100, 67 % likelihood (median scenario)	EF3.1 (EC-JRC, 2022) Maximum nitrogen concentration of 1.75 mg N _{tot} /L	ReCiPe2016 (Beylot et al., 2019) ReCiPe2016 (Huijbregts et al., 2017) 50 % of land conservation	EF3.1 (EC-JRC, 2022) Reduction of material consumption by a factor 2	ReCiPe2016 (Huijbregts et al., 2017) Consumption to reflect water stress factors and environmental flows requirements
Individual budgets calculation	Adapted PB	1.30E+13	2.00E+13	2.01E+11	5.29E+13	2.19E+08	2.12E+12
	Global yearly budget (2050)		IPCC (2022)	Sala et al. (2020)	Noss et al. (2012)	Sala et al. (2020)	Bjorn and Hauschild (2015)
Individual budgets calculation	Primary source	Galán-Martín et al. (2021)					
	Individual yearly budget (2050)	1.34E+03	2.06E+03	2.07E+01	5.46E+03	2.26E-02	2.19E+02

A corresponding global annual budget was determined using the same metrics applied to lifestyle impacts and the 23 assessed activities. Notably, the global budgets used in this study do not necessarily align with the latest exceedance state of the Planetary Boundaries, as updated by (Richardson et al., 2023). For instance, while the PB for climate change (atmospheric CO₂ concentration of 350 ppm) has already been exceeded, the selected budget is positive, as the current level of warming has not exceeded 2 degrees (IPCC, 2023). Further details on the methodological choices to estimate the global budgets are provided in Supplementary Information 1.

The global budgets for 2050 were subsequently downscaled to the individual level using an equal per capita (EPC) approach, a widely adopted method (Ryberg et al., 2020). World population projections for 2050 were sourced from The UN's World Population Prospects (UN, 2022), estimating a global population of 9.69 billion people. The resulting individual environmental budgets for the impact categories considered in this study are presented in Table 2.

3. Results

3.1. The sustainability impact of the average Danish lifestyle

The estimation of the current impact of an average Danish citizen among the 6 impact categories show a clear exceedance of all environmental budgets, except for water consumption, which comes close to the budget (99.7 %) (Fig. 2). Exceedances are particularly high for resource use (overshooting with factor 12), functional biodiversity (factor 11), and climate change (factor 7).

For functional biodiversity, land use, and marine eutrophication, the results show that the biggest contributor is food, which by itself consumes more than the allowed budget for four environmental categories (functional biodiversity 536 %, climate change 143 %, land use 152 %, resource use 138 %). Impacts linked to mobility overshoot alone the budget for functional biodiversity (206 %), climate change (145 %) and resource use (454 %). Housing impacts are also above the defined budget for climate change (215 %) and resource use (142 %). For most

impacts, consumables represent a smaller portion of the overall impacts than the other categories, but still represent a large consumption of the environmental budgets (from 13 % for water consumption to 232 % for resource use).

Overall, the results demonstrate that the average Danish inhabitant overshoots all impact categories, apart from water consumption, highlighting the need to understand how these impacts can be minimized. It is finally important to note that the impact categories in this study are not weighted, meaning no hierarchy of importance is established among them. Consequently, the fact that resource use shows the highest exceedance rate does not necessarily indicate that it represents a greater concern than other categories, such as climate change, land occupation or marine eutrophication.

3.2. The environmental impact of 23 everyday activities

The impact scores of 23 everyday activities were calculated and related to the yearly environmental limits (Fig. 3). For each activity, the different options are ranked, from having the lowest environmental impact (1) to the highest (highest number). The results show that several activities alone exceed the yearly budget for functional biodiversity (omnivorous and vegetarian diets), climate change (many short-haul plane trips, gasoline and diesel car usage, omnivorous diet), land use (omnivorous diet) or resource use (e.g. EV usage, living in a new home, using a TV).

