



Planetary Boundaries and absolute sustainability in the life cycle assessment: Past, present, and future

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Abstract

Efforts to steer the social metabolism (i.e., how human societies interact with nature) toward sustainability are pulling assessment practice in two directions: “relative” product-to-product comparisons and “absolute” product-to-limit benchmarking, where the limit works as a benchmark for the assessment. Within approaches such as Safe and Sustainable by Design, inherently threshold-based “absolute” chemical risk assessment is coupled to life cycle assessment, which has traditionally been used as a tool for comparing alternatives. This coupling is driving the development of methodologies for comparative assessment of (eco)toxicological impact potentials (e.g., chemical footprinting). In parallel, the emergence of the Planetary Boundaries framework has renewed the interest in shifting from comparative assessments toward absolute benchmarking against global environmental limits, leading to absolute environmental sustainability assessment. This article reviews how environmental limits are incorporated into life cycle assessment through early distance-to-target methods, such as ecological scarcity, environmental themes, and Eco-Indicator 95, to support business-driven eco-efficiency decisions and how impacts were anchored in national or regional targets and critical loads. We then discuss how the Planetary Boundaries framework reorganizes limits around Earth system processes and how Planetary Boundaries-based life cycle assessment translates global boundaries into life cycle assessment indicators and Planetary Boundaries-based “budgets” for products and sectors. Across these developments, we show that setting and allocating thresholds reflects conflicting notions of “weak” and “strong” sustainability and is unavoidably value laden, and we argue that making this “valuesphere” explicit is crucial if Planetary Boundaries-based life cycle assessment is to inform credible, product-level Safe and Sustainable by Design decisions on absolute sustainability.

Keywords: Planetary Boundaries, life cycle assessment, absolute sustainability, environmental limits, Safe and Sustainable by Design

Introduction

Efforts to steer the social metabolism of nature toward sustainability are increasingly organized around the idea of environmental limits. From *The Limits to Growth* in 1972 (Meadows et al., 1972) to the more recent Planetary Boundaries (PB) framework (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015), the idea that humans must respect environmental limits is based on the recognition that the substitutability of the natural capital is limited (i.e., the stock of resources but also the set of interactions of biotic and abiotic natural systems), while the ecosystem services provided are essential for life-supporting functions. Therefore, consumption of natural

capital should be monitored and constrained to avoid irreversible losses. This paradigm is known as *strong sustainability*. In contrast, the current socioeconomic system and structures are grounded in the weak sustainability paradigm: the acceptance of technological substitution for natural functions that often prioritizes what is politically feasible over what is ecologically necessary (Pelenc et al., 2015). As a result of this tension, some tools and methodologies have been developed in the field of environmental science to perform “absolute” product-to-limit and “relative” product-to-product assessments, where limits and reference products respectively function as benchmarks for the assessment. A typical example of the first direction is risk assessment (van Leeuwen & Vermeire, 2007), while life cycle

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Historically, incorporating limits in LCA has been based on weighting methods. Weighting methods in LCA can be grouped by their approaches for aggregating results in three classes: expert panel or similar, monetary valuation, and distance to target (DtT; [Pennington et al., 2004](#)). Developed in the 1990s, early DtT methods responded to industrial needs for a gradual definition of environmental limits at a time when LCA was still establishing its methodological robustness and gaining broader acceptance as a decision support tool ([Guinée et al., 1993](#)). Distance-to-target methods such as the ecological scarcity method (ESM), environmental themes (ETs), and Eco-Indicator 95 (EI95) anchored impacts in national or regional targets, critical loads, and risk-based criteria, largely to support business-driven eco-efficiency decisions. Their goal was to condense complex impact profiles into a single score for products or processes to support fast and informed design choices. The choice of targets was based on scientific evidence but also reflected political acceptance ([Muhl et al., 2021](#)). These approaches already moved LCA

We pay particular attention to how thresholds are defined and allocated, how strict boundaries are set and global limits are shared among actors and functions, and how these practices encode conflicting notions of weak and strong sustainability. We propose to conceptualize these normative underpinnings as a “valuesphere” that co-evolves with scientific and methodological advances, as introduced in [Hofstetter et al. \(2000\)](#). We argue that making this valuesphere explicit is crucial for the future development of PB-LCA and absolute sustainability approaches and for their credible use in product-level decision making within SSbD and related agendas. The article is organized as follows: first, the materials and methods used to carry out this research are presented; the following section presents the results, which include an overview of the past, present, and future of environmental limits in LCA; the discussion elaborates on findings and possible developments for the operationalization of absolute sustainability; and the final section summarizes the conclusions of the study.

This study seeks to explore the historical evolution of the conceptualization and use of limits in LCA. We reviewed seminal scientific and gray literature to (a) identify LCA studies that apply the “relation to standards” weighting and (b) evaluate their conceptual and methodological connection to the PB framework. Exchanges with experts within and outside the Horizon Europe projects BioSusTex, SunRise, and CheMatSustain helped refine the research questions and ensure comprehensive coverage of the relevant literature. Given the historical character of our study, we organized the material into three sections: past (from early DtT methods until the emergence of PB-LCA), present (PB-LCA), and future.

The literature review was structured around the research questions of this study and does not aim to be exhaustive. The research team met regularly to discuss the historical methods, current methodological developments, challenges, and opportunities ahead, which collectively informed the discussion presented in this article. The work began with a review of some the LCA-based methods developed in the 1990s that integrated DtT weighting to support decision making; regarding PB-LCA, several approaches have been proposed, including weighting, normalization, and the calculation of new characterization factors for PB processes.

Literature review

Past

The selection of DtT methodologies included in the “Past” section was based on an initial screening proposed by one of the authors, who was active in the LCA community during the period in which these approaches were developed. This preliminary list was subsequently discussed and validated by the research team. [Table 1](#) lists the methods reviewed and included in the “Past” section. These methods were selected as historically relevant, well-documented, and frequently discussed examples of DtT weighting approaches in life cycle impact assessment (LCIA). They were developed or consolidated during the formative phase of LCIA in the 1990s, when weighting methods were actively explored as a way to support interpretation and aggregation of environmental impacts. In addition, sufficient methodological documentation is available for these approaches, allowing a transparent critical analysis. The selection was not intended to provide an exhaustive review of all DtT methods but rather to examine representative examples that show how target-based reasoning entered early LCIA practice and informed subsequent methodological developments. For the ESM method, the reference indicated is citing the original document, which was not found in literature. The analysis relied on the earliest accessible official publication ([Frischknecht et al., 2009](#)), assuming continuity of the underlying conceptual framework across updates. For the ET method, the reference reported is the earliest description of the method retrieved from literature, even though the original version is dated a few years before.

Table 1 Distance-to-target weighting methods reviewed in this study.

Method	Year	Region	Commissioner	References
Ecological scarcity method	1978	Switzerland	Frisco-Findus AG	Müller-Wenk (1978): Die ökologische Buchhaltung: Ein Informations- und Steuerungsinstrument für umweltkonforme Unternehmenspolitik. Campus Verlag Frankfurt (cited by Frischknecht et al., 2009)
Environmental themes method	1990s	The Netherlands (adapted for Sweden)	Dutch chemical industry and the Dutch government	Annema (1992) , McKinsey & Company Inc (1991) , cited by Baumann & Rydberg, 1994), Lindfors et al. (1995)
Eco-Indicator 95	1995	The Netherlands	National Reuse of Waste Research Program	Goedkoop (1995)

Note. AG = Aktiengesellschaft (Swiss joint stock company).

