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Published in:
Journal of Industrial Ecology

Link to article, DOI:
10.1111/jiec.13050

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Hjalsted, A. W., Laurent, A., Andersen, M. M., Olsen, K. H., Ryberg, M., & Hauschild, M. Z. (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. *Journal of Industrial Ecology*, *25*(1), 6-19. https://doi.org/10.1111/jiec.13050

DOI: 10.1111/jiec.13050

METHODS, TOOLS, AND SOFTWARE

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Sharing the safe operating space

Exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels

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Editor Managing Review: Mark Huijbregts

Abstract

In the light of increasing human pressures on the Earth system, the issue of sharing in the face of scarcity is more pressing than ever. The planetary boundary framework identifies and quantifies nine environmental boundaries and corresponding human pressures. However, when aiming to make the concept operational for decision support it is unclear how this safe operating space (SOS) within each of the planetary boundaries should be shared. This study proposes a two-step approach, where the operating space is first downscaled to the individual level using ethical allocation principles and next scaled up to a higher organizational level using different upscaling methods. For the downscaling, three allocation principles are demonstrated: egalitarian (equal per capita); grandfathering (proportional to current share of the total impacts); and ability to pay (proportional to economic activity). For upscaling from the individual level final consumption expenditure is used as a proxy for the priority that the individual gives to the product or sector. In an alternative upscaling approach, an additional upscaling factor is based on the eco-efficiency (ratio between turnover and environmental impact) of the product or sector. A demonstration of the method's application is given by applying the framework to two of the planetary boundaries, climate change and biogeochemical flows, with the Danish, Indian and global dairy sectors as cases. It is demonstrated how the choices of allocation and upscaling approaches influence the results differently in the three cases. The developed framework is shown to support an informed and transparent selection of allocation principles and upscaling methods and it provides a step toward standardization of distributing the SOS in absolute environmental sustainability assessments.

KEYWORDS

absolute sustainability assessment, allocation principles, ethics, industrial ecology, planetary boundaries, safe operating space

1 INTRODUCTION

As global population and living standards surge, increasing human pressures on the environment threaten the stability of the Earth system as we know it (IPCC, 2018). The urgency of a transition toward sustainable development was underlined in the recent IPCC report, the so-called SR1.5, calling for immediate, comprehensive, and ambitious measures to limit global warming to 1.5°C above pre-industrial levels (IPCC, 2018). Global warming, while often the main environmental impact addressed in environmental sustainability assessments, is just one consequence of human pressures on the Earth system. A more holistic view is provided by the planetary boundary (PB) framework, which quantifies planetary boundaries and corresponding human pressures on nine separate but interlinked environmental processes of perceived importance for the stability of the global climate regulation, for example, biosphere integrity or biogeochemical flows (Rockström et al., 2009). Steffen and co-workers assess that staying within these boundaries is needed in order to keep the planet in the Holocene state, which over the last 12,000-yr period has kept the Earth system climate remarkably stable, enabling human civilization to flourish. In contrast, violating one or more PBs increases the risk of pushing the planet out of its current state and potentially leads to abrupt and irreversible changes (Steffen et al., 2015).

Originally, the PBs were introduced to quantify and monitor the environmental state of the Earth, not intended to be operationalized at smaller scales than the planet. Yet, several attempts have been made at downscaling the PBs in order to apply them for policy or local decision-making. This includes Teah et al. (2016) who downscaled the PBs with the Gobi Desert as their regional focus; Häyhä, Lucas, van Vuuren, Cornell, and Hoff (2016) who proposed a framework to consistently translate the PBs addressing bio-physical, socio-economic, and ethical dimensions of the operationalization; Hossain, Dearing, Eigenbrod, and Johnson (2017) who use system dynamic modelling to operationalize the PBs; Dao, Peduzzi, and Friot (2018) who discuss distributional systems and operationalize the PBs from a consumption-based perspective with Switzerland as their case region; Heck, Hoff, Wirsenius, Meyer, and Kreft (2018) who use a dynamic vegetation model to assess land use options for staying within the PBs on global, regional, and national levels; McLaughlin (2018) who applies the PB framework at a regional level in the Pacific North West and argues that the PBs define environmental tipping points that must constrain policy outcomes; Ryberg et al. (2018a) who bring absolute sustainability into decision-making by operationalizing the planetary boundaries demonstrated on an industry case study; Cooper and Dearing (2019) who model future resource sharing on a regional level in India, operationalizing the concepts of PBs and a safe and just operating space; and Lucas, Wilting, Hof, and van Vuuren (2020) who analyze the distributional consequences of applying different allocation principles to operationalize the PBs for large economies (EU, United States, China, and India).

With public concerns about our pressures on the environment comes the interest of many companies and organizations to communicate about their sustainability performance, but if they are founded on any documentation at all, claims about sustainability are often based on assessments like life cycle assessment (LCA) which assesses the relative sustainability of products and services (i.e., the impact per unit of product or service provided). For claims of sustainability of products or companies in absolute terms, the question of when something is *sustainable* per se prevails. While a given product (or nation, or sector) may be *more* sustainable than another, these assessments fail to address whether the product is sustainable in the absolute sense of the term (Bjørn & Hauschild, 2015). What does it mean then, to be *absolute sustainable*? This article argues that a company, or in fact any agent, can only be absolute sustainable if they do not exceed their share of the safe operating space (SOS) which is defined by a quantitative set of environmental load limits, such as the PBs (Fang, Heijungs, Duan, & de Snoo, 2015). However, a string of normative choices arises: How should we define the type or size of space which is to be shared, making up the so-called SOS? Once agreed upon, how should the SOS be distributed and between which stakeholders? As noted by Ryberg et al. (2018a) and Gardiner (2010), such issues are interdisciplinary in their scope and call for further research, as stressed in recent literature (e.g., Clift et al., 2017; Häyhä et al., 2016; Heck et al., 2018; McLaughlin, 2018; Ryberg et al., 2018a).

This study seeks to address these questions by developing and testing a framework for determining the size of the SOS to be assigned to a given stakeholder. The framework consists of a two-step process of downscaling to the individual followed by upscaling to a higher level. A demonstration of the feasibility of the method is given by implementing the framework to two of the planetary boundaries (climate change and biogeochemical flows) for the dairy sectors in India, Denmark, and globally.

2 METHODS

2.1 Overall methodology

The focus of the methodology is on environmental sustainability, with other dimensions of sustainability (economic or social) being outside the scope of this work. Figure 1 shows the conceptual framework for absolute environmental sustainability assessment.