For mobility, activities related to the use of a car or flying represent a substantial consumption of environmental budgets, especially for climate change (linked to the use of fossil fuels) and resource use (use of metals), as shown in Fig. 4. Driving one year in a gasoline or diesel car is for example enough to consume the entire climate change budget for that year (129 % and 110 % for a standard gasoline and diesel car, respectively). Shifting to a small electric car brings it down to 50 % but increases the impact on resource use (from 67 and 69 % for a standard gasoline and diesel car, respectively, to 230 %). Using an electric bike instead of a gasoline car to commute to work decreases the climate budget consumption from 62 % to 5 %. Regarding flying, depending on

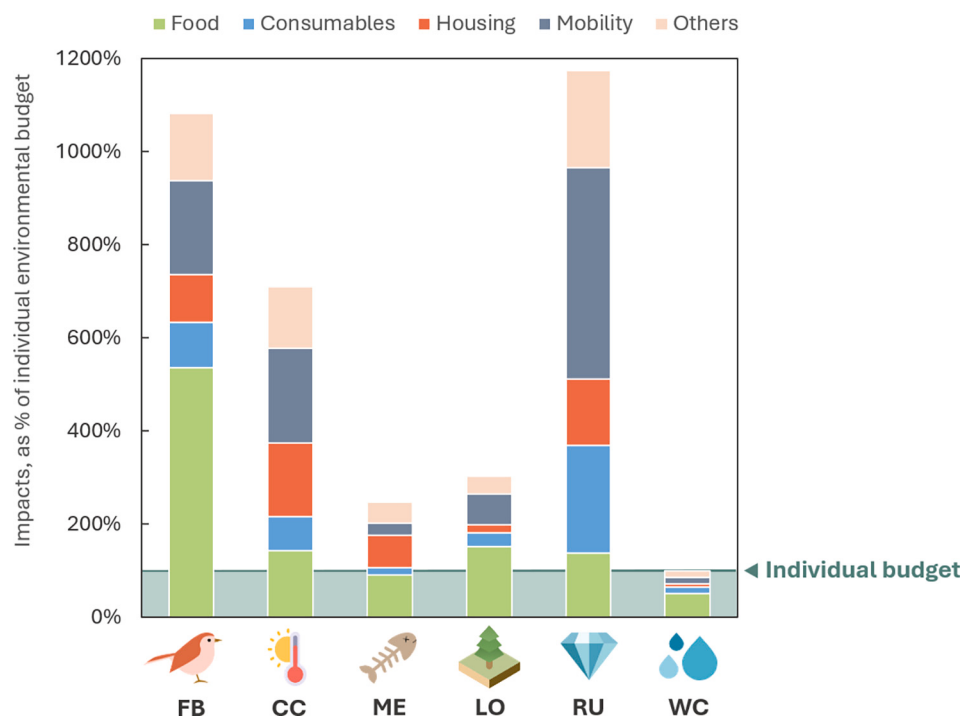


Fig. 2. Estimation of the current environmental footprint of an average Danish citizen, expressed as a share of the individual environmental budget (100 %). Order of the impact categories: FB = Functional biodiversity, CC = Climate change, ME = Marine eutrophication, LO = Land occupation, RU = Resource use, WC = Water consumption. All characterized and normalized impact scores are available in Supplementary Information 2.