Present

The “Present” section was developed through a targeted critical review aimed at identifying methodological contributions to operationalize the integration of PB into LCA. The process began with the review paper of [Bjørn et al. \(2020\)](#), which provided a consolidated starting point. References cited therein were screened through backward snowballing, and additional relevant studies were identified through an independent literature search using combinations of terms related to “Planetary Boundaries,” “life cycle assessment,” “absolute environmental sustainability assessment,” and “PB-LCA.” Articles were not included if they focused on the operationalization of one boundary or presented case studies rather than methodological advancements. [Table 2](#) summarizes approaches that integrate PB into LCA.

Future

To complement the historical and methodological analysis, we examined selected application contexts in which PB is being operationalized for industrial decision making. The selection was guided by two criteria: (a) an explicit conceptual or methodological link to AESA and/or operationalization and (b) relevance for industrial decision making at the level of products, technologies, chemicals, value chains, or companies. Based on these criteria, we focused on three application contexts: the Science Based Targets (SBTs) for nature initiative, research addressing the novel entities boundary, and the SSbD framework ([Table 3](#)). These contexts were selected because they represent possible pathways for the development of applied and practical research on PB, where limits are proposed at the level of industrial activity. Moreover, they represent key topics in the research field. The SBTs are mentioned by [Rockström et al. \(2024\)](#) as a concrete example of PB operationalization; the PB for novel entities is a critical unresolved question in the PB control variables definition ([Jahnke et al., 2026](#)); finally, SSbD is a central element of the European Green Deal, focusing on integrating early assessment for better future planning at the company level, and the context in which our research question arose. Through these efforts, the PB concept is moving from a global perspective toward an operational tool to use in product development, chemical management, and corporate sustainability strategies.

(i.e., at the time) and the critical values (i.e., the values accepted and implemented into policy targets). The critical values are based on national or international targets adopted by Switzerland. For the environmental impact assessment, all processes included within the system boundaries are assigned eco-factors, which are calculated through characterization, normalization, and DtT weighting. Each emission, resource use, or substance flow is thus assigned a number of eco-points (i.e., the unit of eco-factors) that reflect its environmental burden, based on the actual values measured and the corresponding environmental target. For example, the eco-factor assigned to CO₂ for 2010 is 0.023 eco-points, resulting from characterizing greenhouse gases, normalizing to Switzerland, and weighting based on the 10% reduction goal (current flow/critical flow; Frischknecht et al., 2009). In ESM, products or processes receive an aggregated eco-point score that represents the overall environmental burden of the system, with contributions weighted according to the severity of each environmental issue. This method is particularly useful for facilitating the practical use of LCA results, especially in industrial contexts, where it informs design choices in a fast and comprehensible manner. Many product-oriented applications of ESM are documented in gray literature and industrial reports rather than in peer-reviewed scientific articles, while published contributions have often focused on methodological development and the derivation of national or regional eco-factor sets (Ahbe et al., 2018; Grinberg et al., 2012). A useful example, even if based on a theoretical case study, is the steel and aluminium study by Muhl et al. (2021). The work provides a useful example of how ESM can be applied to product systems and supply chain interpretation. The authors derived regional eco-factors and tested three DtT weighting perspectives: consumer regions, producer regions, and worst-case regions. The study shows how the choice of target-setting perspective can substantially affect the aggregated eco-point results and the relative importance of impact categories and producing countries. Under the EU consumer regions perspective, acidification dominated the aggregated results for both metal products. By contrast, under the producer region perspective, the aluminium results shifted strongly toward water resources because part of the production mix was allocated to highly water-scarce countries. The study also shows that countries with smaller production shares may still drive the final eco-point score when their country-specific eco-factors are high. Integrating these perspectives into product design and supply chain assessment can therefore help identify not only which environmental issues dominate a product system but also where regional environmental scarcity and target-setting assumptions drive the final single-score result.

Environmental themes method: ET short, ET long

With a similar aim of supporting industry in integrating sustainability into product design, the ET method was developed in the Netherlands through an initiative by the Association of the Dutch Chemical Industry and the Dutch government in the early 1990s. Its development was carried out by the Centre of Environmental Science in Leiden, the Dutch National Institute for Health and Environment, and the McKinsey & Company Inc (Baumann & Rydberg, 1994; Seppälä & Härmäläinen, 2001). The method was later refined by Chalmers Industriteknik to be

adapted to the Swedish condition (Baumann et al., 1993; Rydberg, 1996). Two versions of the method were established to address short- or long-term sustainability targets, using political goals (ET short) or ecological critical loads (ET long). The latest development of the method was tested and implemented in several Chalmers Industriteknik projects, in contrast with the rest of the methods designed for industrial application. As the scientific literature mainly covers the Swedish adaptation, the present work refers to this version.

The ET method groups environmental pressures into a set of impact themes (or categories), for which the required reduction and an associated weighting factor are determined. The ET short uses the 1995 policy targets, whereas the ET long is based on a set of scientifically derived criteria. In both cases, sustainable loads are defined according to assumptions on ecological critical loads for each theme. For example, the global warming critical load is defined by the 1995 Swedish policy target of reducing or maintaining emissions constant (short) or by the calculated sustainable load of 0.1 °C increase every decade (long). The themes addressed include global warming, ozone depletion, acidification, eutrophication, photochemical ozone formation, dispersion of toxic substances, disruption, disposal of waste, and depletion of natural resources. Weighting in ET is calculated as the ratio between the normalization reference and the selected target reference. Baumann and Rydberg (1994) tested this adaptation of the ET method through a milk-packaging example, comparing 1-L brick-shaped cartons with refillable polycarbonate bottles. The environmental loads from the life cycle inventory were first assigned to ETs, expressed as theme-specific impact fractions, and then aggregated after weighting according to the relative severity of each theme. The resulting impact ratio between the packaging options was used to compare their environmental performance. The ET score indicated no substantial difference between the systems, while the disaggregated results helped identify the main contributors and thus possible priorities for environmental improvement. Since normalization is based on the geographical location scope of the assessment, the resulting weighting factors are region specific. These weights are then used to calculate an indicator of total impact for each category relative to the system under study. The indicators can then be aggregated into a single score, producing a one-number result. The ET thus provides a structured tool to support the integration of environmental considerations into product design.

Eco-Indicator 95

Around the same time as the ET method, the EI95 was developed in the Netherlands by the National Reuse of Waste Research Program. A multidisciplinary team, including representatives from industry, science, and government, contributed to defining a weighting approach for the Dutch LCA method (Heijungs et al., 1992). The target values incorporated into EI95 were supported by a scenario study produced by the Dutch National Institute for Health and Environment for the GLOBE Europe organization and complemented by the World Health Organization's air quality (World Health Organization Regional Office for Europe, 1987) and water quality (World Health Organization, 1993) guidelines for Europe. Unlike methods based on policy goals, EI95 relies on scientifically derived

Present

(2015), Richardson et al. (2023) and annual Planetary Health Check reports since 2024 (Sakschewski et al., 2025).