The frequently cited Brundtland Commission definition of sustainable development (Brundtland, 1987) is anthropocentric in the sense that it revolves around the fulfillment of human needs. In other words, sustainability is arguably not perceived as an intrinsic value in itself but rather a goal by virtue of its ability to fulfil the needs of humans. While other views have also been defended in the literature, such as the view that all

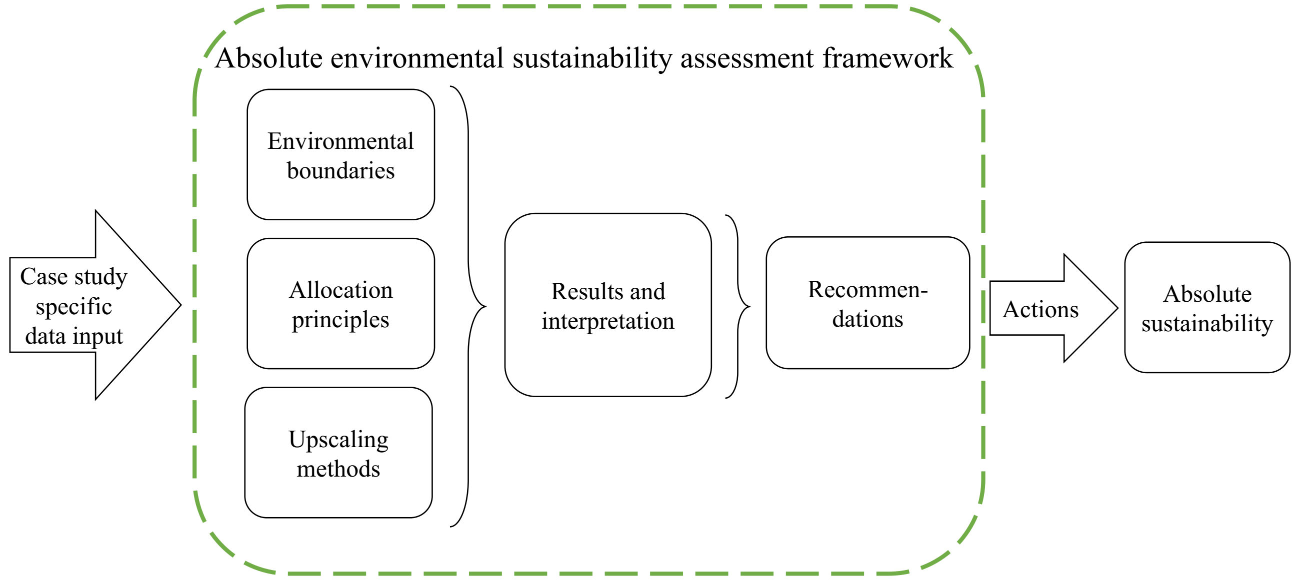

FIGURE 1 Conceptual model of the developed framework. The dashed green line encompasses the whole framework developed for absolute environmental sustainability assessment. The three boxes of "environmental boundaries," "allocation principles," and "upscaling methods" constitute the body of the framework, where the main choices are to be made. Once the parameters within each box have been chosen, the results from applying the framework on data from a specific case study should be interpreted in order to provide recommendations for the stakeholder or case study provider in question. Finally, implementing these recommendations should lead toward sustainability in absolute terms

fauna and flora have rights along with humans (Naess, 2005), the anthropocentric and more conventionally accepted motivation behind sustainable development is assumed in this study. This means that only individuals (and not institutions, products, or companies) have moral rights to be allocated a share of whatever is being shared, for example, the available SOS of a PB (Ryberg, Andersen, Owsianiak, & Hauschild, 2020). We acknowledge that this is an anthropocentric and instrumentalist perspective, which is morally and politically justifiable for the two PBs assessed in this study. However, it is not necessarily a universally acceptable assumption for all PBs, particularly for biosphere integrity, as nature including animals and plants are seen to have intrinsic value and hold moral rights to existence along with humans (Naess, 2005). The point in this study is not to exclude animals or ecosystems. The point is to exclude institutions, companies, products, etc. from having any share of the SOS independently of the human individuals they serve. Thus any other agent, be it a nation, a product, or a sector, can only obtain rights through the individual.

Therefore, it is deemed natural that the first step in allocating shares of the available SOS must always be to downscale it to the level of the individual. The main choices to be made are in the first three vertical boxes of Figure 1, namely choices of environmental boundaries to address, allocation principles, and upscaling methods to apply. The links between these three choice categories are shown in Figure 2 and the following sections elaborate separately on each of them. The process of translating from individual to a higher level is called upscaling. Levels to upscale to could include companies and organizations, households, products, sectors, or nations, as shown in Figure 2.

The share of the safe operating space (SoSOS) allocated to a given stakeholder s is denoted SoSOS_s and is calculated by combining an allocation principle with an upscaling method according to Equation (1):

$$\text{SoSOS}_s = \text{AP} \times \text{UM}, \tag{1}$$

where AP is the allocation factor representing the chosen allocation principle for downscaling to individual level, while UM is the upscaling factor representing the chosen upscaling method for upscaling. $\text{SoSOS}_{\text{ind}}$ denotes an individual's allocation of the SOS. Note that $\text{SoSOS}_s = \text{SoSOS}_{\text{ind}}$ if $\text{UM} = 1$, which it will be if the stakeholder is an individual. For other values of UM, SoSOS_s represents the SOS allocated to a given stakeholder at a higher than individual level.

The absolute sustainability ratio (ASR) for the stakeholder is then calculated as shown in Equation (2):

$$\text{ASR} = \frac{\text{Impact}_s}{\text{SoSOS}_s} = \frac{\text{Impact}_s}{\text{AP} \times \text{UM}}, \tag{2}$$

where Impact_s is the impact of the stakeholder in question.