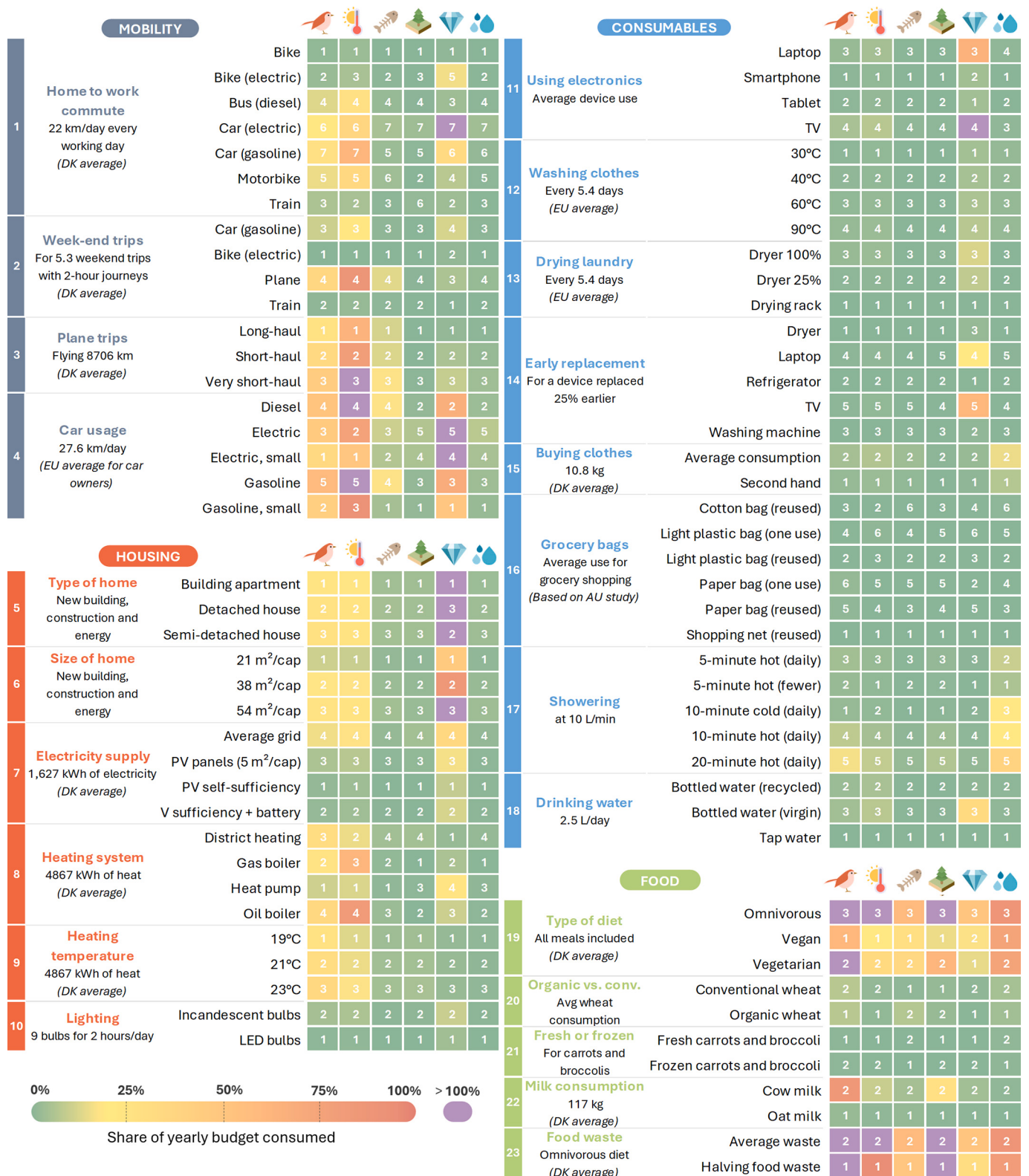


Fig. 3. Share of yearly (individual) environmental budget consumed by the activities. The options are listed in the lexicographical order. The heat map indicates the consumption of the yearly budget by the activity. For each impact category, the numbers in white (to be read vertically for each activity) indicate the rankings of the options within each activity. Lower numbers indicate lower environmental impacts (1 for the option with the lowest impacts). Order of the impact categories: Functional biodiversity, Climate change, Marine eutrophication, Land occupation, Resource use, Water consumption. All characterized and normalized impact scores are available in Supplementary Information 3.