The need to operationalize PB within an AESA has positioned LCA as the most robust methodological framework for this purpose. The LCA methodology provides a comprehensive representation of environmental impacts across the life cycle of a system, reducing the risks of burden shifting while covering a broad set of impact categories (Hauschild, 2015). The relevance of LCA in this context was reinforced by the explicit call to move beyond eco-efficiency and toward absolute sustainability in LCA practice (Bjørn et al., 2015), which coincided with a sharp increase in scientific output following the introduction and first update of the PB framework (Rockström et al., 2009; Steffen et al., 2015). Supporting our comparison of DtT weighting and AESA, early attempts to integrate PB into LCA focused on weighting and normalization. Tuomisto et al. (2012) proposed a PB-based DtT weighting, framing weighting as a necessary step to support the interpretation of LCA results. They argued that this method could become the optimal way to define weights, in a research field where the incomplete but sufficient understanding of environmental systems is the key to prevent dangerous tipping points. Although grounded in PB, these factors require further adaptation for LCA use, as direct equivalence between PB control variables and LCA impact categories is not yet established. Then, Bjørn and Hauschild (2015) developed carrying capacity-based normalization factors, highlighting that several LCA indicators implicitly address carrying capacity but only in terms of threshold exceedance, failing to consider values close to but below the threshold. By explicitly integrating appropriate measures of carrying capacity, they proposed the use of PB as sustainability reference within the normalization step of LCA. This approach was adapted to align with the Product Environmental Footprint method (Sala et al., 2020), which provided equivalences between PB metrics and Product Environmental Footprint indicators.

Parallel developments explored how to link the global thresholds to lower scales. The set of PB delimits the global safe operating space (SOS): the ecological space within which humans can operate while maintaining the planet in predictable and stable conditions (Rockström et al., 2009). To operationalize AESA and PB-LCA, it is necessary to determine whether a product, process, or sector's environmental impact is compatible with a specified share of SOS. Sandin et al. (2015) proposed product-level reduction targets by linking current PB values to a future time horizon (2050), representing one of the first attempts to assign a share of SOS to a regional market scale (i.e., the Swedish clothing market segment). In contrast, Ryberg, Owsianiak, Richardson, & Hauschild (2018) proposed redefining LCIA impact categories such that Earth system processes could be used as new impact categories in the LCIA phase; that is, conventional LCA impact category indicators could be replaced with Earth system processes and their control variables, effectively reversing the integration logic by adapting LCA to PB rather than vice versa.

Following these foundational contributions, recent literature has refined the operationalization of PB-LCA and AESA rather than replacing their core methodological architecture. Recent work has addressed specific unresolved issues, including the allocation of the SOS through alternative sharing principles, the

treatment of uncertainty, impact category prioritization, prospective modeling, and the development of practical guidance for applying AESA at different scales. For instance, Heide et al. (2023) proposed a sharing principle based on human needs fulfillment; Lund et al. (2025) used AESA to prioritize impact categories in building LCA; and Manthos et al. (2026) combined prospective LCA, AESA, Shared Socioeconomic Pathways, and market penetration modeling to evaluate emerging biorefinery products against future environmental thresholds. These developments confirm the increasing methodological maturity of the field. However, a comprehensive review of recent AESA refinements is beyond the scope of the present article, which focuses on the historical and conceptual transition from DtT weighting methods to PB-based absolute sustainability approaches. For detailed and up-to-date reviews of PB-LCA and AESA operationalization, see Paulillo and Sanyé-Mengual (2024), Acevedo et al. (2026), and the recent Joint Research Centre guidance on AESA application at different scales (Bjørn et al., 2025). These approaches have been tested across case studies at different scales.

A comprehensive review by Bjørn et al. (2020) published a few years ago highlighted that a key challenge lies in linking global PB to the assessed system when assigning a share of SOS according to distributional justice theory principles. This is currently one of the main limitations of AESA studies for comparability, as discussed more recently by Paulillo and Sanyé-Mengual (2024) and Zhang et al. (2025). As no unequivocal allocation principle exists, most studies carry out a sensitivity analysis applying multiple sharing approaches to avoid an impossible choice of defining a just principle (Paulillo et al., 2026). The outcome is a few sets of limits, which struggle to be operational due to significant variability. We identify this issue as a debate for the “valuesphere” of AESA, as this methodological choice cannot avoid a subjective element that significantly affects results. This concept was introduced by Hofstetter et al. (2000) to indicate the inevitability of integrating and explicating the subjective element in a LCA assessment; that is, in a study the decision maker’s views and the practitioner’s choices are building blocks of the analysis as much as the techno- and ecosphere. This element is part of the current ReCiPe LCIA method, grouped in three perspectives that account for different sets of uncertainty and choices regarding each impact category (Huijbregts et al., 2016). As proposed in their work, we use the *valuesphere* term to denote the broader normative environment within which PB-LCA and absolute sustainability approaches become operational. The concept does not refer to a single value choice nor to one specific allocation rule. Rather, it captures the set of ethical, social, institutional, and methodological commitments that shape how biophysical limits are translated into decision-relevant thresholds for products, sectors, actors, or functions. Additional challenges arise from the regional nature of environmental processes (i.e., they have location-specific thresholds), the uneven availability of data, and the globalized structure of supply chains in contemporary socioeconomic systems. While regional thresholds can sometimes be calculated, their limited feasibility often leads to the use of global boundaries, increasing uncertainty. This trade-off is widely acknowledged in literature (Bjørn et al., 2020), and ongoing efforts aim to develop regionalized boundaries. In the meantime, a degree of uncertainty is accepted

to enable practical application of AESA without restricting its use to data-rich, predominantly high-income countries.

Future

What is absolute sustainability (assessment) for? The answer to this question can help to set targets for the future of sustainability assessment. On the global level, it is evident that avoiding the exceedance of the PB is crucial to support human development through the stable Holocene conditions. Yet, when it comes to economic dynamics, business models, and individual companies, the path is less straightforward. The framework is positioned in a context of strong sustainability, while policy and decision makers instead aim for weak sustainability principles. With this prevailing dissonance, the question of how to define pragmatic yet scientifically sound absolute sustainability thresholds remains unanswered. To address this question with practical examples, in this section we review approaches to operationalize absolute sustainability for industrial decision making.