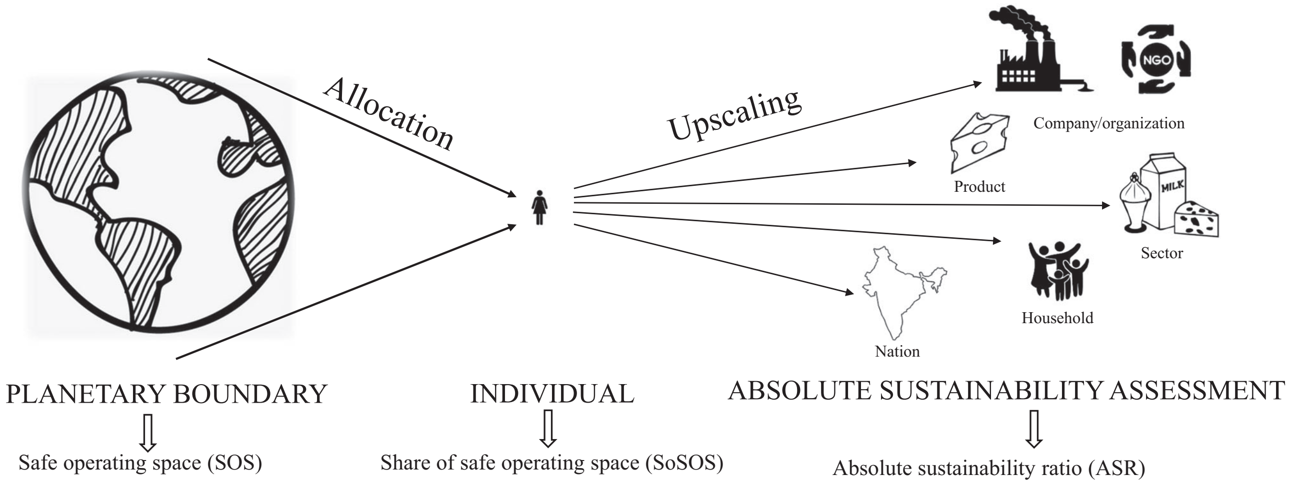

FIGURE 2 Overview of the two-step process proposed consisting of allocation followed by upscaling, progressing through three stages. The first stage is selecting one or more quantified planetary boundaries, from which the safe operating space (SOS) is calculated, depending on corresponding current human pressures. The second stage is dividing the SOS between individuals, using allocation principles from the philosophical literature, resulting in an individual share of the safe operating space (SoSOS). The third stage is upscaling from the individual to a higher level such as a company, organization, product, service, sector, household or nation. The assessment results in the absolute sustainability ratio (ASR), which is the ratio between the actual impact of the stakeholder in question and the assigned SoSOS. If the ASR > 1, the stakeholder can be deemed not absolute sustainable

TABLE 1 Overview of planetary boundaries used in this study. Uncertainty ranges are shown after the PB value in brackets. Building on Table 1 in (Steffen et al., 2015) with the last two columns added. The control variable for P is the P flow from fertilizers to erodible soils (fixation) and the control variable for N is the industrial and intentional biological fixation of N

Earth system process	Control variable	Unit	PB	Current	Pre-industrial	SOS
Climate change	Radiative forcing	$W\ m^{-2}$	+1.0 (+1.0–+1.5)	+2.3	0	+1
Biogeochemical flows (N)	N fixation	$Tg\ N\ yr^{-1}$	62 (62–82)	150	0	62
Biogeochemical flows (P)	P fixation (agriculture)	$Tg\ P\ yr^{-1}$	6.2 (6.2–11.2)	14	0	6.2

2.2 | Using the planetary boundaries to define the safe operating space

Allocating "rights to impact" the Earth starts with defining the SOS. In line with Ryberg, Owsianiak, Richardson, and Hauschild, (2018b), this study defines the SOS as the difference between the PBs and the pre-industrial value (i.e., the natural background level). The PBs of both biogeochemical flows (expressed as phosphorus [P] and nitrogen [N] flows) and climate change have been transgressed (see Table 1), and it is thus critical to reduce impacts to a level within the PBs. Here, the underlying assumption is that reducing the human impact on these processes to within the SOS will, in the long term, bring the pressure below the PBs. Climate change was chosen in this study because of its dominant position in the current political debate on sustainability and because it is interlinked with multiple other PBs (e.g., ocean acidification via increased oceanic carbon uptake and biodiversity loss due to lost habitats) (Mace et al., 2014; Ryberg et al., 2016). Biogeochemical flows were also chosen because of the close link to agricultural industry, which is essential for feeding a growing population.

Each of the PBs are associated with one or more measurable control variables. The PB for climate change is expressed by two control variables. One is atmospheric CO_2 concentration (ppm CO_2) which only includes CO_2 and its precursors but not other greenhouse gases; the other control variable is the change in energy balance (i.e., radiative forcing; $W\ m^{-2}$) at the top of the atmosphere, which covers all substances that affect radiative forcing. Because $W\ m^{-2}$ is the more comprehensive of the two that is the one applied in this study. The control variable for N is the industrial and intentional fixation of N. The control variable for P at regional scale is the application of P fertilizers on erodible soils, while at global scale, it is the P flow from freshwater systems into the ocean (Steffen et al., 2015). In line with life cycle impact assessment methodology, this study assesses N for marine eutrophication impacts and P for freshwater eutrophication impacts, since the two nutrients are the limiting factors in the two systems, respectively (Goedkoop et al., 2013).

For operationalization of the method, the PBs must be expressed as annual budgets which can be shared among individuals. Thus, each PB metric must be translated into a corresponding annual mass flow rate. The PBs for biogeochemical flows are already expressed as annual mass flow rates of N and P. For climate change, the metric of radiative forcing was translated into corresponding boundaries expressed as CO_2-eq. This was based

on the normalization references derived by Bjørn and Hauschild (2015) which express that a maximum of 3.6 Gt CO_2-eq can be emitted per year without exceeding the climate carrying capacity. The normalization reference for climate change in terms of radiative forcing is calculated to be 0.522 ton CO_2 per person per year (Bjørn & Hauschild, 2015). Please note that throughout this article "tons" refer to metric tons. Characterization factors (CFs) developed by Ryberg et al. (2018b) were applied to translate emissions of N and P to the environment into metrics of the PBs ($2.44 \cdot 10^{-8}$ Tg N yr^{-1} kg^{-1} yr and $3.68 \cdot 10^{-8}$ Tg P yr^{-1} kg^{-1} yr for N and P, respectively). The CFs are based on steady-state inverse modeling to convert emissions of N and P to the aquatic environment into equivalents of anthropogenic fixation of N and application of P to soil as fertilizer (Ryberg et al., 2018b). Global warming potentials were used to translate emissions of GHGs into CO_2-eq (Myhre et al., 2013). Evaluation of the validity of the environmental boundaries and models used is outside the scope of this study. Indeed, it is very likely that both boundaries and models are subject to refinement and improvements over time as science progresses and the method outlined in this paper is designed to be flexible and allow for adaptation and use of new and updated models and boundaries.

2.3 | Sharing the safe operating space

The process of allocating a specific share of the SOS is normative in the sense that it prescribes how resources should be divided (Ryberg et al., 2018a). How to share an environmental budget is widely discussed in the literature, for example, by Caney (2017), Grasso (2007), Raworth (2013), and van den Berg et al. (2019).

In this study the term *allocation principle* is used to mean a principle by which decisions about how to allocate a given resource between individuals can be made. In this study, an allocation principle together with an upscaling method constitutes a sharing principle. In the literature *allocation principle* is used interchangeably with the terms sharing principle (Ryberg et al., 2018a), equity principle (Häyhä et al., 2016), and distributive principle in the field of political philosophy (Lippert-Rasmussen & Holtug, 2007). An allocation principle thus forms the normative foundation of a distribution of something to be shared (in our case, the SOS). As such, it is essential to spend some time understanding and selecting them. Distributive justice concerns the just distribution of goods among agents. There are multiple dimensions of distributive justice, at least five of which have been deemed essential to this work. These include the pattern of distribution (e.g., equality), the currency (e.g., welfare, money, CO_2 emissions), the target (between whom is the distribution made? e.g., individuals, animals, companies, nations), the scope (e.g., Europe, the World), and the time span (e.g., infinite, one generation) (Lippert-Rasmussen, 2015).

