

Planetary Boundaries and Absolute Sustainability in Life Cycle Assessment – past, present, and future

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Conflicts of interest

The author declares no conflict of interest for this work.

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PLANETARY BOUNDARIES AND ABSOLUTE SUSTAINABILITY IN LCA – PAST, PRESENT, AND FUTURE.

ABSTRACT

Efforts to steer the social metabolism (i.e., how human societies interact with nature) towards sustainability are pulling assessment practice in two directions: “relative” product-to-product comparisons and “absolute” product-to-limit benchmarking, where the limit works as 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 towards absolute benchmarking against global environmental limits, leading to Absolute Environmental Sustainability Assessment. This paper reviews how environmental limits are incorporated into Life Cycle Assessment through early distance to target methods (such as Ecological Scarcity, Environmental Themes, 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 argue that making this “valuesphere” explicit is crucial if

24 Planetary Boundaries based Life Cycle Assessment is to inform credible, product-level Safe
25 and Sustainable by Design decisions on absolute sustainability.

26 **KEYWORDS**

27 Planetary boundaries; life cycle assessment (LCA); Absolute sustainability; Environmental
28 limits; Safe and Sustainable by Design (SSbD).

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INTRODUCTION

Efforts to steer the social metabolism of nature towards 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 (PBs) 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 (i.e., the stock of resources but also the set of interactions of biotic and abiotic natural systems) is limited, 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 socio-economic system and structures are grounded in the weak sustainability paradigm, i.e., 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 both “absolute” product-to-limit and “relative” product-to-product assessments, where, respectively, limits and reference products function as benchmarks for the assessment. A typical example of the first direction is Risk Assessment (RA) (van Leeuwen & Vermeire, 2007), while Life Cycle Assessment (LCA) is a characteristic case of the latter (Olsen et al., 2001). Chemical risk assessment compares exposure concentrations against specified effect thresholds, yielding a binary notion of safety (safe: yes/no), while LCA commonly reports comparative impact profiles (sustainable: more/less). Emerging frameworks such as Safe and Sustainable by Design Chemicals and Materials EC framework (SSbD) (Caldeira et al., 2022; Garmendia Aguirre et al., 2025) aim to couple chemical RA to LCA to guide safe and sustainable innovation. This coupling exposes an asymmetry at the core of current SSbD practice.

Two lines of LCA method development have emerged in response to this asymmetry. First, comparative toxicological impact assessment methods, often framed as chemical footprinting, have been developed to quantify human and ecotoxicological impact potentials analogously to other LCA impact categories such as global warming and ozone depletion (Bjørn et al., 2014). This approach extends the relative nature of LCA to toxicity-related pressures and aligns naturally with weak sustainability interpretations that emphasize trade-offs and substitutions within an overall environmental impact budget.

Second, “absolute” sustainability assessment methods have emerged, aiming at benchmarking product systems against explicit environmental limits rather than against alternatives, as is typical in conventional LCA. The PB framework plays a central role in this second line, serving as the backbone for methods such as Absolute Environmental Sustainability Assessment (AESAs), of which PB-based LCA (PB-LCA) is the most popular subset (Bjørn, Chandrakumar, et al., 2020). By identifying control variables and boundary ranges for key Earth-system processes, PBs re-organize environmental limits from a list of more context-dependent and politically defined regional targets into a set of non-negotiable global Earth-system boundaries.

The PB framework emergence coincided with the standardization phase of LCA (ISO 2006a, b) and the advancement of assessment methods (Finnveden, 2009), renewing the interest in including environmental limits in LCA to support decision-making (Bjørn & Hauschild, 2014). However, incorporating environmental limits in sustainability assessments has been a longstanding objective, well before the PB framework and the corresponding emergence of PB-LCA and AESAs.

Historically, incorporating limits in LCA has been based on weighting methods. Weighting methods in LCA can be grouped based on their approaches for aggregating results in three

classes: 1) expert panel or similar, 2) monetary valuation, 3) distance to targets (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). DtT methods such as Ecological Scarcity Method (ESM), Environmental Themes (ET), 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 beyond purely internal comparisons, but did so within fragmented, context-specific notions of “absolute” grounded in particular policy and protection goals.

The integration of environmental limits in sustainability assessment has matured alongside the development of i) production systems, ii) the state of scientific knowledge - including the PB framework –, and iii) the social and political readiness to implement changes in production, partially reflected in the SSbD agenda. We thus need to explore the emergence of the PBs and absolute sustainability concepts within the history of LCA thus far, to provide a perspective on their potential development. We critically review how environmental limits have been integrated into LCA historically and analyze how the PB framework reshapes this integration, and what this implies for operationalizing absolute sustainability, especially within SSbD. The need for this review emerged in discussions among researchers working in the Horizon Europe projects BioSusTex (GA 101135372), SunRise (GA 101137324), and CheMatSustain (GA 101137990), as these projects seek to address similar questions on the relationship of absolute sustainability and SSbD. Our aim is to address the RA-LCA asymmetry in the SSbD framework from the perspective of the historical integration of environmental limits into LCA - from early

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103 DtT methods to PB-LCA and AESA - and examine how these developments reflect different
104 understandings of sustainability.

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

MATERIALS AND METHODS

This study seeks to explore the historical evolution of conceptualization and use of limits in LCA. We reviewed seminal scientific and “grey” literature to identify LCA studies that apply the “relation to standards” weighting and evaluate their conceptual and methodological connection to the PB framework. Exchanges with experts both within and outside the Horizon Europe projects BioSusTex (GA 101135372), SunRise (GA 101137324), and CheMatSustain (GA 101137990) helped refine the research questions and ensure comprehensive coverage of the relevant literature. Given the historical character of our study, we organized the material in three sections: past (from early DtT methods until the emergence of PB-based LCA), present (PB-based 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, the current methodological developments, challenges, and opportunities ahead, which collectively informed the discussion presented in this manuscript. The work began with the review of some LCA-based methods developed in the 1990s integrating DtT weighting as support to decision making, while regarding PB-based LCA, several approaches have been proposed, including weighting, normalization, and the calculation of new characterization factors for PBs 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, that 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.

Literature review – Present.

The *Present* section was developed through a targeted critical review aimed at identifying methodological contributions to operationalize the integration of PBs into LCA. The process began with the review paper of Bjørn, Chandrakumar, 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 focusing on the operationalization of one boundary or presenting case studies rather than methodological advancements were not included. Table 2 summarizes approaches that integrate PBs into LCA (*Present*).

Literature review – Future.

To complement the historical and methodological analysis, we also examined selected application contexts in which PBs are being operationalized for industrial decision-making. The selection was guided by three criteria: i) an explicit conceptual or methodological link to absolute environmental sustainability assessment and/or operationalization, and ii) 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 (NEs) 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 PBs, 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 as a concrete example of PBs operationalization (2024); the PB for NEs is a critical unresolved question in the PBs 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 PBs concept is moving from a global perspective towards an operational tool to use in product development, chemical management, and corporate sustainability strategies.

Comparative approach.

We focused on four dimensions for analyzing the literature and synthesizing it in a comprehensive manner: i) comparing the LCA methods reviewed in terms of the impact categories included, weighting approach, and target-setting, ii) describing the historical transformation of environmental limits in the scientific research to which these LCA methods correspond, iii) exploring the broader limits-based LCA practices within their historically-specific scientific and political era, and iv) reflecting on subjective elements included in the

190 methods. The literature reviewed for the first two dimensions is the same as the one listed in
191 Table 1 and 2. For the third dimension, we turned to literature on ecological/environmental
192 limits (e.g., carrying capacities, critical loads, socio-ecological principles, and the PBs), and
193 revisited major global agendas that served as sustainability-steering instruments (e.g.,
194 Millenium Development Goals, Rio Declaration, Sustainable Development Goals). The scope
195 of this review is to understand the origins and future of the limits-based LCA from an SSbD
196 perspective and therefore for third dimension we focused on key-studies / agendas. For the last
197 dimension, we analyzed the same literature paying attention to how subjective decisions were
198 described and reported for each section.

RESULTS

Past.

We identified and reviewed three distinct DtT methods established prior to the emergence of the PB-based LCA approaches: the ESM, ET, and EI95. In these approaches targets were typically calculated as annual load limits set at the national level by environmental protection agencies, legislations, or regulations. The aim of introducing DtT approaches was to streamline the use of LCA in industry practice as a day-to-day decision-making tool to provide fast and informed design choices. To integrate LCA into product development and support industrial application needs, weighting was used to guide impact prioritization and obtain a single score associated with products/processes. At a time when LCA was still establishing its methodological robustness and gaining broader acceptance as a decision-support tool, target setting based on scientific evidence and political acceptance aligned with the need for a gradual definition of environmental limits.

Specifying a value for each target requires a vast set of data, detailed environmental models, and political acceptance of what constitutes a defined threshold. The ESM, proposed by Muller-Wenk in 1978 to interpret LCA impacts, was the earliest DtT method we identified (Frischknecht et al., 2009). The EI95 (Goedkoop, 1995) and ET method (Baumann & Rydberg, 1994; Lindfors et al., 1995) were independently developed in the Netherlands and the Nordic countries, respectively. In the following paragraphs, the ESM, ET, and EI95 DtT weighting methods are presented according to their (i) intended application, (ii) coverage and target values, (iii) weighting principles, and (iv) use of results.