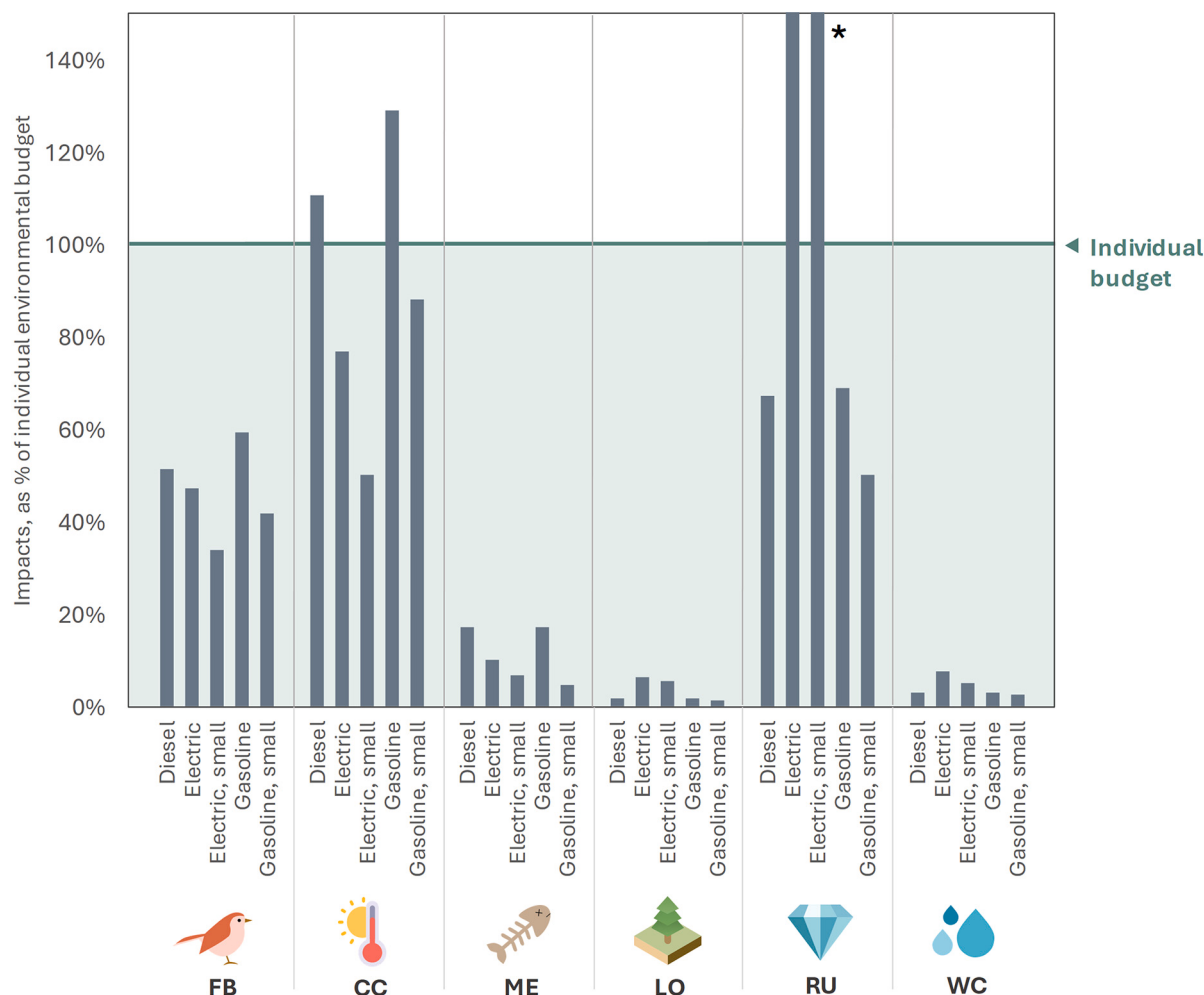


Fig. 4. Share of yearly (individual) environmental budget consumed by car usage (27.6 km/day). *For resource use, the graph bars for “Electric” and “Electric, small” cars (respectively at 382 % and 230 %) have been cut to bring more readability to the rest of the graph. More graphs and data as to the other activities can be found in Supplementary Information 3.

how the yearly average flying distance is done, between 64 % and 103 % of the climate budget is consumed.