Changing the variables in one or more of the mentioned dimensions results in different allocation principles. It is not the aim of this article to lay out every possible allocation principle—indeed, some combinations of variables would probably be advocated by no one–but rather to identify and underpin a handful of key allocation principles frequently used in the literature which can facilitate the downscaling of the two PBs in question.

For each of the suggested allocation principles (presented in Table 2) four of the five dimensions mentioned above are kept fixed for better comparability, namely: (i) the *currency*: the unit of the PB in question (e.g., kg N yr^{-1} for nitrogen), (ii) the *target*: human individuals (secondly, industry sector), (iii) the *scope*: global, and (iv) the *time span*: following the time span of the modeling for the specific PB(s). The remaining dimension, namely the *pattern of distribution*, is left to vary. The final distribution is quite sensitive to the pattern of distribution.

2.4 | Development of allocation principles

In contemporary political philosophy and theory, we find four dominating principles of distributive justice. These are (1) utilitarianism (Crisp, 2002), (2) egalitarianism (including luck egalitarianism (Lippert-Rasmussen, 2015), and Rawlsianism (Daniels, 1989), (3) prioritarianism (Holtug, 2017), and (4) sufficientarianism (Hirose, 2015). All principles come in different interpretations. Moreover, there are many questions of interpretation when applying these principles to the more specific matter of distributing the right to impact the environment. *Utilitarianism* holds that we should (always) maximize the sum of welfare. We leave it out here because it implies that we should distribute environmental impact rights such that we maximize the sum of welfare, yet it is impossible to find non-controversial economic modeling to support it (including all assumptions of what welfare is and how sensitive it is to wealth, rights, and so on). *Egalitarianism* holds that some agents (targets), typically individuals, should be equal in terms of something (currency), for example, welfare or resources (Lippert-Rasmussen & Holtug, 2007). We interpret egalitarianism here to be the equal per capita principle where every individual in the world has an equal right to impact the environment. *Prioritarianism* holds that a benefit has greater moral value the worse the situation of the individual to whom it accrues. We therefore take it to be the theoretical base for the ability to pay allocation principle which we apply and discuss in Section 3.4.3. Prioritarianism could also be given an interpretation to support the widespread view that countries which have suffered historical injustices should be compensated in terms of a right to impact the environment relatively more than other countries (Neymeyer, 2000). In order to allocate based on this principle, reliable impact data on historical impacts is essential. While such data is obtainable for some PBs, such as climate change and ocean acidification (which both have CO_2 emissions as main contributor), it is difficult or impossible to obtain for others, such as land-system change or biosphere integrity. Therefore, we leave this interpretation out of this study, although it may well be introduced to the framework when and if reliable data becomes available across the PBs. *Sufficientarianism* holds

TABLE 2 Allocation principles and upscaling methods used in this study. The allocation principles scale to the individual level, while the upscaling methods upscale to higher than individual levels. The equations for calculating the share of the safe operating space (SoSOS) on individual and sector levels are shown. Unless the final target of the assessment is an individual, a combination of one allocation principle and one upscaling method must be chosen. Since three allocation principles and two upscaling methods are suggested here, a total of six combinations are possible—providing six different ways of sharing the SOS

Allocation principle	Equation for individual allocation	Explanation
Equal per capita	$SoSOS_{ind}(t) = \frac{SOS_{PB}}{Pop_{World}(t)}$ (3)	Where $SoSOS_{ind}(t)$ is the share of the safe operating space allocated for an individual given time (t), SOS_{PB} is the global safe operating space for the chosen PB, and $Pop_{World}(t)$ is the world population at a given point of time (t) (this would typically be a year, such as 2019)
Grandfathering	$SoSOS_{ind}(t) = \frac{SOS_{PB}}{Impact_{PB}(t)} \times \frac{Impact_{PB,local}(t)}{Pop_{local}(t)}$ (4)	Where $Impact_{PB,local}(t)$ is the total consumption-based impact in a given country/region for a given PB and $Pop_{local}(t)$ is the population of the given country/region at a given time (t). $Impact_{PB}(t)$ is the global pressure on the chosen PB at time (t), so $\frac{SOS_{PB}}{Impact_{PB}(t)}$ is the global factor which must be reduced to stay within the SOS of the selected PB (all countries/regions reduce to an equal fraction of original impact)
Ability to pay	$SoSOS_{ind}(t) = \frac{SOS_{PB}}{Pop_{World}(t)} \times \frac{(GDP/cap)_{World}(t)}{(GDP/cap)_{local}(t)} \cdot \alpha$ (5)	Where $GDP/cap_{World}(t)$ is the average global gross domestic product (GDP) per capita and $GDP/cap_{local}(t)$ is the average GDP per capita for the given country/region. α is a scaling factor that avoids the exceedance of the total available SOS (see Equation S1 in the Supporting Information)[a]
Upscaling method	**Equation for upscaling**	**Explanation**
Final consumption expenditure	$SoSOS_s(t) = SoSOS_{ind}(t) \cdot Pop_{local}(t) \cdot FCE_{local,k}(t)$ (6)	Where $SoSOS_s$ is a chosen allocation principle allocating to a given stakeholder at a higher than individual level at a given time (t), $FCE_{local,k}(t)$ is the local final consumption expenditure (FCE) in % for the type of product or service or activity/sector k in question
Green incentive	$SoSOS_s(t) = SoSOS_{ind}(t) \times Pop_{local}(t) \times FCE_{local,k}(t) \times \frac{Turnover_{local,k}(t)}{Impact_{PB,\ local,k}(t)} \times \frac{Impact_{PB,\ global,k}(t)}{Turnover_{PB,global,k}(t)} \cdot \beta_k$ (7)	Where $Turnover_{local,k}(t)$ yearly turnover of the sector or activity k at year (t) in the given local region (e.g., country), and $Impact_{PB,\ local,k}(t)$ is the impact of the sector k for the selected PB in that region. $Turnover_{global,k}(t)$ is the yearly global turnover of the sector/activity k at year (t), and $Impact_{PB,\ global,k}(t)$ is the total, consumption-based global impact from sector k for the selected PB. Multiplying by the inverse ratio of global impact:turnover for the sector/activity in question allows for a weighting of the stakeholder compared to the global average turnover:impact ratio so that countries with lower than average turnover:impact ratios receive a <1 weighting while countries with higher than average impact:turnover ratios receive a >1 weighting, thus favoring and incentivizing high turnover:impact ratios. β_k is a scaling factor for k that avoids the exceedance of the total available SOS (see Equation (S2) in the Supporting Information)[a]

[a]For the ability to pay allocation principle and the green incentive upscaling method, scaling factors α and β have been included in the equations to ensure that the sum of all allocated shares of the SOS would not exceed the SOS, which in these two cases, it technically could. The factor α, which is independent from the considered PB, was calculated to be 0.243 for 2017. The factor β is dependent on the stakeholder in focus for the upscaling and needs to be calculated on a case-by-case basis. The full equations for and derivation of these factors are shown in the Supporting Information.

that what matters is that everyone has "enough." However, deciding what is "enough" is complicated and undetermined in the literature (Hirose, 2015) and sufficientarianism is therefore unfeasible as an allocation principle in this study. Further, it is likely that to allocate "enough" to each individual on Earth would not be possible within the SOS's for climate change and biogeochemical flows, and thus the allocation would, in a common interpretation, fall back on equal per capita (Caney, 2012).