Ecological scarcity method (ESM). The ESM was introduced for the internal environmental assessment of the Frisco-Findus AG company, based in Switzerland. Later, the Migros corporate group set up a team (Ahbe, S., Braunschweig, A., Muller-Wenk, R.) to improve the

calculations and based it on the Swiss national objectives. The company was driven by the need for a method to measure its efforts toward improved sustainability, particularly in packaging selection. The results of the study were published by the Federal Office for Environment, Forestry, and Landscape as a series of papers “Methodology for Ecobalances” from the study group in 1990 (*eco-scout*, 2025). The ESM covers several resource/substance’s flows for the Swiss region, considering both the current (at the time) values and the critical values, i.e., the values accepted and implemented into policy targets. The critical values are based on either 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 GHGs, 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 grey literature and industrial reports rather than in peer-reviewed scientific articles, while published contributions have often focused on methodological development and on 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 both 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-regions perspective, the aluminium results shifted strongly towards 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 (VNCI) and the Dutch government in the early 1990s. Its development was carried out by the Centre of Environmental Science in Leiden (CML), The Dutch National Institute for Health and Environment (RIVM), and the McKinsey & Company Inc were in charge for the development (Baumann & Rydberg, 1994; Seppälä & Hämäläinen, 2001). The method was later refined by Chalmers Industriteknik (CIT) 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, respectively using political goals (i.e., ET short) or ecological critical loads (i.e., ET long). The latest development of the method was tested and implemented in several CIT 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 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 Environmental Theme method through a milk-packaging example, comparing 1 L brick-shaped cartons with refillable polycarbonate bottles. The environmental loads from the Life Cycle Inventory (LCI) were first assigned to environmental themes, 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 two packaging options was used to compare their environmental performance. The ET score indicated no substantial difference between the two 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,

297 producing a one-number result. The ET thus provides a structured tool to support the
298 integration of environmental considerations into product design.

299 *Eco-indicator95 (EI95)*. Around the same time as the ET method, the EI95 was developed in
300 the Netherlands by the National Reuse of Waste Research Program (NOH). A multidisciplinary
301 team, including representatives from industry, science, and government, contributed to
302 defining a weighting approach for the Dutch LCA method (Heijungs et al., 1992). The target
303 values incorporated in EI95 were supported by a scenario study produced by RIVM for the
304 GLOBE Europe organization and complemented by the World Health Organization's Air
305 Quality (WHO, 1987) and Water Quality Guidelines for Europe (WHO, 1993). Unlike methods
306 based on policy goals, EI95 relies on scientifically derived targets, defined as low damage
307 thresholds. Targets were selected by evaluating the effects of processes detrimental to the
308 environment and/or human health. Each target corresponds to a specific level of damage caused
309 to the environmental effect considered. For instance, the greenhouse effect is characterized in
310 terms of ecosystem impairment resulting from rising temperatures. From this, a reduction
311 factor is estimated to bring the impairment down to an acceptable level. An acceptable damage
312 level was assumed to correspond to one human fatality per million inhabitants per year,
313 impairment of 5% of the ecosystem (e.g., reduction of agricultural yield by %), or the absence
314 of smog periods. These three levels were selected as equivalent reference points. The EI95
315 method evaluates the effects of a product system on human health and ecosystem at the
316 European scale. The resulting impacts are weighed according to how close the measured effects
317 are to the defined target level. Based on the shape of the damage-effect curve, a reduction factor
318 is derived to reach the acceptable damage level, and this value is applied as the weighting
319 factor. The EI95 developed a set of 100 material and processes associated with eco-indicators,
320 intended to support decision-making in research and product development. As illustrated in the
321 EI95 Manual for Designers (Goedkoop et al., 1996), a product's LCI can be linked to these

predefined materials and processes, and the final score is calculated by multiplying each process amount by the corresponding eco-indicator. In the worked example of a coffee machine, the use phase dominates the overall result due to electricity consumption, highlighting where design intervention would be more effective.

Present.

In this section we review the process that led from the conceptualization of the PB framework to setting “absolute sustainability” targets in LCA. Absolute sustainability builds on the PBs concept, in which environmental limits are defined as a set of global thresholds that integrate both scientific evidence and normative judgement. The former refers to the Holocene-based control variables of key earth system processes, while the latter reflects societal perception of safety, risk, and uncertainty (Rockström et al., 2009). Each boundary is defined using pre-industrial Holocene conditions as target levels, as the industrial revolution is a candidate watershed of pre- and post-Anthropocene periods. With that set as the baseline, the extent of human-driven planetary deviations is evaluated. Rockström et al., (2009) used various approaches to establish and quantify individual boundaries, depending on data availability and the current scientific understanding derived from analytical and modelling studies of the relevant Earth system processes. Data availability is considered a limitation for the definition of appropriate control variables, and continuous updates aim at integrating the best available knowledge. Modelling includes estimations of the levels of disturbance that may trigger impacts or alter interactions and feedbacks, potentially leading to irreversible changes in Earth’s life-support systems (Richardson et al., 2023). Since the first released version (Rockström et al., 2009), numerous studies have been published on it, with noteworthy updates of the framework published by Steffen et al., (2015), Richardson et al., (2023), and annual Planetary Health Check reports since 2024 (Sakschewski et al., 2025).

The need to operationalize PBs 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 further reinforced by the explicit call to move beyond eco-efficiency and towards 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 PBs 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 (Tuomisto et al., 2012). Although grounded in PBs, these factors require further adaptation for LCA use, as a direct equivalence between PBs control variables and LCA impact categories is not yet established. Then, Bjørn & Hauschild (2015) developed carrying capacity-based normalization factors, highlighting that several LCA indicators implicitly address carrying capacity but only in terms of threshold exceedance, missing to consider values close but below them. By explicitly integrating appropriate measures of carrying capacity, they proposed the use of PBs as sustainability reference within the normalization step of LCA. This approach was later adapted to align with the Product Environmental Footprint (PEF) method (Sala et al., 2020), that provided equivalences between PBs metrics and PEF indicators.

Parallel developments explored how to link the global thresholds to lower scales. The set of PBs delimits the global Safe Operating Space (SOS), i.e., 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 PBs 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, Clavreul, et al. (2018) proposed redefining LCIA impact categories by that the earth system processes could be used as new impact categories in the LCIA phase, by replacing conventional LCA impact category indicators with Earth system processes and their control variables, effectively reversed the integration logic by adapting LCA to PBs rather than vice versa.

Following these foundational contributions, recent literature has further refined the operationalisation 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 prioritisation, prospective modelling, 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 fulfilment, Lund et al. (2025) used AESA to prioritise impact categories in building LCA, and Manthos et al. (2026) combined prospective LCA, AESA, SSPs and market-penetration modelling 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 instead 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 operationalisation, readers are referred to Paulillo & Sanyé-

Mengual (2024), Acevedo et al. (2026), and the recent JRC 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, Chandrakumar, et al. (2020) published already a few years ago highlighted that a key challenge lies in linking global PBs 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 also discussed more recently in Paulillo & 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 already introduced by Hofstetter et al. (2000), to indicate the inevitability of integrating and explicating the subjective element in a LCA assessment, as 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 socio-economic 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, Sim, 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 PBs is crucial to support the human development through the stable Holocene conditions. On the other hand, 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, and yet scientifically sound absolute sustainability thresholds remains unanswered. To address this question with practical examples, in this section we reviewed approaches to operationalize absolute sustainability for industrial decision making.

Science based targets for nature (SBTs). The first practical application of absolute sustainability in case studies grounded in the PB framework is found in the Science Based Targets Network (Science Based Targets Network, 2026a), which supports companies in setting validated greenhouse gases (GHGs) reductions targets. Established in 2015 following the Paris agreement, the initiative initially focused on aligning corporate GHGs emissions reduction with global climate goals. Its founding partners include the World Wide Fund for

Nature (WWF), the United Nations Global Compact (UNGC), and the World Resources Institute (WRI) (Romito et al., 2024). With the growing influence of the PB framework, the SBTs initiative has developed by integrating ecological limits into its scientific basis for target setting. Complementing the Science Based Target initiative (SBTi), which addresses only the Climate Change boundary, it 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 PBs compliance in a target year. This allocation is based on distributional justice theories, with grandfathering being the most applied. As discussed above, 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 land targets by H&M Group illustrates how science-based targets can operationalise absolute sustainability thinking in corporate decision-making (Science Based Target Network, 2026b). Rather than relying only on 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 (Science Based Target Network 2026a). The scope of SBTN is now expanding to cover not only target setting for companies but also for cities.

Novel entities. Chemicals and materials have come to play a central role in the global economy, making chemical and material pressure on PBs a growing concern, as the rapid expansion in production and diversification of synthetic substances increasingly outpaces the capacity to assess their potential health and environmental impacts prior to market release. This pressure,

originally framed within the PB framework as *chemical pollution*, (see section *Comparison and synthesis* above), has progressively expanded to encompass a broader set of anthropogenic components, including plastic polymers (Villarrubia-Gómez et al., 2018), engineered nanomaterials (Jahnke et al., 2026), and radioactive materials (Böse et al., 2026). Renamed *novel entities*, the boundary now covers “anthropogenic and naturally occurring chemicals, materials, and other human-generated entities that have the potential to disrupt Earth system processes through biological or physical effects, whose likelihood and scale of impact are increased by persistence, mobility, accumulation, and delayed detectability” (Jahnke et al., 2026). The novel entities boundary thus functions as a placeholder for a yet unknown boundary lacking a well-defined control variable and is characterized by interactions with other PBs (Kosnik et al., 2022). Persson et al. (2022) and Richardson et al. (2023) suggest to define the boundary as *no release of untested anthropogenic introductions*, implying that the threshold is already transgressed due to the large numbers of new substances synthesized and introduced every year without comprehensive assessment. A growing body of literature is exploring alternative definitions, metrics, and potential control variables for novel entities (Dragsdahl et al., 2025; Reppas-Chrysovitsinos et al., 2025), highlighting concerns related to their persistence, long-range transport, accumulation pathways, and also the pace of production, which hinders systematic safety evaluation and long-term environmental sustainability assessment.