For housing, the most consumed budgets are those of functional biodiversity, climate change and resource use. This is mainly due to the construction materials and heating systems (especially when fossil fuel-based). Living in an average new home today is enough to consume more than the entire allowed personal resource budget (between 115 % and 121 %). Heating up an average home with an oil boiler, alone, consumes 82 % of the climate change budget of each of its occupiers. Using a heat pump increases the resource budget consumption (from 10 % to 25 %) but decreases considerably the climate change budget occupation (from 82 % to 12 %). Installing PV panels, even when associated with battery storage, reduces impacts for all impact categories, compared to consuming electricity from the average Danish grid. For climate change for example, impacts are reduced from 17 % to 4 % of the yearly budget.

Taken separately, consumables do not represent a big share of the environmental budgets, except for resource use for large electronic objects. Owning a TV largely overshoots the resource budget (188 %), and having a laptop gets close to the threshold (65 %). The results also show that some individual actions, that are sometimes today considered as key to implementing to reduce environmental impacts, do not lead to considerable impact changes for any environmental category. That is for

example the case for the laundry washing temperature or the use of different bags for grocery shopping. Showering, as well as production and washing of clothes, represents a considerable consumption of water. Taking a 5-min shower instead of a 10-min one could bring the water budget consumption from 20 % to 10 %.

Eating an average omnivorous diet overshoots three boundaries by itself: functional biodiversity (384 %), climate change (101 %) and land occupation (149 %). Turning vegetarian or vegan substantially reduce environmental impacts to 33 % and 22 % for climate for example, respectively. An average cow milk consumption is enough to take up 84 % of the functional biodiversity budget and 28 % of the land occupation budget. Replacing it by oat milk has shrinks it considerably, to 2 % and 1 %, respectively.

4. Discussion

4.1. The necessity of lifestyle changes

The study draws attention to the fact that major shifts in our current lifestyles are necessary to bring the impact down to sustainable levels. By comparing the impact scores to a defined personal environmental budget, the results provide concrete examples of what this can mean for actions that are done by most consumers daily. Some lifestyle changes,

that may be perceived as important in the eyes of many consumers, actually lead to low magnitudes of impact changes. Such an example is the ban of plastic bags for grocery shopping or washing clothes at a lower temperature. Those actions should not be dissuaded, especially if they are easy to implement, as they can come with co-benefits in other aspects (e.g. saving money) and serve as a stepping-stone for more significant actions later. However, the results emphasize that these actions are far from sufficient, considering the substantial gap between today's environmental impacts in countries like Denmark, and the environmental budgets that must be respected to stay within a safe operating space. A major shift should, additionally and in priority, on actions that have considerable mitigation potentials for different environmental categories. For climate change, for example, the results show that they are linked to diets, car usage, air transportation, and housing (through construction and heating systems), which is aligned with what has already been put forward in the past literature (Ivanova et al., 2020; Wynes and Nicholas, 2017).

4.2. Awareness as a crucial yet insufficient step

The study does not consider the feasibility of implementing the lifestyle shifts. While information and awareness are important, even individuals who understand the environmental benefits of impactful actions may find it challenging to adopt them (Schill et al., 2019). People are embedded within economic and societal systems that often constrain their choices, sometimes leaving them dependent on certain products and services. Structural changes at the societal level are needed to facilitate sustainable lifestyle shifts. Consistent with findings from (Bjørn et al., 2018), both individual and systemic efforts are necessary to reduce environmental impacts below critical thresholds. For example, public transportation is only a viable alternative when supported by adequate societal infrastructure.