Finally, in contemporary political philosophy and theory we find various non-fixed principles of distributive justice, typically historical accounts of justice (Nozick, 1974). Though such accounts typically are much more detailed than merely holding that one has the right to what one historically has acquired, we include in our set up the principle of grandfathering, holding that distribution of environmental impact rights should be based on the actual status quo distribution of environmental impact. This very simple view probably has no theoretical justification, but we include it because it is widespread in the environmental literature and regulation (Caney, 2009; Houghton, 1995). The selected principles have been translated into equations that allocate the SOS according to the principle as presented in Table 2.

As shown in Figure 2, the allocation to individual level is followed by upscaling to the scale of the actor that is considered in the sustainability assessment. This means that there must be some sort of proportionality between a non-individual actor and the individuals affiliated with it, such as the inhabitants of a country or the customers of a company. To represent this proportionality, this study proposes two upscaling methods which are also introduced in Table 2.

Equations (3)–(7) allocate based on individuals (consumers) in one country or region. If the stakeholder in question serves consumers in multiple countries, the final allocation of the SOS for the stakeholder is based on the distribution of their customers across the countries. If, for example, Company A's customers are equally distributed across two countries, Equations (3)–(7) are used to allocate a SoSOS for consumers in each country and 50% of the SoSOS calculated for each country is finally allocated to Company A.

2.4.1 | Equal per capita allocation

The equal per capita allocation principle is quite simple and frequently used and discussed in the literature (Grasso, 2007; Rao, 2014; Sandin, Peters, & Svanström, 2015). It is also known as the egalitarian principle (Greaker et al., 2013). The underlying moral implication is that any individual has the same right to the SOS. Looking into the time-span dimension, however, reveals that the principle can be interpreted in different ways. Here we first divide the time span of the modeling behind the relevant PB into years and secondly, we divide each year by the population in that year. But one might instead divide the entire time span directly with the number of individuals expected to exist in that time span. This principle, while easy to operationalize, has been criticized for being much too simplistic and insufficient as an allocation principle (Caney, 2009; Grasso, 2007). It does not take into account that a "just" distribution is not necessarily an even one—if one person needs to consume more calories daily than another, for example, due to sex or activity requirements of their daily life, it may not be fair to allocate the same amount of calories to both. Further, the equal per capita principle only takes into account individuals living at the time of the allocation, and arguably some of the SOS has already been allocated to and used by individuals who are no longer present—an issue not accounted for by the equal per capita principle.

2.4.2 | Grandfathering allocation

The grandfathering allocation principle is based on the status quo regarding emissions and impacts. In other words, future emission rights are inherited based on what was the emission or impact distribution at a certain point in time (Grasso (2007), Sandin et al. (2015)). The grandfathering principle is often used in policy-making due to its pragmatism (Caney, 2012).

A characteristic of the grandfathering allocation principle is that it favors already existing companies and large economies, thus making it difficult for new companies or smaller economies to enter or expand on the market as the SOS is already claimed by the existing companies. Furthermore, the principle does not differentiate between companies based on any moral criteria, such as their contribution to sustainable development or attention to human rights. Thus, a coal mining company would, ceteris paribus, be assigned a higher share of the SOS than a wind power company given that the wind power company starts out with lower emissions, and this is evidently problematic in a sustainability context. It is also worth noting that the grandfathering allocation principle is sensitive to the reference year chosen for the status quo situation.

2.4.3 | Ability to pay allocation

The ability to pay principle proposed in this study is based on a country's capacity to pay based on its GDP per capita. The ability to pay principle can most easily be aggregated and expressed as prioritarianism, the distributive principle in political philosophy aiming to prioritize those who are worst off (Lippert-Rasmussen & Holtug, 2007). The ability to pay principle does this by allocating a larger share of the SOS to low

GDP countries than to high GDP countries, thus favoring poorer and less developed nations. The allocation is inversely proportional to national GDP per capita in relation to global GDP per capita, as shown in Equation (5). An implication of this allocation principle is that, while countries with high GDP often have high environmental footprints, they get a lower share of the SOS and will thus be more challenged to reduce their impacts to stay within their share. As with all allocation principles the ability to pay principle is sensitive to the choice of reference year.

2.5 | Development of upscaling methods

2.5.1 | Final consumption expenditure for upscaling

Given that the first step in the two-step framework is downscaling to the individual level, the share of non-human entities must be allocated in proportion to how many individuals they relevantly affect—be it, for example, population in a nation/region or customers of a company or sector. This article suggests an approach based on final consumption expenditure (FCE), namely the spending patterns of the individual, in line with Ryberg et al. (2018a). It is worth noticing that the FCE upscaling method resembles grandfathering to some degree in the sense that it bases its allocation on the status quo in terms of consumer preference for existing companies and products. In other words, the demand pattern upon which it is based is the present and not a sustainable demand pattern, and it inherently assumes an even distribution of environmental impacts per cost over the range of consumed products.

2.5.2 | Green incentive-based upscaling

The green incentive (GI) upscaling method builds on the FCE method, multiplying it with a factor favoring "green" companies that have a high ratio between turnover and environmental impacts. The scaling factor is normalized with an average turnover:impact ratio for the given sector on a global (or regional, if more relevant) level. In practice this means that two clothing companies with the same turnover could have different shares of the SOS assigned to them based on their emissions: the one with lower emissions would be assigned the larger share, given its higher turnover:impact ratio. This upscaling method is designed to provide an incentive for companies to continue striving to maintain or increase turnover, while also reducing impacts on the PBs. This upscaling method motivates an improvement of the eco-efficiency of the company (Bjørn & Hauschild, 2015). A limitation of this method is its data demand—to be accurate and up to date, it requires information about turnovers and impacts that change continuously, and the global normalization factors would also need to be updated regularly.