Safe and sustainable by design (SSbD). A further opportunity for operationalization is currently being explored within the EC SSbD framework for chemicals and materials. One of the framework’s key objectives is to aggregate results of safety and sustainability assessments, echoing the interpretation need of the DtT weighting methods. This is challenged by the comparative approach used in sustainability assessment, which generally prevents the formulation of a yes/no conclusion regarding the sustainability of a system. In this context, the

SSbD framework suggests that Step4 (environmental sustainability assessment) should consider an absolute perspective based on the PBs and carrying capacity concepts, aiming to safeguard the resource needs of future generations (Caldeira et al., 2022). The LCA combination with the limits established within the PB framework could provide a way to overcome the question, by prospectively assessing whether emerging products and technologies operate within their share of the SOS. On the other hand, the recent update of the framework does not explicitly mention a shift towards absolute sustainability but redefines benchmarks to function as threshold values (Garmendia Aguirre et al., 2025). The definition of PB-based sustainability impact thresholds is currently being investigated, building on emerging applications of AESA at the product level, a scale that is central to the SSbD framework. Although SSbD has already been tested in several application contexts and case studies, examples explicitly integrating SSbD with PB-based AESA are missing. This confirms the prospective character of this research stream. As highlighted by Hussein et al. (2025), there is currently no general framework to guide the SSbD assessment of chemicals, materials and products using PBs. Existing AESA applications are still often disconnected from early-stage design decisions, low-TRL technologies and material- or component-level assessment. Ultimately, translating global environmental boundaries to the product level is essential for implementing the PB framework in practice: companies must be able to understand and manage their contribution to respecting these boundaries. Indeed, policies set directions, but businesses are the primary actors tasked with measuring and managing their environmental performance. Translating global boundaries to smaller systems introduces substantial variability, depending on the principle used, and high uncertainty, increasing as the system scale narrows. In other words, assigning a share of SOS to a product system involves considerably greater uncertainty than assigning it to a country system. Nevertheless, this translation is particularly important especially for emerging technologies, which are often expected to support sustainability

transitions by improving or substituting existing practices. An SSbD assessments should therefore also consider whether their potential large-scale deployment would improve the product-system compatibility with environmental limits. In this perspective, integrating PB-based considerations into SSbD could help orient innovation towards solutions that are not merely less impactful, but aligned with the strong sustainability and transformative change required to respect PBs.

Comparison and synthesis.

We present our findings from i) comparing the LCA methods reviewed (Table 4), ii) describing the historical transformation of environmental limits (Figure 1), iii) placing the limits-based LCA within a historical context (Figure 2), and iv) identifying elements of the valuesphere across methods. Table 4 summarizes the criteria applied for the emission or damage levels used as a representation of the planetary or other boundaries used in the methods reviewed in the sections *Past* and *Present*. Direct numerical comparison between the methods is not feasible because the control variables, spatial scales, and indicator definitions are not harmonized. This lack of comparability reflects methodological differences in how environmental limits are conceptualized and operationalized. A recurring pattern is the transgression of the limits measured in the current values, across most methods and impact categories. This indicates a shared understanding of the entity of anthropogenic pressure on the environment, and of the urgency of reducing. As evident also in Figure 1, the control variables for the “Toxic/ecotoxic chemicals” impact category becomes increasingly aggregated over time, going toward the NEs PB that represents an umbrella term including all the substances included in the early methods.

Figure 1 illustrates how impact categories associated with environmental limits have changed over time, supporting the 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 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 PBs Earth system processes terminology) can be traced back to earlier methods and show substantial continuity over time. Notably, the precursors of the NEs 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 of 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*”) discussed above. 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, to which contributed both the theory provided by scientific production and the decisions taken within policy frameworks. The LCA practice has been shaped by both streams, influenced by the historical context (grey 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-based 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 agendas as prevalent instruments to address planetary level sustainability questions (e.g., Millenium 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, 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 of the methods, a background overarching configuration of value choices, normative judgements, distributional justice, and allocation principles functions as the underlying narrative scenario in which the methods operate. In 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 for the DtT methods their valuesphere dependence is more explicit, to the point of being one of the main criticisms of the LCA weighting step, in AESA and absolute sustainability it is less evident. The approaches that have operationalized these methods include few elements attributable to the valuesphere, such as selecting a

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594 temporal horizon, the reference population entitled to that environmental space, which
595 functions are socially necessary, and how responsibility should be distributed. Organizing these
596 elements in structured and coherent sets would help overcome some of the methodological
597 challenges that arose in this first decade of AESA application.

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598 **DISCUSSION**

599 *Linking past and present methods.*

600 Conceptually, despite their differences in goal and scope, we argue that both AESA and PB-
601 LCA i) aim to evaluate how a given system performs relative to predefined environmental
602 limits or targets, ii) align with the weighting step of the LCA procedure, and iii) support the
603 interpretation phase of LCA by indicating which impact categories should be prioritized.
604 Below, we discuss each point with a comparative perspective.

605 *Evaluation against environmental limits.* In the case of the DtT methods examined in this study,
606 the environmental limits are conceived as the maximum acceptable load in a given area.
607 Acceptability is defined at the government level, according to the reference body that produced
608 the evidence. As a result, ideological profiles and societal preferences play a crucial role in
609 accepting targets proposed by the scientific community (Seppälä & Hämäläinen, 2001) and
610 define the valuesphere of reference for the specific DtT method. Because of this dependence
611 on value choices and stakeholders' judgment, it is essential to clearly explain how the
612 weighting factors were determined. For PBs environmental limits definition depends on an
613 integrated Earth-system perspective that synthesizes evidence on key biophysical processes
614 and their interactions across scientific disciplines, aiming to capture the most important
615 anthropogenic influence at the planetary level of the boundary in focus (Richardson et al.,
616 2023). Targets are defined as pre-industrial Holocene conditions for each boundary, where the
617 elements attributable to the valuesphere are the i) selection of studies to produce the evidence
618 synthesis, and ii) the assumption that pre-industrial conditions correspond to Earth-system
619 stability.

620 *Weighting perspective.* According to ISO 14040:2006a and ISO 14044:2006b, the integration
621 of impact categories results using weighting methods is an optional step in LCA. It consists in

assigning weights to the environmental impact categories considered in the assessment to support the interpretation of the results. The PB-based 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 applying DtT weighting, weights are calculated based on 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 assumes that all targets are considered as 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, both DtT weighting and PB-based LCA discuss results considering the deviation from targets levels, according to the purpose of the study. When these DtT approaches were conceptualized, datasets and models were less comprehensive than in 2009, when Rockstrom 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.

645 *Valuesphere*. In this article, we reviewed how the concept of environmental limits was
646 interpreted and implemented in the past, present, and how we envision it to be in the future of
647 LCA. The differences in the thresholds set in the past and present stress how much a boundary
648 for absolute assessment is dependent on the criterium set for its establishment. This choice will
649 ultimately be made by a partly subjective decision depending on the social and historical
650 context to which it pertains. In weighting, setting a target value can coincide with the definition
651 of a threshold for a PB, where pollutant critical loads (i.e., ESM), environmental themes' limits
652 (i.e., ET), or eco-points (i.e., EI95) are substituted by Earth system process control variables.
653 The values to set the limits for DtT methods were found to be predominantly subject to political
654 willingness to integrate scientifically defined targets in policy, or else focus on compromise-
655 based targets. A limitation of this approach is the gap between policy limits and best-case
656 scenario for environmental protection, as they are the results of debates matching science and
657 societal acceptance. This is evident when comparing the different definitions of goals in the
658 environmental sciences context and in global agendas, even with the shared aim of maintaining
659 the earth system in an acceptable status for human prosperity. On the contrary, the PB
660 framework, although openly anthropocentric, was conceived to be independent from any
661 country or policy. However, while pursuing objectivity in boundaries definition, AESA too
662 cannot, at this point, be decoupled from social values and preferences. This happens when
663 selecting the principles that guide the sharing of the PBs allowance, choices that reflect various
664 understanding of fairness. The share of SOS works additively, meaning that the sum of all
665 production and consumption should equal the earth system carrying capacity, resulting in a set
666 of scenarios of sustainability results for the same system according to different distribution of
667 SOS. In this way, the "absolute" element of sustainability advocated by this approach falls into
668 relativity because of the very nature of distributional justice theories, by definition providing
669 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, et al., 2018; Sandin et al., 2015). This distinction is particularly important because AESA is absolute in their reference to biophysical limits, but not value-free in their operationalization. The definition of thresholds, the translation of PBs into LCA-compatible indicators, the allocation of global limits to product-level functions, and the interpretation of transgressions all involve context-dependent normative judgements. 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 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: can absolute sustainability aim to produce stronger claims than DtT weighting?

Future.