Science-based targets for nature

The first practical application of absolute sustainability in case studies grounded in the PB framework is found in the Science Based Targets Network (SBTN; 2026b), which supports companies in setting validated greenhouse gas reduction targets. Established in 2015 following the Paris agreement, the initiative initially focused on aligning corporate greenhouse gas emission reduction with global climate goals. Its founding partners include the World Wide Fund for Nature, the United Nations Global Compact, and the World Resources Institute (Romito et al., 2024). With the growing influence of the PB framework, the SBTs initiative was developed to integrate ecological limits into its scientific basis for target setting. Complementing the SBTs initiative, which addresses only the climate change boundary, the SBTN provides companies with a framework to assess and prioritize impacts on freshwater, land, ocean, and biodiversity. Companies calculate their responsibility share or their allowed SOS share and define a reduction pathway consistent with PB compliance in a target year. This allocation is based on distributional justice theories, with grandfathering being the most applied. As discussed earlier, this approach raises concerns regarding fairness (Bjørn et al., 2022; Tilsted et al., 2023). Nonetheless, SBTs represent the first concrete example of practical implementation of PB-informed science, and the methodology continues to be refined. The recent adoption of SBTN (2026a) land targets by the H&M Group illustrates how science-based targets can operationalize absolute sustainability thinking in corporate decision making. Rather than relying on only relative improvements, the company defined measurable land-related targets for its upstream supply chain, including no conversion of natural ecosystems, absolute agricultural land footprint reduction, and engagement in regenerative landscape projects. Although not an LCA-based AESA application, this example shows how boundary-oriented approaches are increasingly translated into corporate targets for specific environmental pressures and value chain hotspots (SBTN, 2026b). The scope of the SBTN is now expanding to cover target setting not only for companies but also for cities.

Table 4 Threshold in early attempts to link life cycle assessment impacts to planetary or other related absolute boundaries.

Impact category				
Ecological scarcity method ^a	Eco-Indicator 95 ^b	Environmental themes: short ^c	Environmental themes: long ^c	Planetary Boundaries framework ^d
GW/GHG effect				
Current (CH): baseline, 1990; 41.1 million t CO ₂ -eq	Current (EU): $\Delta T = +0.2^\circ\text{C}/10\text{ yr}$	Current (SE): CO ₂ -eq = $9.0 \times 10^{13}\text{ g}$	Current (SE): not specified	Current (GLO): [CO ₂]: 417 ppm CO ₂ , RF: + 2.91 W/m ²
Target: CO ₂ /yr ₂₀₁₀ ≤ 37 million t or 10% reduction by 2010 CO ₂ /yr ₂₀₅₀ ≤ 80.6 million t or 80% reduction by 2050	Target: 60% reduction	Target: CO ₂ -eq $\leq 9.0 \times 10^{13}\text{ g}$	Target: CO ₂ -eq $\leq 2.7 \times 10^{13}\text{ g}$ or 70% reduction	Target: [CO ₂]: 350 ppm CO ₂ , RF: + 1.0 W/m ²
Criteria: 10% fuel reduction from the 1990 baseline in the Swiss CO ₂ Act (2010); Swiss Sustainable Development Strategy (2050)	Criteria: $\Delta T \leq +0.1^\circ\text{C}/10\text{ yr}$ or ecosystem impairment $< 5\%$	Criteria: policy target for year 1995	Criteria: $\Delta T \leq 0.11^\circ\text{C}/10\text{ yr}$	Criteria: possibility of extreme Earth system impacts $> 1.5^\circ\text{C}$ warming
Ozone depletion				
Current (CH): 2006; 391 t R11-eq/a	Current (EU): 2.6% of ozone layer depletion	Current (SE): R11-eq = 4.1×10^9	Current (SE): not specified	Current (GLO): 284.6 DU
Target: R11-eq/a ≤ 188 in 2015	Target: CFC emissions = 0 by 2000 or 60% reduction	Target: 95% reduction	Target: R11-eq $\leq 3.1 \times 10^{13}\text{ g}$ or 92.5% reduction	Target: 276 DU
Criteria: estimation on releases of the stocks of substances already in use and substances ban	Criteria: probability of 1 death per year per million people (due to melanoma)	Criteria: policy target for year 1995	Criteria: Cl/Br concentrations below formation of the polar ozone hole	Criteria: max $< 5\%$ reduction from preindustrial level
Acidification				
Current (CH): 2006 91,000 t NO _x as NO ₂ /yr 44,000 t NH ₃ -N/yr 19,000 t SO ₂ /yr	Current (EU): location dependent, value missing	Current (SE): SO ₂ -eq = 7.6×10^{11}	Current (SE): not specified	Current (GLO): carbonate ion concentration on the ocean surface = $2.8\ \Omega_{\text{aragonite}}$
Target: 45,000 t NO _x as NO ₂ /a 25,000 t NH ₃ -N/a 25,000 t SO ₂ /a	Target: 90% reduction	Target: 50% reduction	Target: SO ₂ -eq $\leq 3.0 \times 10^{11}$ or 60% reduction	Target: carbonate ion concentration on the ocean surface $\geq 3.44\ \Omega_{\text{aragonite}}$
Criteria: ambient limit values defined within the Swiss Federal Air Pollution Control Ordinance	Criteria: 5% system impairment	Criteria: policy target for year 1995	Criteria: ion balance (Ca + Mg + K):Al > 1 in soils	Criteria: avoid major disturbance in marine ecosystems (i.e., aragonite desaturation, leading to inhabitable corrosive water)
Eutrophication				
Current: n/a	Current (EU): $\sim 200\text{ kg P-eq/ha}$ per year in Benelux countries, North-Rhine Westphalia, and Po valley region	Current (SE): NO _x -eq = 6.4×10^{11}	Current (SE): not specified	Current (GLO): 22.6 Tg P/yr global, 17.5 Tg P/yr regional; 190 Tg N/yr

(continued)

Table 4 (continued)

Impact category				
Ecological scarcity method ^a	Eco-Indicator 95 ^b	Environmental themes: short ^c	Environmental themes: long ^c	Planetary Boundaries framework ^d
Criteria: ambient limit values defined within the Swiss Federal Air Pollution Control Ordinance, PAH target within the International Commission for the Protection of the Rhine	Criteria: <i>Pesticides</i> : groundwater contamination, 5% system impairment <i>Heavy metals in air</i> : Pb levels in children's blood, limited life expectancy and learning ability in an unknown number of people <i>Heavy metals in water</i> : cadmium content in rivers, ultimately also effect on people <i>Carcinogenic substances</i> : probability of 1 death per year per million people	Criteria: policy target for year 1995	Criteria: critical load of deposition of mercury	Criteria: percentage of untested synthetics released globally; e.g., among chemicals currently registered under the EU REACH regulation, at least ~80% had been in use for at least 10 yr without yet having undergone a safety assessment (Richardson et al., 2023)

Note. The Planetary Boundaries biosphere integrity, land system change, and freshwater change are missing in the early methods and are not reported for the purpose of comparison. The ecological scarcity method includes more substances under the impact category "Toxic/ecotoxic chemicals," not listed for the purpose of comparison. GW = global warming; GHG = greenhouse gas; Current = at the time of the reference publication; CH = Switzerland; EU = Europe; SE = Sweden; GLO = global; CO₂ = carbon dioxide; ΔT = temperature change; yr = year; [CO₂] = CO₂ concentration; RF = radiative forcing; R11 = trichlorofluoromethane; DU = Dobson units; CFC = chlorofluorocarbons; Cl = chlorine; Br = bromine; NO_x = nitrogen oxides; NO₂ = nitrogen dioxide; NH₃-N = nitrogen content in ammonia; SO₂ = sulphur dioxide; Ωaragonite = aragonite saturation state; Ca = calcium; Mg = magnesium; K = potassium; Al = aluminum; n/a = not available; P = phosphate; N = nitrogen; NMVOC = nonmethane volatile organic compound; ΔAOD = interhemispheric difference in aerosol optical depth; PM = particulate matter; PAH = polycyclic aromatic hydrocarbons; Pb = lead; Cd = Cadmium; REACH = Registration, Evaluation, Authorization and Restriction of Chemicals.