2.6 | Assessment of absolute sustainability

Based on the given data and the chosen thresholds, allocation principles, and scaling methods, the allocation tool helps answering the question of whether the stakeholder is absolute sustainable or not. The result is given as a ratio indicating how close to absolute sustainable the stakeholder is: whether or not a stakeholder can call itself absolute sustainable within a PB is quite simply a question of whether the company uses more or less than its allocated share of the identified SOS. This can be assessed based on sustainability ratios calculated as shown in Equations (8) and (9),

$$\frac{\text{Actual Impact}}{\text{Allocated SoSOS}} \leq 1 : \text{Absolute sustainable,} \tag{8}$$

$$\frac{\text{Actual Impact}}{\text{Allocated SoSOS}} > 1 : \text{Not absolute sustainable,} \tag{9}$$

where Actual Impact is the impact caused by the actor, expressed in the metric of the SOS, and allocated SoSOS is the SoSOS assigned to the company. This method of assessment is also proposed elsewhere in the literature (Fang et al., 2015; Ryberg et al., 2018a)).

The ratio between the actual impact and the allocated SoSOS is thus an estimation of how sustainable a stakeholder is, in absolute terms. Equations (8) and (9) are used to assess absolute sustainability independently of the allocation principle and scaling method. As the actual use of the SOS (the impact of the company) stays the same (at least for the reference year of choice), the interesting variable in this equation is the allocated SoSOS, which depends on the allocation principle and the scaling method, as will be illustrated in the following.

2.7 | A case study on the dairy sector

The global demand for food is expected to double by 2050 (FAO, 2019). In 2007, 4% of global GHG emissions (ca. 2 billion tons CO_2-eq) could be attributed to the dairy sector, which was estimated at a market value of 330 billion USD in 2014 (FAO, 2008, 2019). FAO also estimates that more than 80% of the World's population consume dairy products regularly (FAO, 2019).

For this study, the global dairy sector as well as the dairy sectors of India and Denmark have been used as case studies for demonstration of the developed framework. For simplicity, the case study deals with consumers globally and within a single country, but the framework is easily applied to cases with consumers in multiple countries as described in Section 2.4. The environmental impact data in the case study (for emissions of N, P, CO_2, CH_4, and N_2O) is sourced from the environmentally extended multi-region input–output (MRIO) model Exiobase version 3.7, with data for the year 2011 (Wood et al., 2015). The data used is consumption based and includes related emissions from upstream processes occurring outside the case study region. When converting greenhouse gas emissions into CO_2-eq the global warming potentials (GWP_{100}) from the IPCC Assessment Report 5 were used: $GWP_{100}(CH_4) = 28$ g CO_2-eq/g and $GWP_{100}(N_2O) = 265$ g CO_2-eq/g (Adger et al., 2007). Other GHGs were deemed to have negligible impact and thus omitted from the case study. An industry by industry approach was used, and data for dairy products and raw milk production for India, Denmark, and the World were extracted. The case is intended to serve as a demonstration of the method, and the results should not be interpreted as determination of the absolute sustainability status of the analyzed dairy sector(s). For transparency and full reproducibility all data, sources, and calculations are provided in Tables S1–S9 in the Supporting Information.

3 | RESULTS AND DISCUSSION

3.1 | Case study results

The ASRs shown in Figure 3 are calculated using the described two-step process of first allocating to the individual level—with each of the three allocation principles—and next upscaling from the individual to the company level using two approaches: the FCE upscaling method and the GI upscaling method. The results for the allocation of SoSOS to the level of individuals is not shown here but can be found in Tables S7–S9 in the Supporting Information. The horizontal dashed line in Figure 3 marks the level where the ASR = 1, meaning that the actual impact of the sector exactly matches its allocated SoSOS with the applied combination of allocation principle and upscaling method. Any value below this line indicates absolute sustainability of the sector in the sense that the sector has used less than its allocated SoSOS, while the bars that rise above the line indicate that the sector is not absolute sustainable.

For the Indian dairy sector (Figure 3a), the biogeochemical flows indicate some absolute sustainability for the ability to pay allocation principle, with the sustainability amplified by the GI upscaling method. This is expected as it reflects India's relatively lower GDP per capita compared to the global average, giving high allocated SoSOS to the Indian individual under this allocation principle. For the Danish dairy sector (Figure 3b), as well as the global dairy sector (Figure 3c), none of the calculated ASRs indicate absolute sustainability. Across all allocation principles and upscaling methods, the ASRs for India are much lower than those for Denmark, while the global ASRs lie in-between the Danish and the Indian ASRs.

The overall trend for the upscaling methods for Denmark is that the GI method systematically results in higher ASRs (less sustainable) than the FCE upscaling method, whereas the opposite is true for India. This is an implication of the turnover:impact ratio being larger for India than for Denmark. On a global level, the two upscaling methods (FCE and GI) yield the same results because the GI factor is 1 because the global sector is compared to itself in terms of the turnover:impact ratio. In practical application of the methodology for decision support, a sensitivity and uncertainty analysis addressing parameter uncertainties and methodological choices would be necessary to aid the evaluation and interpretation of the results. It is not performed here since the case study only serves as an illustrative demonstration, but it should be performed in applications of the framework to support analysis of absolute sustainability of real systems.

3.2 | Ethical and policy considerations

Figure 3 demonstrates that the expressions presented for the allocation principles and upscaling methods work as intended. The ability to pay principle yields more of the SOS to India than to Denmark, and more eco-efficient sectors are allocated larger shares of the SOS than less eco-efficient sectors. This can seem contradictory since they need less of the SOS to operate, given their lower than average impact compared to turnover. However, this way of allocating can create an incentive for actors (e.g., companies if applied to these) to increase their rate of eco-efficiency improvement, which in turn will decrease the global impact of companies. In principle, any excess shares of the SOS could be traded to further benefit the company (trading shares falls outside the scope of this article, but could be interesting for future research).