Towards absolute sustainability. Grounded in the principles of strong sustainability, the PBs 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 along 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 (ICS) and the International Union of Geological Sciences (IUGS), 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, that means trying to be “less unsustainable” without engaging on concerns on growth (Steffens et al., 2025). On the other hand, PBs implicitly set limits to growth. By stating that the system studied exceeds its shares of SOS, AESA results call for less 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 but, 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 rely on context-specific reference systems that may not yet exist for novel solutions and 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 manuscript is their positioning with respect to 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 PBs. 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 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 above, 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 above 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 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 / Outlooks. Our systems – economic, political, social – are not (yet?) built to function within the PBs. To bring the Earth system back into its SOS several perspective changes are required, along with a more radical socio-economic transition. The PBs 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, both 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 address jointly with social sciences, broadening the meaning of *just* safe operating space (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 to prioritize 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 Socio-economic Pathways (SSPs) (O’Neill et

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al., 2017), that 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 PBs-based absolute way. Parallel to this modelling 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 based on 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 towards PBs 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 context were also limited by policy-based target-setting compared to the science-based target-setting approach which, underpinned by the PB framework, forms the basis of the modern PB-based LCA. The main PB-based 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 PBs in sustainability assessment and agreeing on the strength of the PB framework. In our view, PB-based LCA needs to address the challenges of i) linking global and local scales, including the use of appropriate data in sustainability assessments, and ii) considering the great variability of system-level thresholds and their role in target-setting. We further 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 scenario and consumption discussion and modelling, 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.

Figure captions

Figure 1. Comparison of impact categories in DtT weighting methods and PBs 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 along 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)); P: Phosphorus; N: Nitrogen The overlap of colours in “ozone layer depletion”, “acidification”, and “eutrophication” represent an overlap of terms in the respective methods.

Figure 1 – Alt text

Timeline diagram showing the evolution and continuity of environmental impact categories across the Ecological Scarcity Method, Environmental Themes method, Eco-indicator 95, and successive Planetary Boundaries 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 later emergence of Earth-system processes such as biosphere integrity, land-system change, freshwater change, and novel entities.

Figure 2. Conceptual representation of the interactions of Life Cycle Assessment practice, scientific understanding of environmental limits, and policy frameworks. ■ Science; ■ LCA; ■ Policy. PBs: Planetary Boundaries; LCA: Life Cycle Assessment; CH: Switzerland; NL: The Netherlands; DtT: Distance to Target; PB-LCA: Planetary Boundaries based Life Cycle Assessment; AESA: Absolute Environmental Sustainability Assessment; NEPA: National

Environmental Policy Act; MDGs: Millenium Development Goals; SDGs: Sustainable Development Goals; SSbD: Safe and Sustainable by Design; CE: Circular Economy.

Figure 2 – Alt text

Timeline showing the co-evolution of environmental science, Life Cycle Assessment (LCA) practice, and sustainability policy. Scientific concepts and policy developments precede and influence successive LCA approaches, from early environmental limits and distance-to-target (DtT) weighting methods to Planetary Boundaries (PBs), PB-LCA, Absolute Environmental Sustainability Assessment (AESAs), and Safe and Sustainable by Design (SSbD).

Figure 3. *A proposal to reframe the asymmetry between safety and Sustainability in SSbD. LCA: Life Cycle Assessment; SSbD: Safe and Sustainable by Design; SOS: Safe Operating Space.*

Figure 3 – Alt text

Conceptual diagram comparing two approaches to sustainability assessment within Safe and Sustainable by Design (SSbD). The upper panel shows a shift from comparative to absolute assessment: safety is evaluated against a yes/no threshold, while comparative Life Cycle Assessment (LCA) based on more/less impact is replaced by an absolute LCA assessment against an allocated share of the Safe Operating Space (SOS). The lower panel shows the proposed combined approach, in which safety retains its yes/no threshold and sustainability integrates both comparative LCA between alternatives and absolute assessment against the SOS.

REFERENCES

- Acevedo, L. I., Pigosso, D. C. A., & McAloone, T. C. (2026). Understanding a new emerging philosophy: Absolute sustainability. *Sustainable Production and Consumption*, 66, 74–91. <https://doi.org/10.1016/j.spc.2026.04.010>
- Ahbe, S., Weihofen, S., & Wellge, S. (2018). The ecological scarcity method for the European Union. Springer Fachmedien Wiesbaden.
- Annema, J. A. (1992). Life-cycle assessment. In *Life-cycle assessment: Proceedings of a SETAC-Europe workshop on environmental life-cycle assessment of products* (pp. 73–80). Society of Environmental Toxicology and Chemistry-Europe.
- Baumann, H., Ekvall, T., Eriksson, E., Kullman, M., Rydberg, T., Ryding, S. O., Svensson, G., & Steen, B. (1993). Miljömässiga skillnader mellan återvinning/återanvändning och förbränning/deponering [Environmental differences between recycling/reuse and incineration/landfill] (FoU No. 79). REFORSK.
- Baumann, H., & Rydberg, T. (1994). Life cycle assessment: A comparison of three methods for impact analysis and evaluation. *Journal of Cleaner Production*, 2(1), 13–20. [https://doi.org/10.1016/0959-6526\(94\)90020-5](https://doi.org/10.1016/0959-6526(94)90020-5)
- Bjørn, A., Diamond, M. L., Birkved, M., & Hauschild, M. Z. (2014). Chemical footprint method for improved communication of freshwater ecotoxicity impacts in the context of ecological limits. *Environmental Science & Technology*, 48(22), 13253–13262. <https://doi.org/10.1021/es503797d>
- Bjørn, A., & Hauschild, M. Z. (2014, May 4–8). Integrating planetary boundaries into the life cycle assessment framework for assessing absolute environmental sustainability of products and systems [Conference presentation]. Third International Resilience Science and Policy Conference, Montpellier, France.

- 875 Bjørn, A., Diamond, M., Owsianiak, M., Verzat, B., & Hauschild, M. Z. (2015).
876 Strengthening the link between life cycle assessment and indicators for absolute sustainability
877 to support development within planetary boundaries. *Environmental Science & Technology*,
878 49(11), 6370–6371. <https://doi.org/10.1021/acs.est.5b02106>
- 879 Bjørn, A., & Hauschild, M. Z. (2015). Introducing carrying capacity-based normalisation in
880 LCA: Framework and development of references at midpoint level. *The International Journal*
881 *of Life Cycle Assessment*, 20(7), 1005–1018. <https://doi.org/10.1007/s11367-015-0899-2>
- 882 Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., Hauschild,
883 M. Z., Kerkhof, A., King, H., Margni, M., McLaren, S., Mueller, C., Owsianiak, M., Peters,
884 G., Roos, S., Sala, S., Sandin, G., Sim, S., Vargas-Gonzalez, M., & Ryberg, M. (2020). Review
885 of life-cycle-based methods for absolute environmental sustainability assessment and their
886 applications. *Environmental Research Letters*, 15(8), 083001. <https://doi.org/10.1088/1748-9326/ab89d7>
- 887
888 Bjørn, A., Sim, S., King, H., Patouillard, L., Margni, M., Hauschild, M. Z., & Ryberg, M.
889 (2020). Life cycle assessment applying planetary and regional boundaries to the process level:
890 A model case study. *The International Journal of Life Cycle Assessment*, 25(11), 2241–2254.
891 <https://doi.org/10.1007/s11367-020-01823-8>
- 892 Bjørn, A., Tilsted, J. P., Addas, A., & Lloyd, S. M. (2022). Can science-based targets make
893 the private sector Paris-aligned? A review of the emerging evidence. *Current Climate Change*
894 *Reports*, 8, 53–69. <https://doi.org/10.1007/s40641-022-00182-w>
- 895 Bjørn, A., Paulillo, A., Sanyé-Mengual, E., De Laurentiis, V., Veà, E. B., Hauschild, M. Z.,
896 & Sala, S. (2025). Guidance for applying absolute environmental sustainability assessment on
897 activities at different scales: Beta version (JRC142099). Publications Office of the European
898 Union. <https://doi.org/10.2760/7677803>

Revised Manuscript 26.08.2026

- Böse, F., Neugebauer, J., Lösel, T., Nickel, M.-S., Wimmers, A., & von Hirschhausen, C. (2026). Bridging a gap: Analyzing radioactive materials within the planetary boundary framework. *Ecological Economics*, 244, 108971. <https://doi.org/10.1016/j.ecolecon.2026.108971>
- Caldeira, C., Farcal, R., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). Safe and sustainable by design chemicals and materials: Framework for the definition of criteria and evaluation procedure for chemicals and materials (EUR 31100 EN; JRC128591). Publications Office of the European Union. <https://doi.org/10.2760/487955>
- Downing, A. S., Bhowmik, A., Collste, D., Cornell, S. E., Donges, J., Fetzer, I., Häyhä, T., Hinton, J., Lade, S., & Mooij, W. M. (2019). Matching scope, purpose and uses of planetary boundaries science. *Environmental Research Letters*, 14(7), 073005. <https://doi.org/10.1088/1748-9326/ab22c9>
- Dragsdahl, A. L. S. T., Olsen, S. I., Hansen, S. F., & von Borries, K. (2025). Toward defining an absolute sustainability boundary for nanomaterials. In 1st International Conference on Absolute Sustainability—From Less Bad to Good Enough: Programme and book of abstracts (p. 49). DTU Centre for Absolute Sustainability.
- Eco-Scout. (2025). History of the ecological scarcity method (ESM). <https://eco-scout.org/en/history/>
- Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Cleaner Production*, 17(7), 905–916. <https://doi.org/10.1016/j.jclepro.2009.01.012>
- Frischknecht, R., Steiner, R., & Jungbluth, N. (2009). The ecological scarcity method—Eco-Factors 2006: A method for impact assessment in LCA (Environmental Studies No. 0906). Federal Office for the Environment.