This study also emphasizes that, while major lifestyle changes are essential, they alone may not bring lifestyles within the defined environmental budgets. This highlights the need to consider, in addition to individual actions, other key leverage points. One such leverage point is in production systems, particularly through technological advancements. A limitation of this study is its reliance on current technological systems to calculate impacts, despite setting a 2050 target for impact reduction across categories. While behavioral changes are crucial, improvements in the eco-efficiency of products (e.g. through the underlying energy systems) can also contribute significantly to overall impact reduction (Bjørn et al., 2018; IPCC, 2022; Olhoff et al., 2024).

An additional strategy involves adopting simpler lifestyles and prioritizing essential needs. The analysis here focused on various options to fulfill common activities, based largely on the current activity levels of the average Danish citizen—a lifestyle that tends to be more resource-intensive than that of citizens in other countries. Beyond changing how activities are conducted, a more profound impact might come from reducing certain activities altogether. For instance, giving up on high-impact activities such as air travel could substantially lower environmental footprints (Table 1). Some of today's high-impact activities may not require alternative methods but rather drastic downscaling or complete elimination to stay within the defined environmental budgets.

4.3. Uncertainties and limitations

4.3.1. Representativeness of activities and options

The selection of specific activities, along with their associated options, only represent a fraction of all the activities performed by an average person living in Denmark. Due to data limitations, significant uncertainty, and the need to prioritize among countless potential activities, some activities, which can represent considerable impacts (e.g., such as having pets, as noted by Ivanova et al., 2020) were excluded.

Moreover, the activities included reflect a predominantly urban lifestyle and may include options that are not available to everyone (e.g.,

public transportation to commute to work) or because of other socio-economic factors (e.g., installing solar panels may be too expensive). Additionally, for most activities, the impact calculated corresponds to the national average, which may mask significant regional variations within the country. This also means that the results should be generalized to other countries with caution. First, the average yearly consumption of products may vary depending on population needs, which can depend on, e.g., geographical and cultural factors. Second, the same product or system may have different impacts depending on their location. That is especially the case for activities which impacts are driven by the consumption of electricity and/or heat, which mix is different across regions. Denmark has a large share of renewable electricity in its grid mix, which has lower impact compared to countries relying more on fossil-fuel for electricity generation.

The mitigation potential of switching from one option to another cannot in all cases be added across activities (Fig. 3), since some activities are included, or overlapping with others. For instance, installing PV panels will result in a lower impact from all electric devices and appliances of the consumption category. The mitigation potential of, e.g., reducing washing temperature from 60 to 30 °C will then be lower than the one originally calculated with the average Danish electricity mix. Future research could address this limitation by modeling not just individual actions in isolation, but also a set of lifestyle profiles as a whole. This would allow for a more comprehensive analysis of how the initial total lifestyle impacts can change because of multiple interventions.

4.3.2. Modeling of lifestyles and activities

GMRIO tables, utilized here for calculating consumption-based national footprints, rely on various assumptions that introduce uncertainties into the results (Giljum et al., 2016; Tukker et al., 2018; Wood et al., 2018). MRIO tables consist of national inventories of monetary flows between different product categories and regions. The reporting quality of such flows may vary from regions, while monetary data may not represent accurately physical data. Products within the same sector are assumed to have a uniform impact per unit of cost, despite considerable variation among them. For instance, all vegetables are grouped under a single category (“Vegetables, fruits, nuts”), while they present different climate impact intensities (in kg CO₂-eq/€) in reality.

For the modeling of the 23 activities, the processes used to model the different options of each activity are based on those included in the latest available version of Ecoinvent (Ecoinvent, 2022). However, those processes are often built from data coming from average processes or case studies of the available literature, some of them dating back from several years ago, or representing products and systems that are different to those used in Denmark. Modifying those processes to better represent the activities of this study was, in some cases, only partially possible. Moreover, the products assessed in the different activities may have different impacts in the future, linked to the evolution of the technologies that are involved in their life cycle. Parameters like supply chain efficiency, the share of renewable energy in electrical systems, and end-of-life treatment processes were based on historical data. These parameters may change significantly over time, which could notably affect the impact of certain activities, especially energy-intensive ones (e.g., transportation systems, industrial processes) or those involving long-lifetime products (e.g., buildings). As a robustness check, the life-cycle impact results for most options across the 23 activities were compared with previous scientific literature. This was done for climate change only, as it is the impact category most commonly included by existing literature. These comparisons, presented in Supplementary Information 1, confirm consistency with previous research.