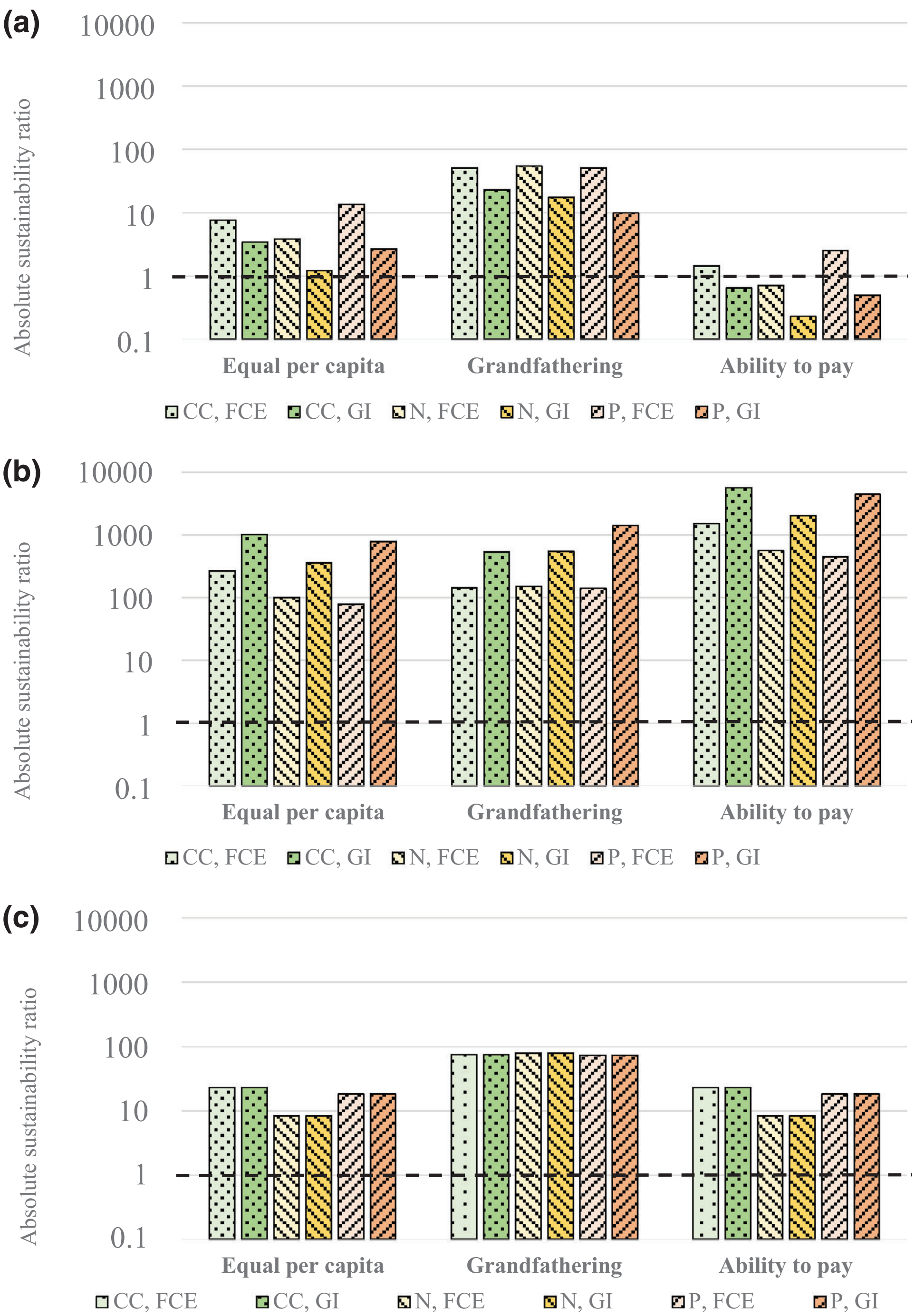

FIGURE 3 ASRs for the (a) Indian, (b) Danish, and (c) global dairy sector for climate change and biogeochemical flows. Note that the *y*-axis is logarithmic. Bars lower than the dashed line at 1.0 indicates absolute environmental sustainability, while bars higher than the dashed line indicate the opposite. CC denotes the climate change PB, FCE denotes the final consumption expenditure upscaling method while GI denotes the green incentive upscaling method. P stands for phosphorus and N stands for nitrogen, both within the PB of biogeochemical flows. The underlying data used is presented in Tables S4–S6 in the Supporting Information

In this study we chose to normalize the country-specific dairy sector's turnover:impact ratios with the global average turnover:impact ratio for the dairy sector. However, alternative normalization factors with continental, regional, or local scales could also be used instead of comparing to the global market. This could be based on moral and political considerations to reflect the common but differentiated responsibilities principle (the CBDR principle), as this principle is fundamental to the UNFCCC climate negotiations (Winkler, Letete, & Marquard, 2013). One could compare to, for example, the European market, or the Asian market, or another market of interest.

Arguably, a limitation of using FCE as a proxy for consumer preference is that products which are non-essential to basic human needs may be given disproportional preference in regions with high prosperity, thus apparently justifying their existence over more basic needs-fulfilling products such as food and water. A solution to this could be to model FCE in a world where all consumption is already sustainable. An example of this could be the "*steady state economy*" explored by (Fanning & O'Neill, 2016), maintained within shares of planetary boundaries. The approach taken in this study leaves out any question about the importance or moral status of a product in itself—however, that is a discussion for another paper. Here the importance and moral worth of all products and services are regulated only by demand. Another assumption made in this study is that environmental impact is evenly distributed across sectors, although some sectors have much larger impacts in certain PBs than others, and some PBs are largely attributed to one sector, such as biogeochemical flows to the agricultural sector. It thus seems unfair to let other sectors pay for these N and P emissions. Further research could go into developing differentiated sector-based reduction goals, as proposed for CO_2 emissions in Krabbe et al. (2015). The flexibility of the present framework would make it simple to update accordingly.

Another interesting question regarding the FCE upscaling method is that of its applicability to intermediate sectors such as the power sector. As the data used in this case study was end-user data, some adjustments would have to be made in order to apply it to intermediate sectors. While we consider it outside the scope of this paper, it is clearly a topic for further research.

3.3 | Applicability of the developed framework

The framework is developed to be robust and transparent with its two-step process of first allocating a share of the global SOS to an individual, based on a deliberately chosen allocation principle, and, if the case demands, secondly upscaling to another level. The framework is flexible in the sense that any quantified planetary boundary or other measure of environmental carrying capacity may be used to determine the global SOS, and using the individual as an anchoring point makes the upscaling to any larger entity transparent, following a set of preset considerations.

As indicated in the conceptual framework in Figure 1, the case study results from the basis of the next step, namely concrete recommendations for action toward absolute sustainability. To this end, the ASRs illustrated in Figure 3 can focus a sector or company's efforts, where the size of the ratio could be a guideline. If attributing equal weight to each of the applied thresholds, the threshold with the largest ASR could be the one to tackle first or spend the most resources on. Another way could be to prioritize any thresholds which do not have ASRs at or below 1. One example of how to base improvement recommendations for a stakeholder on the results from using the developed framework is given in Table 3 to illustrate applicability. The recommendations should be seen as non-exhaustive examples that serve the purpose of showcasing how recommendations could be communicated. In Table 3, they are given priority based on a combined qualitative evaluation of their perceived feasibility and potential impact.

The inclusion of multiple allocation principles and upscaling methods is to provide a nuanced view on the issue of the stakeholder's absolute sustainability status and to demonstrate the influence of different perspectives. A potential drawback could be that when presented with the varying ASRs, it could be tempting for the stakeholder to pick and focus on the combination which yielded the ASRs closest to or below 1. This calls for transparency in reporting the assessment and the reasoning behind the underlying choices and ideally showing the results for several allocation and upscaling principles.