^aFrischknecht et al. (2009).

^bGoedkoop (1995).

^cRydberg (1996).

^dRichardson et al. (2023).

notion that the underlying concept is not new, while the language, frameworks, and methodologies developed around it are progressively changing. Almost all impact categories across methods could be grouped according to the environmental pressure that they assess, differing mainly in the control variable adopted or in impact nomenclature. The historical development of impact categories such as climate change, stratospheric ozone depletion, acidification, and novel entities (using PB Earth system processes terminology) can be traced back to earlier methods and show substantial continuity over time. Notably, the precursors of the novel entities category consist of a collection of substances included in the current definition of the corresponding PB, reflecting a progressively improved understanding of the global issue. On the contrary, land system change, change in biosphere integrity, and freshwater use emerged only with the conceptualization of the PB framework (and in some updates of DtT methods, which are outside the scope of this review; e.g., Frischknecht et al., 2009). Waste- and energy-related impact categories were included only in ESM and ET methods.

Figure 2 provides a conceptual overview of the co-evolution of environmental limits ("Science"), LCA practice integrating

targets ("LCA"), and policy frameworks ("Policy") previously discussed. The relevant elements to describe the process of co-evolution are organized along a timeline. LCA is positioned in the center as the methodology in focus in this review. It represents the practice in which environmental limits have been operationalized, thanks to the theory provided by scientific production and the decisions taken within policy frameworks. The LCA practice has been shaped by both streams, as influenced by the historical context (gray arrows). Scientific production on environmental limits has progressively contributed to the formalization of LCA as a standardized methodology, initially addressing a need to measure and reduce impacts at the local scale—for example, by informing weighting approaches to thresholds, targets, or critical loads. These developments consolidated the use of LCA as a predominantly comparative tool, pursuing eco-efficiency in the short term. More recently, the emergence of the PB framework has reopened the discussion on the role of environmental limits in LCA, fostering the development of PB-LCA approaches that explore absolute sustainability benchmarking at various scales. This trajectory has been reinforced by national and international policies, steering sustainability efforts and informing environmental law with global

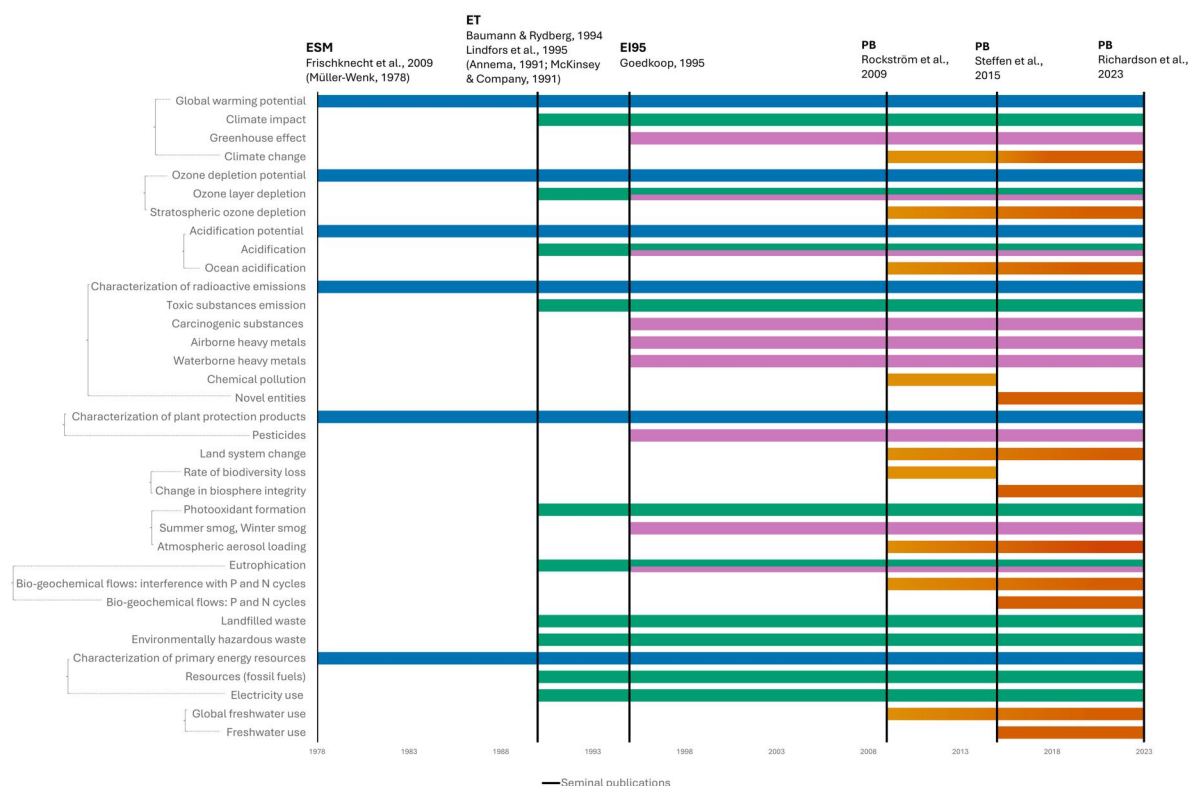


Figure 1 Comparison of impact categories in distance-to-target weighting methods and PB Earth system processes over time. Each term starts with the method that developed it. The reference used, if not corresponding to the original document, is cited in brackets. Some categories have been grouped as pertaining to the same area of protection, either broadening or narrowing the scope with scientific understanding of the processes. ■ ESM: ecological scarcity method. The impact categories introduced in 2009 were excluded. ■ ET long: environmental themes–long term. ■ EI95: Eco-Indicator 95. ■ PB: Planetary Boundaries; shaded light (2009) to dark (2023). The overlap of colors in “ozone layer depletion,” “acidification,” and “eutrophication” represent an overlap of terms in the methods. Timeline diagram shows the evolution and continuity of environmental impact categories across the ESM, ET method, EI95, and successive PB frameworks from 1978 to 2023. Horizontal bars indicate when related environmental categories appear across methods, highlighting continuity in climate change, ozone depletion, acidification, and eutrophication, as well as the emergence of Earth system processes such as biosphere integrity, land system change, freshwater change, and novel entities.

P = phosphorus; N = nitrogen.

agendas as prevalent instruments to address planetary-level sustainability questions (e.g., Millennium Development Goals, Rio Declaration, Sustainable Development Goals). The PB framework gained momentum because it offers a scientifically robust basis to assess sustainability at the planetary scale, addressing the need to coordinate action in response to weak sustainability practices that have proven inadequate (Downing et al., 2019). The underlying idea is that LCA practice depends on how society thinks and takes decisions about the environment through policies, as visible in Figure 2 showing science and policy mostly preceding LCA innovation.