- 924 Garmendia Aguirre, I., Abbate, E., Bracalente, G., Mancini, L., Cappucci, G. M., Tosches,
925 D., Rasmussen, K., Sokull-Klüttgen, B., Rauscher, H., & Sala, S. (2025). Safe and sustainable
926 by design chemicals and materials: Revised framework (EUR 40399; JRC143022).
927 Publications Office of the European Union. <https://doi.org/10.2760/5103785>
- 928 Goedkoop, M. (1995). The Eco-indicator 95: Weighting method for environmental effects
929 that damage ecosystems or human health on a European scale: Final report (NOH Report 9523).
930 PRé Consultants.
- 931 Goedkoop, M., Demmers, M., & Collignon, M. (1996). The Eco-indicator 95: Manual for
932 designers (NOH Report 9524). PRé Consultants.
- 933 Grinberg, M., Ackermann, R., & Finkbeiner, M. (2012). Ecological scarcity method:
934 Adaptation and implementation for different countries. Environmental and Climate
935 Technologies, 10, 9–15. <https://doi.org/10.2478/v10145-012-0019-5>
- 936 Guinée, J. B., Udo de Haes, H. A., & Huppes, G. (1993). Quantitative life cycle assessment
937 of products: 1. Goal definition and inventory. Journal of Cleaner Production, 1, 3–13.
938 [https://doi.org/10.1016/0959-6526\(93\)90027-9](https://doi.org/10.1016/0959-6526(93)90027-9)
- 939 Guinée, J. B., de Koning, A., & Heijungs, R. (2022). Life cycle assessment-based absolute
940 environmental sustainability assessment is also relative. Journal of Industrial Ecology, 26(3),
941 673–682. <https://doi.org/10.1111/jiec.13260>
- 942 Hauschild, M. Z. (2015). Better—but is it good enough? On the need to consider both eco-
943 efficiency and eco-effectiveness to gauge industrial sustainability. Procedia CIRP, 29, 1–7.
944 <https://doi.org/10.1016/j.procir.2015.02.126>
- 945 Heide, M., Hauschild, M. Z., & Ryberg, M. (2023). Reflecting the importance of human needs
946 fulfilment in absolute sustainability assessments: Development of a sharing principle. Journal
947 of Industrial Ecology, 27(4), 1151–1164. <https://doi.org/10.1111/jiec.13405>

Revised Manuscript 26.08.2026

- 948 Heijungs, R., Guinée, J. B., Huppes, G., Lankreijer, R. M., Udo de Haes, H. A., Wegener
949 Sleeswijk, A., Ansems, A. M. M., Eggels, P. G., van Duin, R., & de Goede, H. P. (1992).
950 Environmental life cycle assessment of products: I. Guide; II. Backgrounds (NOH Reports
951 9266–9267). CML.
- 952 Hofstetter, P., Baumgartner, T., & Scholz, R. W. (2000). Modelling the valuesphere and the
953 ecosphere: Integrating the decision makers' perspectives into LCA. *The International Journal*
954 *of Life Cycle Assessment*, 5, 161–175. <https://doi.org/10.1007/BF02978618>
- 955 Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Veronesi, F., Vieira, M.
956 D. M., Hollander, A., Zijp, M., & van Zelm, R. (2016). ReCiPe 2016: A harmonized life cycle
957 impact assessment method at midpoint and endpoint level. Report I: Characterization (RIVM
958 Report 2016-0104). National Institute for Public Health and the Environment.
- 959 Hussein, Z., Benetto, E., & Saidani, M. (2025). Integrating planetary boundaries into the safe
960 and sustainable by design framework: A systematic literature review. *Sustainable Production*
961 *and Consumption*, 60, 64–77. <https://doi.org/10.1016/j.spc.2025.09.004>
- 962 International Organization for Standardization. (2006a). ISO 14040: Environmental
963 management—Life cycle assessment—Principles and framework (2nd ed.).
- 964 International Organization for Standardization. (2006b). ISO 14044: Environmental
965 management—Life cycle assessment—Requirements and guidelines (1st ed.).
- 966 Jahnke, A., Bai, Y., Brack, W., Carney Almroth, B., Diamond, M. L., Dragsdahl, A. L. S. T.,
967 Escher, B. I., Fantke, P., Kühnel, D., MacLeod, M., Ragas, A. M. J., Sakschewski, B., Schmidt,
968 C., Strauss, V., Treu, G., Villarrubia-Gómez, P., Wang, Z., Wendt-Potthoff, K., Ågerstrand,
969 M., & Caesar, L. (2026). Planetary boundary for novel entities: Time for a reboot.
970 *Environmental Science & Technology*, 60(28), 19761–19770.
971 <https://doi.org/10.1021/acs.est.6c03044>

Lindfors, L. G., Christiansen, K., Hoffmann, L., Virtanen, Y., Juntilla, V., Hanssen, O. J., Rønning, A., Ekvall, T., & Finnveden, G. (1995). Nordic guidelines on life-cycle assessment (Nord 1995:20). Nordic Council of Ministers.

Lund, M. N., Schjerbeck, A. K., & Bjørn, A. (2025). Using absolute environmental sustainability assessment and mid-to-endpoint modeling to identify the most relevant impact categories to include in a building LCA. *Building and Environment*, 278, 112985. <https://doi.org/10.1016/j.buildenv.2025.112985>

Manthos, G., Owsianiak, M., Siqueira, G., Nyström, G., Hauschild, M. Z., & Fozer, D. (2026). Evaluating prospective environmental impacts and market integration for enzymatic sugar beet pulp treatment against planetary boundaries. *Environmental Impact Assessment Review*, 118, 108339. <https://doi.org/10.1016/j.eiar.2026.108339>

McKinsey & Company Inc. (1991). Integrated substance chain management. Association of the Dutch Chemical Industry (VNCI).

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W., III. (1972). The limits to growth: A report for the Club of Rome's project on the predicament of mankind. Universe Books.

Muhl, M., Berger, M., & Finkbeiner, M. (2021). Distance-to-target weighting in LCA—A matter of perspective. *The International Journal of Life Cycle Assessment*, 26(1), 114–126. <https://doi.org/10.1007/s11367-020-01837-2>

Olsen, S. I., Christensen, F. M., Hauschild, M., Pedersen, F., Larsen, H. F., & Tørsløv, J. (2001). Life cycle impact assessment and risk assessment of chemicals—A methodological

Revised Manuscript 26.08.2026

comparison. *Environmental Impact Assessment Review*, 21(4), 385–404.

[https://doi.org/10.1016/S0195-9255\(01\)00075-0](https://doi.org/10.1016/S0195-9255(01)00075-0)

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42, 169–180.

<https://doi.org/10.1016/j.gloenvcha.2015.01.004>

Paulillo, A., & Sanyé-Mengual, E. (2024). Approaches to incorporate planetary boundaries in life cycle assessment: A critical review. *Resources, Environment and Sustainability*, 17, 100169. <https://doi.org/10.1016/j.resenv.2024.100169>

Paulillo, A., Wierzgala, P., Biganzoli, F., & Sanyé-Mengual, E. (2026). Investigating methodological aspects of absolute environmental sustainability assessment based on planetary boundaries. *Environmental Impact Assessment Review*, 117, 108154. <https://doi.org/10.1016/j.eiar.2025.108154>

Pelenc, J., Ballet, J., & Dedeurwaerdere, T. (2015). Weak sustainability versus strong sustainability [Brief for the Global Sustainable Development Report 2015]. United Nations.

Pennington, D. W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., & Rebitzer, G. (2004). Life cycle assessment part 2: Current impact assessment practice. *Environment International*, 30(5), 721–739. <https://doi.org/10.1016/j.envint.2003.12.009>

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environmental Science & Technology*, 56(3), 1510–1521. <https://doi.org/10.1021/acs.est.1c04158>

Revised Manuscript 26.08.2026

Targets initiative. *Business Strategy and the Environment*, 33(4), 2817–2831.

<https://doi.org/10.1002/bse.3639>

Ryberg, M. W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., & Hauschild, M. Z. (2018). How to bring absolute sustainability into decision-making: An industry case study using a planetary boundary-based methodology. *Science of the Total Environment*, 634, 1406–1416. <https://doi.org/10.1016/j.scitotenv.2018.04.075>

Ryberg, M. W., Owsianiak, M., Richardson, K., & Hauschild, M. Z. (2018). Development of a life-cycle impact assessment methodology linked to the planetary boundaries framework. *Ecological Indicators*, 88, 250–262. <https://doi.org/10.1016/j.ecolind.2017.12.065>

Rydberg, T. (1996, November 4). The environmental theme method (ET) in Sweden [Conference presentation]. International Seminar on Weighting Methods, Oslo, Norway.