It is arguably beneficial to include all affected PBs in the absolute sustainability assessment in order to avoid problem shifting between the PBs, and a strength of the developed framework is its versatility in terms of potential expansion to other PBs as well as other allocation principles and upscaling methods. It can operate with any quantitative boundary or threshold of interest, such as the 1.5°C or the 2°C temperature increase limits in the Paris Agreement or specific, quantifiable targets within the United Nations' Sustainable Development Goals (SDG) framework. The underlying assessment framework remains the same (as introduced in Figure 1). For those PBs that have quantified boundaries, the same methodology can be applied given that impact data from the stakeholder in question is available. Data availability likely poses the strongest issue when expanding the framework to other PBs, since not all stakeholders, be it individuals, companies, or sectors, have access to reliable data about their own impact on the PBs. Three of the PBs at present either do not have indicators or the indicators have not been quantified (biosphere integrity representing

TABLE 3 Example of what a prioritized list of recommendations could look like based on the results in Figure 3

Recommendation	Main PB affected[a]	Feasibility	Impact	Priority
Consider alternative milk products (oat, rice, etc.)	CC	Difficult	High	High
Increase eco-efficiency by using renewable energy	CC	Easy	High	High
Increase reuse of manure for fertilizer	BGF	Easy	Medium	High
Increase eco-efficiency by minimizing waste	CC, BGF	Moderate	Medium	Medium
Increase eco-efficiency by streamlining production	CC, BGF	Moderate	Low	Low

[a]CC stands for climate change while BGF stands for biogeochemical flows.

functional and genetic biodiversity, aerosol loading, and novel entities), and as of now, hence do not offer quantitative thresholds on which to base absolute sustainability assessment.

3.4 | Assumptions and uncertainties

The proposed methodology for scaling the SOS within an environmental sustainability limit entails a number of assumptions and methodological choices that may influence the results strongly and even change the conclusion on absolute sustainability in the presented case study as illustrated by Figure 3. Important assumptions are the ethically based choice of allocation principle and upscaling principle and the choice of parameters to represent them, for example, the use of GDP/capita as expression of ability to pay (ignoring how the GDP is generated may affect the actual ability to pay) or the use of current FCE for upscaling, which in affluent regions gives a high weight to luxurious consumption at the expense of products for basic need fulfilment.

Apart from the variation caused by these choices there are uncertainties accompanying models and parameter values used for calculation of the allocation and upscaling factors (expressions in Table 2). An important source of uncertainty here is the calculation of the SOS_{PB} which is used in all allocation factors and upscaling methods and relies on the environmental models underlying the planetary boundary method. These models are used to link the desired level of impact to a corresponding annual emission flow (e.g., the annual emissions of greenhouse gases that will allow the planet to remain below the planetary boundary) as discussed in Ryberg et al. (2018b). Other important sources of uncertainty are the calculation of total annual consumption-based impact in a region $Impact_{PB,local}(t)$ that is used in the calculation of the allocation factor according to the grandfathering principle (Equation 3), and the calculation of annual global and regional sector-specific consumption-based impacts $Impact_{PB,\ global,k}(t)$ and $Impact_{PB,\ local,k}(t)$, used in upscaling according to the green incentive principle (Equation 7). In addition, there are uncertainties accompanying the calculation of emission inventories behind the current level of impact of the studied activities or sectors. These vary with the quality of the concrete study.

4 | CONCLUSION

This paper has proposed a framework for absolute environmental sustainability assessment based on quantitative planetary boundaries and technical science as well as allocation principles drawn from the philosophical literature for assigning shares of the SOS within a planetary boundary to a stakeholder. A two-step process is proposed, first downscaling to the individual level using ethically founded allocation principles and then upscaling to any higher level than the individual (such as product, industry sector, or nation) through separate upscaling methods.

A main strength of the proposed framework is that it allows stakeholders to transparently assess their absolute sustainability status. It also links the fundamental methodological choices to explicit ethical principles in a transparent manner. Further, the framework is flexible and versatile in the sense that more allocation principles can be added, the upscaling target can be altered, equations representing the different allocation principles and upscaling factors can be changed, model and data quality can be improved, and any desired quantitative environmental impact boundary or threshold of interest can be introduced, all following the same conceptual framework as presented in Figure 1. It allows for absolute sustainability assessment of stakeholders operating nationally as well as internationally, as described in Section 3.4, although the case study presented in this paper is focused on two national and a global example. Another strength is that the framework works for any level of allocation, from individual to company to nation, etc., always based on the allocation at individual level in accordance with the underlying ethical principles.

However, there are also uncertainties linked to applying the framework. Its application requires methodological choices to be made, for example, about allocation principle and upscaling method, and these choices are strongly influential on the results. More than a weakness of the framework, this is inherent in any allocation of a scarce resource like the SOS among different actors, and while this is unavoidable it also emphasizes why transparency in choices made is so crucial. The upscaling methods are based on the use of FCE to represent preferences. This inherently assumes an even distribution of impacts across all products and services constituting the entire consumption, which is not the case. Furthermore, the FCE is based on the current, non-sustainable status quo consumption which in affluent regions disfavors stakeholders that provide essential needs like water or basic foods—in stark contrast to what may be relevant in a future sustainable society. Two allocation principles, sufficientarianism and historical responsibility, have so far not been possible to include, the former because it is not yet well developed enough and the latter due to lack of accurate data. Regarding the interpretation of the results, when presented with the varying ASRs from different allocation principles, the user may be tempted to choose the allocation principle that makes them look best. Again, this makes transparency in reporting essential.

In this study, application of the framework on a simplified dairy sector case study shows its ability to support assessments of absolute sustainability of an actor at higher level than the individual, and demonstrates how it can be used to distinguish between such actors and help identify focus points for actions that may lead from current unsustainability toward a state of absolute sustainability. Refinement and demonstration of operationality beyond the case study offered here require testing of the framework in collaboration with a participating stakeholder to provide data of higher quality and quantity. Further research could address other allocation principles and upscaling methods, and experimentation with

the proposed framework. The proposed framework provides a step toward standardization of how to distribute the SOS in absolute environmental sustainability assessments, and is intended to assist stakeholders in managing their environmental impacts in a manner that is consistent with keeping our total environmental pressures within the boundaries of absolute sustainability.

ACKNOWLEDGMENTS

The authors would like to thank Alexandra Segolene Corinne Leclerc from the Section of Quantitative Assessment at DTU Department of Technology, Management and Economics for providing support with the data from Exiobase used in this study, and Andreas Achen from the Department of Philosophy of Science at the London School of Economics for assistance with the mathematical framework.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Hjalsted AW, Laurent A, Andersen MM, Olsen KH, Ryberg M, Hauschild M. 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*. 2020;1–14. https://doi.org/10.1111/jiec.13050