The relation between societal preferences and environmental management is closely related to the previously discussed valuesphere dimension. In each method, a background overarching configuration of value choices, normative judgments, distributional justice, and allocation principles functions as the underlying narrative scenario in which the methods operate. According to Hofstetter et al. (2000), cultural theory is the framework used to systematically organize sets of value choices within the valuesphere environment in which they operate. The DtT, AESA, and “Future” section’s approaches do not explicitly define the virtual valuesphere environment in which they operate. We have

identified political acceptability as the main subjective element in the DtT weighting methods; the allocation of global SOS to smaller levels in AESA and, consequently, in SBTs and SSbD; and the boundary definition for the novel entities environmental pressure. Although valuesphere dependence is more explicit for the DtT methods, to the point of being one of the main criticisms of the LCA weighting step, it is less evident in AESA and absolute sustainability. The approaches that have operationalized these methods include few elements attributable to the valuesphere, such as selecting a temporal horizon, the reference population entitled to that environmental space, which functions are socially necessary, and how responsibility should be distributed. Organizing these elements in structured and coherent sets would help overcome some of the methodological challenges that arose in this first decade of AESA application.

Discussion

Linking past and present methods

Conceptually, despite their differences in goal and scope, we argue that AESA and PB-LCA (a) aim to evaluate how a given

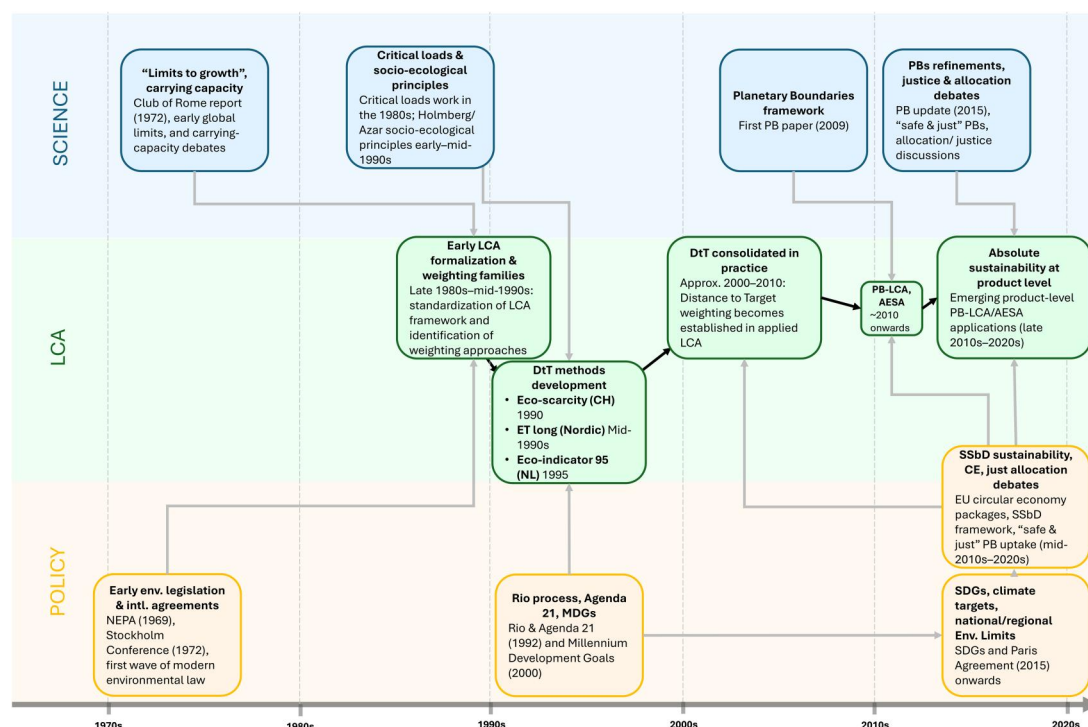


Figure 2 Conceptual representation of the interactions of LCA practice, scientific understanding of environmental limits, and policy frameworks. ■ Science. ■ LCA. ■ Policy. Timeline shows the co-evolution of environmental science, LCA practice, and sustainability policy. Scientific concepts and policy developments precede and influence successive LCA approaches, from early environmental limits and DtT weighting methods to PB, PB-LCA, AESA, and SSbD. LCA = life cycle assessment; DtT = distance to target; PB = Planetary Boundaries; PB-LCA = Planetary Boundaries-based life cycle assessment; AESA = absolute environmental sustainability assessment; SSbD = Safe and Sustainable by Design; CH = Switzerland; NL = the Netherlands; CE = circular economy; EU = Europe; NEPA = National Environmental Policy Act; MDGs = Millennium Development Goals; SDGs = Sustainable Development Goals.

system performs relative to predefined environmental limits or targets, (b) align with the weighting step of the LCA procedure, and (c) support the interpretation phase of LCA by indicating which impact categories should be prioritized. In what follows, we discuss each point with a comparative perspective.

Evaluation against environmental limits

In the case of the DtT methods examined in this study, the environmental limits are conceived as the maximum acceptable load in a given area. Acceptability is defined at the government level, according to the reference body that produced the evidence. As a result, ideological profiles and societal preferences play a crucial role in accepting targets proposed by the scientific community (Seppälä & Hämäläinen, 2001) and define the value-sphere of reference for the specific DtT method. Because of this dependence on value choices and stakeholders' judgment, it is essential to clearly explain how the weighting factors were determined. For PB environmental limits, definition depends on an integrated Earth system perspective that synthesizes evidence on key biophysical processes and their interactions across scientific disciplines, aiming to capture the most important anthropogenic influence at the planetary level of the boundary in focus (Richardson et al., 2023). Targets are defined as preindustrial Holocene conditions for each boundary, where the elements attributable to the valuesphere are (a) the selection of studies to

produce the evidence synthesis and (b) the assumption that pre-industrial conditions correspond to Earth system stability.

Weighting perspective

According to ISO 14040:2006a and ISO 14044:2006b, the integration of impact categories results using weighting methods is an optional step in LCA. It consists of assigning weights to the environmental impact categories considered in the assessment to support the interpretation of the results. The PB-LCA for AESA also aligns to this definition, as it includes an evaluation of the systems according to the targets defined for each boundary. When DtT weighting is applied, weights are calculated by the relative severity of the current environmental impact for each specific impact category. The greater the deviation of an impact indicator from its target, the more urgent the category is considered. While DtT approaches assume that all targets are considered equally important and no impact has more severe consequences than others (Tuomisto et al., 2012), AESA obtains disaggregated values for each boundary to avoid trade-off.

Interpretation and prioritization

In the interpretation phase, DtT weighting and PB-LCA discuss results considering the deviation from target levels, according to the purpose of the study. When these DtT approaches were conceptualized, datasets and models were less comprehensive than in 2009, when Rockström et al. (2009) consolidated existing

knowledge and proposed the PB framework. Accordingly, DtT weighting methods have typically been developed from a local perspective, tailored to specific countries or regions and based on a consumer-oriented perspective (i.e., the country where the product system is consumed). This represents a limitation for interpreting environmental pressures that transcend borders and global production systems, as impacts occurring along their value chain are weighted according to the conditions of the region for which the method was developed (Muhl et al., 2021). The PB-based approaches, by contrast, seek to anchor LCA in global Earth system limits to account for planetary-level changes, globalization of supply chains, and shared responsibility in environmental management, facing different challenges regarding boundary choice and allocation.