Sakschewski, B., Caesar, L., Andersen, L. S., Bechthold, M., Bergfeld, L., Beusen, A. L., Billing, M., Bodirsky, B. L., Botsyun, S., Dennis, D. P., Donges, J. F., Dou, X., Eriksson, A., Fetzer, I., Gerten, D., Häyhä, T., Hebden, S., Heckmann, T., Heilemann, A., ... Rockström, J. (2025). Planetary Health Check 2025: A scientific assessment of the state of the planet. Potsdam Institute for Climate Impact Research. <https://doi.org/10.48485/pik.2025.017>

Sala, S., Crenna, E., Secchi, M., & Sanyé-Mengual, E. (2020). Environmental sustainability of European production and consumption assessed against planetary boundaries. *Journal of Environmental Management*, 269, 110686. <https://doi.org/10.1016/j.jenvman.2020.110686>

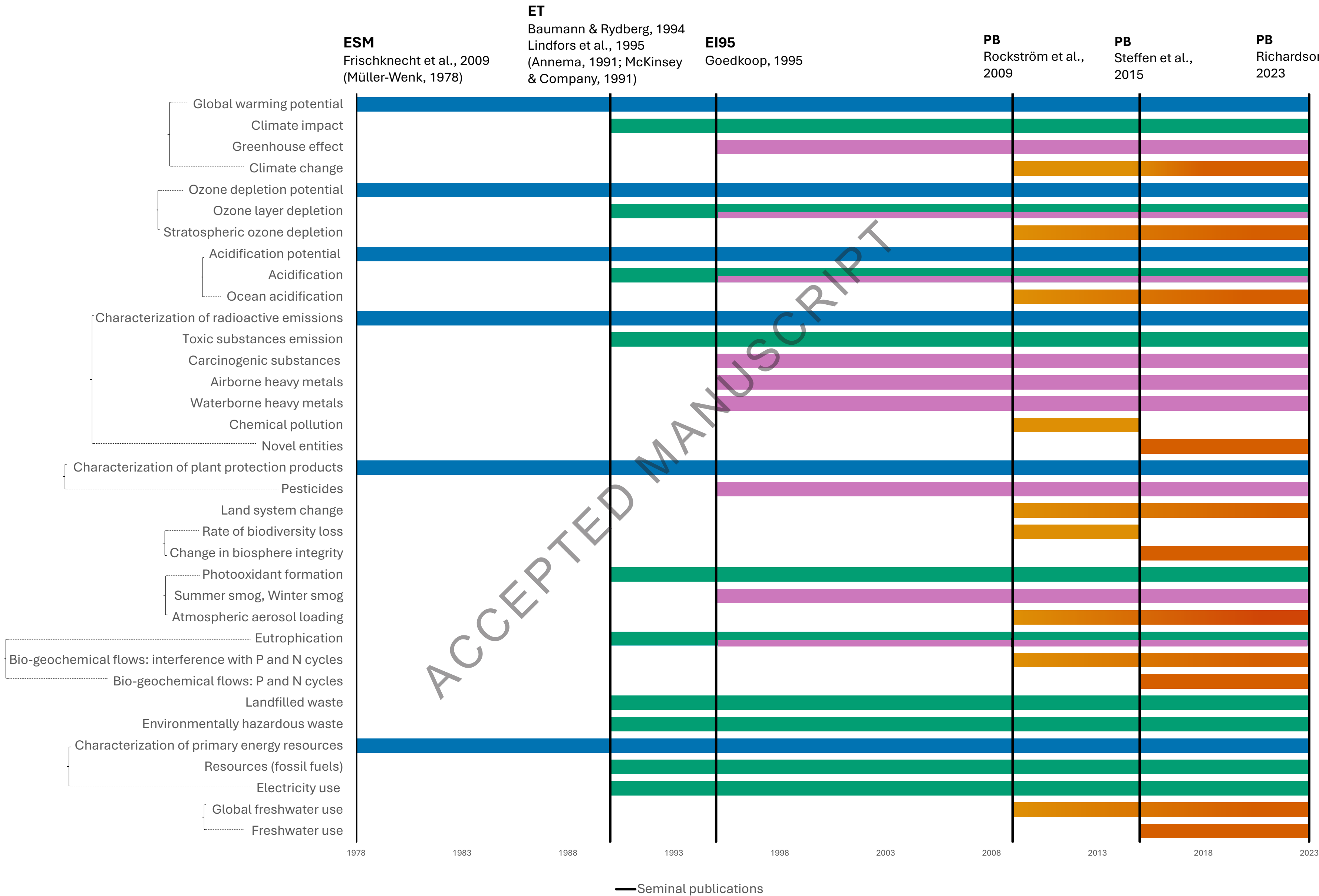
Sandin, G., Peters, G. M., & Svanström, M. (2015). Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. *The International Journal of Life Cycle Assessment*, 20(12), 1684–1700. <https://doi.org/10.1007/s11367-015-0984-6>

Schlesier, H., Schäfer, M., & Desing, H. (2024). Measuring the doughnut: A good life for all is possible within planetary boundaries. *Journal of Cleaner Production*, 448, 141447. <https://doi.org/10.1016/j.jclepro.2024.141447>

- 1070 Science Based Targets Network. (2026a). Science Based Targets Network. Retrieved June
1071 22, 2026, from <https://sciencebasedtargetsnetwork.org/>
- 1072 Science Based Targets Network. (2026b). H&M Group adopts science-based targets for land.
1073 [https://sciencebasedtargetsnetwork.org/news/news/hm-group-adopts-science-based-targets-](https://sciencebasedtargetsnetwork.org/news/news/hm-group-adopts-science-based-targets-for-land/)
1074 [for-land/](https://sciencebasedtargetsnetwork.org/news/news/hm-group-adopts-science-based-targets-for-land/)
- 1075 Seppälä, J., & Hämäläinen, R. P. (2001). On the meaning of the distance-to-target weighting
1076 method and normalisation in life cycle impact assessment. *The International Journal of Life*
1077 *Cycle Assessment*, 6(4), 211–218. <https://doi.org/10.1007/BF02979376>
- 1078 Steffen, W., Crutzen, P. J., & McNeill, J. R. (2007). The Anthropocene: Are humans now
1079 overwhelming the great forces of nature? *Ambio*, 36(8), 614–621.
1080 [https://doi.org/10.1579/0044-7447\(2007\)36\[614:TAAHNO\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2007)36[614:TAAHNO]2.0.CO;2)
- 1081 Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs,
1082 R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G.
1083 M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries:
1084 Guiding human development on a changing planet. *Science*, 347(6223), 1259855.
1085 <https://doi.org/10.1126/science.1259855>
- 1086 Steffens, L., Adams, V., Durand, C., Gómez-Camacho, C. E., Pizzol, L., Saidani, M., &
1087 Giese, B. (2025). From principle to practice: How sustainability is made measurable in safe
1088 and sustainable by design. In *SENTIATECH Congress 2025*.
1089 <https://doi.org/10.2139/ssrn.5762825>
- 1090 Tilsted, J. P., Palm, E., Bjørn, A., & Lund, J. F. (2023). Corporate climate futures in the
1091 making: Why we need research on the politics of science-based targets. *Energy Research &*
1092 *Social Science*, 103, 103229. <https://doi.org/10.1016/j.erss.2023.103229>

Revised Manuscript 26.08.2026

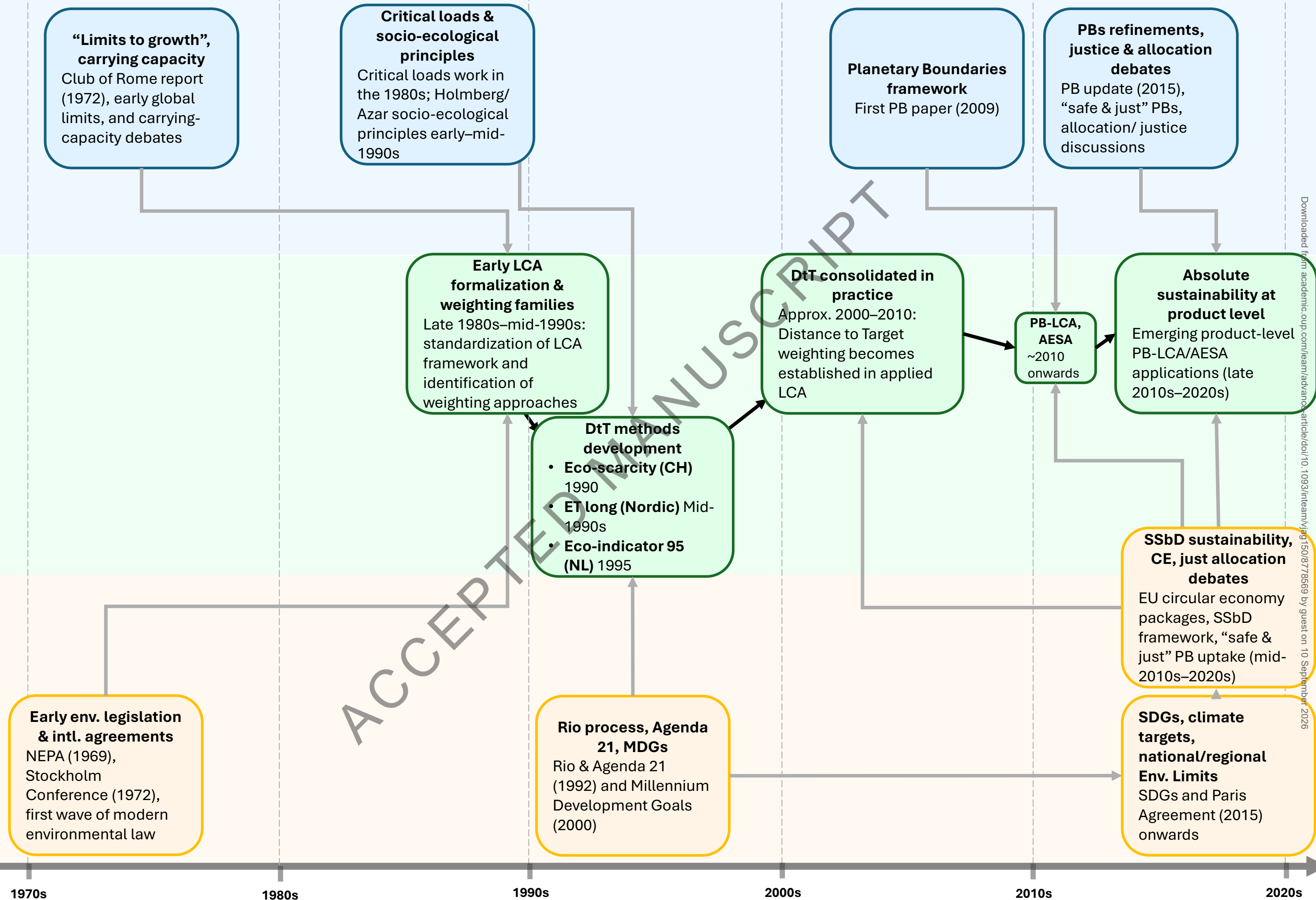
- Tulus, V., Pérez-Ramírez, J., & Guillén-Gosálbez, G. (2021). Planetary metrics for the absolute environmental sustainability assessment of chemicals. *Green Chemistry*, 23(24), 9881–9893. <https://doi.org/10.1039/D1GC02623B>
- Tuomisto, H. L., Hodge, I. D., Riordan, P., & Macdonald, D. W. (2012). Exploring a safe operating approach to weighting in life cycle impact assessment: A case study of organic, conventional and integrated farming systems. *Journal of Cleaner Production*, 37, 147–153. <https://doi.org/10.1016/j.jclepro.2012.06.025>
- van Leeuwen, C. J., & Vermeire, T. G. (Eds.). (2007). Risk assessment of chemicals: An introduction (2nd ed.). Springer. <https://doi.org/10.1007/978-1-4020-6102-8>
- Vargas-Gonzalez, M., Witte, F., Martz, P., Gilbert, L., Humbert, S., Jolliet, O., van Zelm, R., & L'Haridon, J. (2019). Operational life cycle impact assessment weighting factors based on planetary boundaries: Applied to cosmetic products. *Ecological Indicators*, 107, 105498. <https://doi.org/10.1016/j.ecolind.2019.105498>
- Villarrubia-Gómez, P., Cornell, S. E., & Fabres, J. (2018). Marine plastic pollution as a planetary boundary threat: The drifting piece in the sustainability puzzle. *Marine Policy*, 96, 213–220. <https://doi.org/10.1016/j.marpol.2017.11.035>
- World Health Organization. (1993). Guidelines for drinking-water quality (2nd ed., Vol. 1, Recommendations).
- World Health Organization Regional Office for Europe. (1987). Air quality guidelines for Europe.
- Zhang, W., Fang, W., Liu, Y., Ma, N., Shi, J., & Ren, B. (2025). Absolute environmental sustainability assessment of emerging industrial chains within planetary boundaries: A systematic literature review. *Sustainable Production and Consumption*, 55, 185–202. <https://doi.org/10.1016/j.spc.2025.02.023>