4.3.3. Impact coverage and environmental budgets definition

In the covered impact categories, specific impact pathways are still missing to fully cover the impact of human activities. For instance, for functional biodiversity impacts, a simplified assessment of the impacts

has been carried out, as the influence of land occupation and GHGs are the only flows that are assessed. Many other causes impact biodiversity, such as the introduction of toxic chemicals in ecosystems linked to agriculture or industrial processes or other littered novel entities, like plastics (IPBES, 2019), which were not considered due to lack of data. Similarly, only a non-exhaustive set of minerals and metals are included for resource use impacts. The calculation of national footprints using GMRIO involves a smaller number of elementary flows, as many are either aggregated or not included in the environmental extension tables., which can lead to the overlooking of certain impacts (Beylot et al., 2019).

Regarding the calculation of environmental budgets, the PB framework is not the only one defining absolute thresholds to represent the carrying capacities of biophysical systems (Vea et al., 2020). Overall, the choice of the control variables, as well as the values used to define a carrying capacity, even for a defined impact category, can vary substantially in scientific literature. This can have important consequences as to the definition of the space inside which human activities can evolve, and therefore the guidance provided to consumers. Such an element is for example the strictness of the boundary chosen (e.g., 1.5 or 2 degrees of warming compared to the pre-industrial era). Some boundaries chosen, such as the PB for Resource use (based on the precautionary principle of the “factor 2 concept”), are currently largely based on expert judgment, requiring further research for refinement. Boundaries like those for marine eutrophication or water consumption are of a regional or local nature, while, in this study, the budget has been defined at a global level. A spatially differentiated boundary definition could account for the local carrying capacities and better represent the environmental conditions of specific regions (Bjørn et al., 2020b; Vea et al., 2024). Finally, the allocation of global budgets to individuals is done using an equal per capita allocation principle, which does not capture the common but differentiated responsibilities principle of the UNFCCC in the Paris Agreement (UNFCCC, 2015).

5. Conclusion

This study explores new ways of communicating the impacts of lifestyles and daily activities of consumers in the context of Planetary Boundaries. Unlike usually done in LCA, the results are expressed as a share of the yearly environmental budget to comprehend what individual actions can – or cannot – do to lower environmental impacts to a sufficiently low level, i.e. within the assigned share of the safe operating space. When applied to Denmark, the results show a large overshoot of the defined environmental budgets for most categories, i.e., functional biodiversity, climate change, marine eutrophication, land use and resource use. The LCAs of 23 common activities allow us to highlight those that need particular attention representing a substantial share of the yearly budgets consumption. Even with substantial lifestyle changes, reducing impacts to sustainable levels remains difficult with current technologies. This study highlights that to improve our chances of returning to a safe operating space, individual actions should be accompanied by the pursuit of lifestyles that prioritize the fulfilment of fundamental needs, along with the advancement of more efficient technologies.

However, the results must be interpreted considering their underlying assumptions. The environmental impact of most activities is tied to specific lifestyle characteristics, and the modeling was conducted using available data; where data was lacking, proxies were used, which may not fully reflect real-world systems. Additionally, not all environmental impacts were accounted for, and the definitions of certain environmental budgets are based on emerging research in this field. Further studies are needed to better understand the available environmental space, with particular attention to regional variations.

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CRedit authorship contribution statement

Teddy Serrano: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Samir Meramo:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Anders Bjørn:** Writing – review & editing, Supervision, Methodology. **Michael Hauschild:** Writing – review & editing, Supervision, Project administration, Methodology. **Sumesh Sukumara:** Writing – review & editing, Supervision. **Morten O.A. Sommer:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (based on GPT-4) only to improve readability and language in the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

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