Valuesphere

In this article, we review how the concept of environmental limits was interpreted and implemented in the past and present and how we envision it to be in the future of LCA. The differences in the thresholds set in the past and present stress how much a boundary for absolute assessment is dependent on the criterion set for its establishment. This choice will ultimately be made by a partly subjective decision depending on the social and historical context to which it pertains. In weighting, setting a target value can coincide with the definition of a threshold for PB, where pollutant critical loads (i.e., ESM), ET limits (i.e., ET), or eco-points (i.e., EI95) are substituted by Earth system process control variables. The values to set the limits for DtT methods were found to be predominantly subject to political willingness to integrate scientifically defined targets in policy or else focused on compromise-based targets. A limitation of this approach is the gap between policy limits and best-case scenario for environmental protection, as they are the results of debates matching science and societal acceptance. This is evident when comparing the different definitions of goals in the environmental sciences context and in global agendas, even with the shared aim of maintaining the Earth system in an acceptable status for human prosperity. On the contrary, the PB framework, although openly anthropocentric, was conceived to be independent from any country or policy. However, while pursuing objectivity in boundaries definition, AESA too cannot, at this point, be decoupled from social values and preferences. This happens when selecting the principles that guide the sharing of the PB allowance: choices that reflect various understanding of fairness. The share of SOS works additively, meaning that the sum of all production and consumption should equal the Earth system carrying capacity, resulting in a set of scenarios of sustainability results for the same system according to different distributions of SOS. In this way, the “absolute” element of sustainability advocated by this approach falls into relativity because of the very nature of distributional justice theories, by definition providing options rather than an unequivocal answer of what is fair. To support this claim, most of the studies developing such an assessment were obliged to test a few sharing principles, obtaining a set of possible limits rather than an operative result (Ryberg, Owsianiak, Richardson, & Hauschild, 2018; Sandin et al., 2015). This distinction is particularly important because AESA is absolute in its reference to biophysical limits but not value-free in its operationalization. The definition of thresholds,

the translation of PB into LCA-compatible indicators, the allocation of global limits to product-level functions, and the interpretation of transgressions all involve context-dependent normative judgments. Making the valuesphere explicit therefore should be one of the scientific ambitions of absolute sustainability assessment, along with methodological development. This element would improve transparency, interpretability, and credibility, especially when these methods are used to support product-level decision making in SSbD contexts. This tension contributes to the resistance to adopt such an absolute perspective in our system, missing an operational level. We concluded that the valuesphere has in both approaches a significant role that inevitably shapes the results of the study. Our question is this: can absolute sustainability aim to produce stronger claims than DtT weighting?

Future

Toward absolute sustainability

Grounded in the principles of strong sustainability, the PB concept has been proposed to move from pursuing what is merely acceptable or marginally improved to identifying what is essential for maintaining natural capital in the long term. The LCA and its consolidated methodological structure can be combined with the decision support strengths of the PB framework, creating a coherent basis for assessing sustainability (Ryberg, Owsianiak, Clavreul, et al., 2018). The PB framework offers a suitable pathway to operationalize absolute environmental sustainability and address the asymmetry between strong and weak sustainability paradigms. The concept of sustainability is inherently linked to the carrying capacity concept, although it is now widely used to describe any effort aimed at reducing impacts, lowering emissions, or optimizing resource uses. Its original meaning, indicating a status that can be sustained in the long term, is now being reintroduced with the “absolute” specification. Within this perspective, traditional comparative approaches are characterized as “relative,” since product-to-product assessments primarily promote eco-efficiency, which does not necessarily equate to a sustainable system. The shift from regionalized DtT environmental limits to the global PB framework reflects this change in perspective, supported by emerging evidence that human activities drive global environmental change (Steffen et al., 2007, cited in Rockström et al., 2009). This finding supported the debate around the Anthropocene, a concept rejected by the International Commission on Stratigraphy and the International Union of Geological Sciences yet still influential as a scientific and societal narrative. As environmental change increasingly manifests at a planetary scale, the regional level of analysis has become insufficient to guide a sustainable transition.

We associated the relative/absolute contrast to the tension between the strong/weak sustainability paradigms. The stress on the “absolute” terms, we believe, serves to differentiate it explicitly from comparative sustainability, which means trying to be “less unsustainable” without engaging on concerns on growth (Steffens et al., 2025). Yet, PB implicitly sets limits to growth. By stating that the system studied exceeds its shares of SOS, AESA results call for fewer impacts. This cannot derive only from technological improvements but must be paired with changes in production and consumption patterns, when seven

out of nine boundaries are well beyond the SOS (Sakschewski et al., 2025). Weak and relative sustainability has proven more operational; yet, by missing a path to get to the SOS in a safe, just, and economically viable way, it is not enough to address the ecological crisis. This perspective is characterized by awareness of risk exceeding capacity for practical action, which is ultimately a major obstacle to operationalizing strong and absolute sustainability.

Addressing asymmetry in SSbD

We identify an asymmetry in the SSbD framework arising from a methodological mismatch between safety assessment, which follows a product-to-limit logic, and sustainability assessment, which is predominantly product to product. This asymmetry might limit the ability of SSbD to support early-stage innovation, as sustainability assessments (a) rely on context-specific reference systems that may not yet exist for novel solutions and (b) lack a boundary perspective to account for intra- and intergenerational justice. We therefore ask whether a shift toward AESA within SSbD could help overcome these constraints. As one of the key conceptual differences between past and present methods reviewed in this article is their positioning with respect to the comparative approach, it was proposed that integrating the PB framework into Step4 of SSbD may offer a pathway to move beyond comparison (Caldeira et al., 2022). The latest update of

the SSbD framework (Garmendia Aguirre et al., 2025) proposed another way to address the asymmetry and the relative/absolute tension, defining benchmarks on average impacts of chemicals and not grounding the assessment in concepts of absolute sustainability or PB. Considering the role of the SSbD framework as a support for redesign, substitution, and early-stage decision making, we agree that the definition of benchmarks remains crucial in the assessment. We suggest that the asymmetry should be resolved by complementing a relative LCA with AESA to expand the assessment and account for environmental limits. Alternatives would be compared against each other within the share of SOS assigned to the system. To support the vision outlined here, Figure 3 represents a conceptual overview of the proposed workflow. Rephrasing the popular statement of absolute sustainability, we suggest that systems should be better *and* good enough. Improvement of environmental profiles should remain a priority, especially considering the high level of boundaries transgression that studies up to now have proved. This suggestion, acknowledging the limitations discussed so far on operationalization of AESA, provides a different perspective on the relative/absolute assessment relations, within SSbD, and more in general in the field of sustainability assessment. Matching the two types of assessment is essential to avoid two opposite limitations. Comparative LCA anchors the evaluation of emerging technologies in the current system, identifying