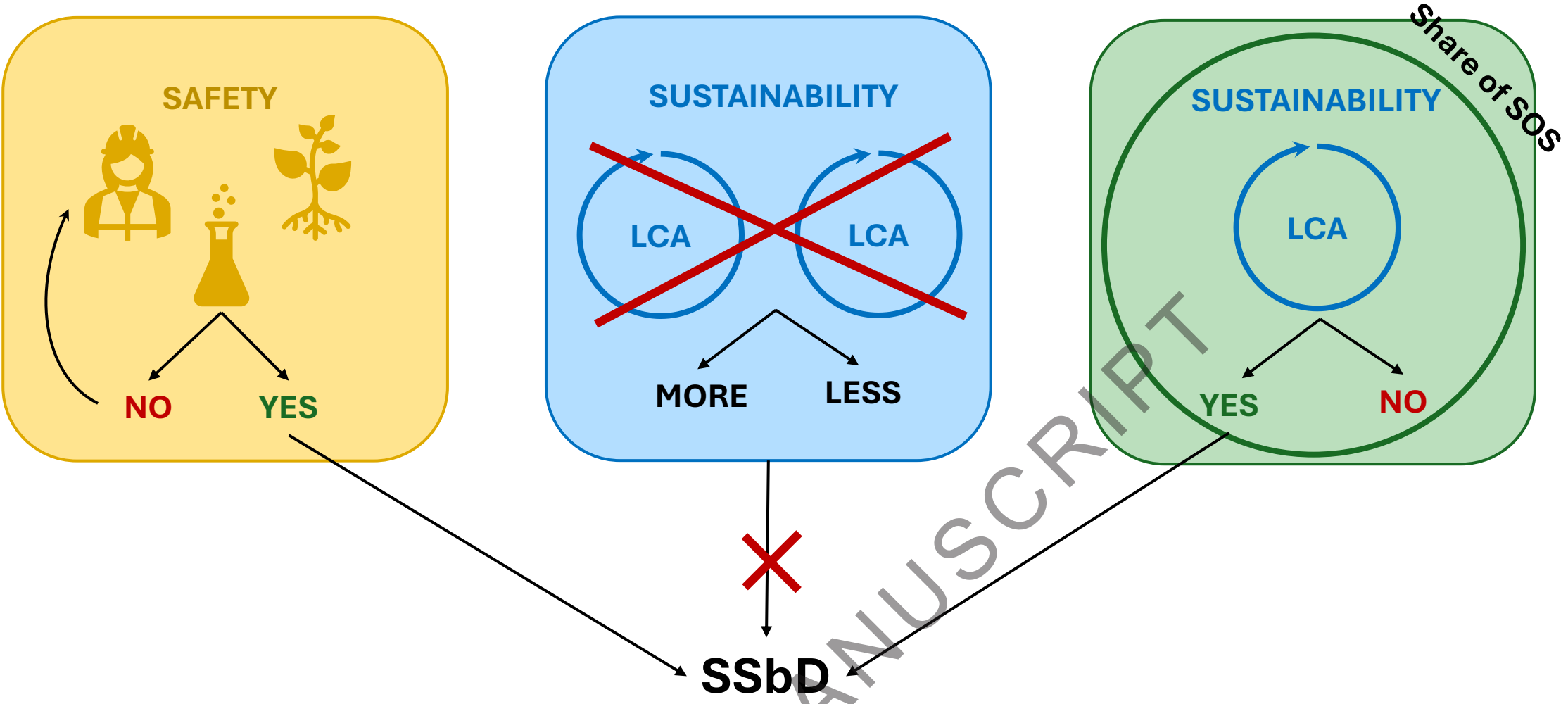
SCIENCE

LCA

POLICY



Comparative → Absolute



Comparative + Absolute

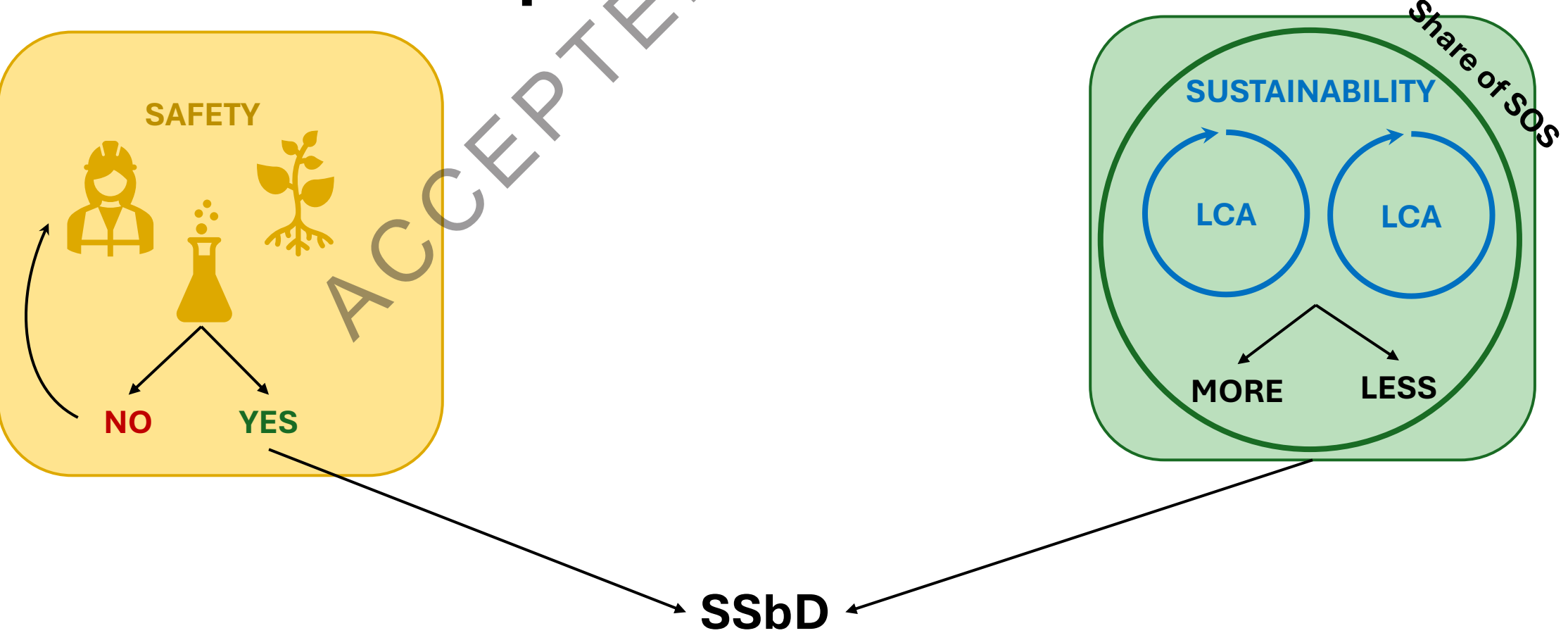


Table 1. Distance-to-target weighting methods reviewed in this study. AG: Aktiengesellschaft (Swiss joint-stock company).

Method	Year	Region	Commissioner	Reference
Ecological Scarcity Method (ESM)	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 (ET)	1990s	The Netherlands (adapted for Sweden)	Dutch Chemical Industry and the Dutch government	Annema, 1991; McKinsey & Company Inc, 1991 – cited by Baumann & Rydberg, 1994; Lindfors et al., 1995
Eco-indicator95 (EI95)	1995	The Netherlands	National Reuse of Waste Research Program	Goedkoop, 1995

Table 1. Planetary Boundaries-based Life Cycle Assessment (PB-LCA) approaches reviewed in this study. PBs: Planetary Boundaries; LCIA: Life Cycle Impact Assessment.