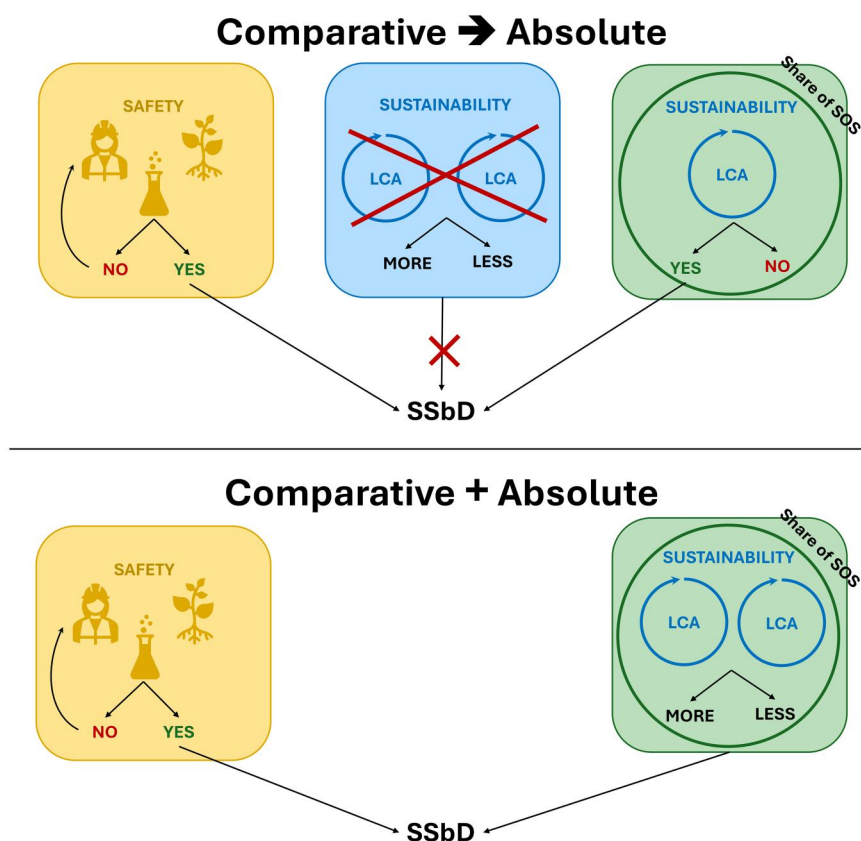


Figure 3 A proposal to reframe the asymmetry between safety and sustainability in SSbD. Conceptual diagram compares two approaches to sustainability assessment within SSbD. The upper panel shows a shift from comparative to absolute assessment: safety is evaluated against a yes/no threshold, while comparative LCA based on more/less impact is replaced by an absolute LCA assessment against an allocated share of the SOS. The lower panel shows the proposed combined approach: safety retains its yes/no threshold, and sustainability integrates comparative LCA between alternatives and absolute assessment against the SOS. SSbD, Safe and Sustainable by Design; LCA, life cycle assessment; SOS, safe operating space.

whether they are environmentally preferable to existing alternatives and where trade-offs may arise. The AESA framework, in contrast, situates these improvements within planetary conditions but may lose interpretability if disconnected from benchmarks and realistic substitution pathways. Combining comparative LCA with AESA therefore allows SSbD to connect the short- to medium-term question of whether an innovation is environmentally “better” than current practice with the long-term sustainability question of whether it is “good enough” in relation to planetary conditions.

Recommendations and outlooks

Our systems—economic, political, social—are not (yet?) built to function within the PB. To bring the Earth system back into its SOS, several perspective changes are required, along with a more radical socioeconomic transition. The PB limits are applied on systems that depend on many factors and stakeholders, across life cycle stages. For this reason, absolute sustainability in practice has to go beyond the assessment-committing party. First, it is important to make discourses on essential use and sufficiency at the global level practical. The AESA community has started to address the question of ideal consumption levels in terms of which products and how much of them (Schlesier et al., 2024). This opens a further question on how to distribute responsibility between producers and consumers and how to deal with individual people’s behavior. This point must be addressed jointly with social sciences, broadening the meaning of *just* SOS (Rockström et al., 2023). To support sufficiency efforts from the producers’ side, sustainable business models need to be adapted to integrate a link to limits and fair share. Concerning LCA, we believe that the shift to an absolute sustainability perspective demands prioritizing integration of scenarios to model sets of possible futures targeted at SOS compliance. Scenarios would have to account for the allowed size of the market sector, possible sustainable business models for companies to adopt, the role of stakeholders along the value chain, and so on. An interesting and established framework to construct scenarios is the Shared Socioeconomic Pathways (O’Neill et al., 2017), which provide development narratives to reach climate goals. These pathways provide five scenarios posing different challenges for mitigation and adaptation strategies, offering a solid basis to discuss possible roads to make our system sustainable in a PB-based absolute way. Parallel to this modeling work, we encourage discussion on the definition of absolute sustainability, which can shape results of this transition and help imagine how the future will look like. We agree with Guinée et al. (2022) that absolute sustainability, as currently framed, is also relative because its validity depends on strong assumptions, including that carrying capacity shares are perfectly assigned to all existing product systems, that functional units are defined by annual consumption levels, and that production remains constant over time. We complement this reasoning by arguing that such relativity also derives from its grounding in a weak sustainability paradigm. To avoid contradictions and greenwashing, we suggest that the absolute sustainability narrative should be primarily coupled to systems aimed at strong sustainability rather than growth. Reframing this discourse to support societal and economic transition could be complemented by the development of global pathways toward PB compliance, envisioning a

future where companies are ready to decouple from market dynamics.

Conclusions

We critically reviewed the historical integration of environmental limits in LCA, motivated by an asymmetry in assessing safety and sustainability within an SSbD context. Our comparison of early DtT weighting methods and modern PB-based approaches showed that the first attempts for LCA-based decision making in industrial contexts were also limited by policy-based target setting as compared with the science-based target-setting approach, which, underpinned by the PB framework, forms the basis of the modern PB-LCA. The main PB-LCA approaches identified include PB-based weighting, carrying capacity-based normalization, product-level reduction targets, and substituting current LCA impact assessment methods with PB-aligned impact categories. The current discussion on limits revolves around the methodologies of integrating the PB in sustainability assessment and agreeing on the strength of the PB framework. In our view, PB-LCA needs to address the challenges of (a) linking global and local scales, including the use of appropriate data in sustainability assessments, and (b) considering the great variability of system-level thresholds and their role in target setting. We highlighted the role of the valuesphere in selecting the distributional justice theory and sharing principles. To overcome the safety–sustainability asymmetry identified in SSbD, we propose a safety–sustainability integration rather than transitioning from a comparative to an absolute sustainability assessment paradigm for novel entities. In the future, we envision the need to strengthen the discussion and modeling of scenarios and consumption, as well as the definition of the role of absolute sustainability for consumers and companies, taking as examples the SBTs initiative and the SSbD framework.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Author contributions

Sarah Devecchi (Conceptualization, Data curation, Methodology, Writing—original draft, Writing—review & editing), Efsthios Reppas-Chrysovitsinos (Conceptualization, Methodology, Supervision, Writing—original draft, Writing—review & editing), Anna Lia S. Tromer Dragsdahl (Writing—review & editing), Lisa Pizzol (Writing—review & editing), Elena Semenzin (Funding acquisition, Writing—review & editing), Alex Zabeo (Writing—review & editing), Danail Hristozov (Funding acquisition, Writing—review & editing), and Tomas Rydberg (Conceptualization, Funding acquisition, Methodology, Supervision, Writing—review & editing)

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Conflicts of interest

The authors declare no conflict of interest for this work.

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