Method	Year	Commissioner	Reference
PBs for Normalization	2015	Technical University of Denmark	Bjorn & Hauschild, 2015
PBs for Interpretation	2015	Chalmers University of Technology	Sandin et al., 2015
PBs in LCIA	2018	Technical University of Denmark	Ryberg et al., 2018a
PBs for Weighting	2019	L'Oréal Research & Innovation	Vargas-Gonzales et al., 2019
PBs for Normalization	2020	European Commission	Sala et al., 2020

Table 1. Research streams operationalizing Planetary Boundaries (PBs) for industry reviewed in this study.

Method / Topic	Year	Commissioner	Reference
Science Based Targets (SBTs) for nature initiative	2015	World Wide Fund for Nature (WWF), the United Nations Global Compact (UNGC), and the World Resources Institute (WRI)	Bjørn et al., 2022; Tilsted et al., 2023; Romito et al., 2024 https://sciencebasedtargetsnetwork.org/
Novel Entities (NEs)	2015	Stockholm Resilience Centre	Steffen et al., 2015; Tulus et al., 2021; Persson et al., 2022; Kosnik et al. 2022; Richardson et al., 2023;
Safe and Sustainable by Design (SSbD)	2022	European Commission Joint Research Centre	Caldeira et al., 2022; Garmendia Aguirre et al., 2025.

Table 1. Threshold in early attempts to link LCA impacts to planetary or other related absolute boundaries. The PBs biosphere integrity, land system change, and freshwater change are missing in the early methods and are not reported for the purpose of comparison. The ESM includes more substances under the impact category “Toxic/ecotoxic chemicals”, not listed for the purpose of comparison. References to compile the table: ESM = Frischknecht et al., 2009; EI95: Goedkoop, 1995; ET: Rydberg, 1996; PB: Richardson et al., 2023. Abbreviations: 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; ppm: parts per million; RF: Radiative Forcing; W/m²: Watt / square meter; 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; P: phosphate; N: nitrogen; NMVOCs: Non-Methane Volatile Organic Compounds; ppb: parts per billion; 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.

Impact Category	Ecological Scarcity Method (ESM)	Eco-Indicator '95 (EI95)	Environmental Themes short (ET short)	Environmental Themes long (ET long)	Planetary Boundaries (PB) framework
GW / GHG effect	<u>Current (CH)</u> : (baseline of 1990) 41.1 million t _{CO₂-eq}	<u>Current (EU)</u> : ΔT=+0.2°C/10yr	<u>Current (SE)</u> : CO ₂ -eq = 9.0*10 ¹³ g	<u>Current (SE)</u> : not specified	<u>Current (GLO)</u> : [CO ₂]: 417ppm CO ₂ , RF: +2.91 W/m ²
	<u>Target</u> : 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	<u>Target</u> : 60% reduction	<u>Target</u> : CO ₂ -eq ≤ 9.0*10 ¹³ g	<u>Target</u> : CO ₂ -eq ≤ 2.7*10 ¹³ g or 70% reduction	<u>Target</u> : [CO ₂]: 350ppm CO ₂ , RF: +1.0 W/m ²
	<u>Criteria</u> : 10% fuel reduction from the 1990 baseline in the Swiss CO ₂ Act (2010); Swiss Sustainable Development Strategy (2050)	<u>Criteria</u> : ΔT ≤ +0.1° C / 10yr or ecosystem impairment < 5%	<u>Criteria</u> : policy target for year 1995	<u>Criteria</u> : ΔT ≤ 0.11°C / 10yr	<u>Criteria</u> : possibility of extreme Earth system impacts above 1.5° C warming
Ozone depletion	<u>Current (CH)</u> : (2006) 391 t R11-eq/a	<u>Current (EU)</u> : 2.6% of ozone layer depletion	<u>Current (SE)</u> : R11-eq = 4.1*10 ⁹	<u>Current (SE)</u> : not specified	<u>Current (GLO)</u> : 284.6 DU
	<u>Target</u> : R11-eq/a ≤ 188 in 2015	<u>Target</u> : CFC emissions = 0 by 2000 or 60% reduction	<u>Target</u> : 95% reduction	<u>Target</u> : R11-eq ≤ 3.1*10 ¹³ g or 92.5% reduction	<u>Target</u> : 276 DU

	<u>Criteria</u> : estimation on releases of the stocks of substances already in use and substances ban	<u>Criteria</u> : probability of 1 death per year per million people (due to melanoma)	<u>Criteria</u> : policy target for year 1995	<u>Criteria</u> : Cl/Br concentrations below formation of the polar ozone hole	<u>Criteria</u> : max of <5% reduction from pre-industrial level
Acidification	<u>Current (CH)</u> : (2006) 91000 t NO _x as NO ₂ /yr 44000 t NH ₃ -N/yr 19000 t SO ₂ /yr	<u>Current (EU)</u> : location dependent, value missing	<u>Current (SE)</u> : SO ₂ -eq = $7.6 \cdot 10^{11}$	<u>Current (SE)</u> : not specified	<u>Current (GLO)</u> : carbonate ion concentration on the ocean surface = 2.8 $\Omega_{\text{aragonite}}$
	<u>Target</u> : 45000 t NO _x as NO ₂ /a 25000 t NH ₃ -N/a 25000 t SO ₂ /a	<u>Target</u> : 90% reduction	<u>Target</u> : 50% reduction	<u>Target</u> : SO ₂ -eq $\leq 3.0 \cdot 10^{11}$ or 60% reduction	<u>Target</u> : carbonate ion concentration on the ocean surface $\geq 3.44 \Omega_{\text{aragonite}}$
	<u>Criteria</u> : ambient limit values defined within the Swiss Federal Air Pollution Control Ordinance	<u>Criteria</u> : 5% system impairment	<u>Criteria</u> : policy target for year 1995	<u>Criteria</u> : ion balance (Ca+Mg+K):Al >1 in soils	<u>Criteria</u> : avoid major disturbance in marine ecosystems (i.e., aragonite desaturation, leading to inhabitable corrosive water)
Eutrophication	<u>Current</u> : n/a	<u>Current (EU)</u> : approx. 200 kg P-eq/ha per yr in Benelux countries, North-Rhine Westphalia, and Po valley region	<u>Current (SE)</u> : NO _x -eq = $6.4 \cdot 10^{11}$	<u>Current (SE)</u> : not specified	<u>Current (GLO)</u> : 22.6 Tg P/yr global, 17.5 Tg P/yr regional; 190 Tg N/yr
	<u>Target</u> : 17000 t N/yr 20 mg/m ³ P in lakes	<u>Target</u> : NO _x ≤ 2.2 mg/l; PO _x ≤ 0.15 mg/L or 80% reduction	<u>Target</u> : 40%	<u>Target</u> : NO _x -eq $\leq 9.2 \cdot 10^{11}$ or -40% (no reduction needed)	<u>Target</u> : P global ≤ 11 Tg/yr, Regional ≤ 6.2 Tg/yr; N ≤ 62 Tg/yr
	<u>Criteria</u> : n/a	<u>Criteria</u> : rivers and lakes, impairment of an unknown number of aquatic ecosystems (5% degradation)	<u>Criteria</u> : policy target for year 1995	<u>Criteria</u> : critical loads of nutrients to sea water surrounding Sweden	<u>Criteria</u> : <i>phosphate</i> : avoid large-scale anoxia; <i>nitrogen</i> : water quality standards (Steffen et al., 2015)
Photo-oxidants	<u>Current</u> : (2006) 116000 t/yr NMVOCs	<u>Current (EU)</u> : O ₃ = 25 ppb average, summer peak 300 ppb	<u>Current (SE)</u> : g ethene-eq = $1.84 \cdot 10^{11}$	<u>Current (SE)</u> : not specified	<u>Current (GLO)</u> : $\Delta\text{AOD} = 0.076$

	<u>Target:</u> 81000 t/yr NMVOCs	<i>Summer smog</i> <u>Target:</u> ≤ 25 ppb or 90% reduction	<u>Target:</u> 30% reduction	<u>Target:</u> g ethene-eq ≤ 5.6*10 ¹⁰ or 70% reduction	<u>Target:</u> annual ΔAOD ≤ 0.1
		<i>Winter smog:</i> <u>Target:</u> 50 µg/m ³ or 75/80% reduction			
	<u>Criteria:</u> ambient limit values defined within the Swiss Federal Air Pollution Control Ordinance	<u>Criteria:</u> occurrence of smog periods health complaints, particularly among asthma patients and old people. For summer period also occurrence of agricultural damage	<u>Criteria:</u> policy target for year 1995	<u>Criteria:</u> 5%-il for damages of ozone to crop)	<u>Criteria:</u> estimation of pre-industrial annual ΔAOD
Toxic/ecotoxic chemicals	<u>Current:</u> (2006) 22000 t PM10/yr, 12745 t PM2.5/yr, 9255 t PM2.5-10/yr, Pb in air 91 t/yr, Cd in air 2 t/yr, 0.004 µg PAH/L	<u>Current (EU):</u> pesticides exceedance in 65% of EU, heavy metals in air exceeded (GLOBE report), heavy metals in water exceeded in Rhine (GLOBE report), carcinogenic substances (PAHs) in Western European cities around 1 ng/m ³ .	<u>Current (SE):</u> tox.-eq = 1.27*10 ⁸	<u>Current (SE):</u> not specified	<u>Current (GLO):</u> transgressed
	<u>Target:</u> <i>Particulate matter:</i> 12000 t PM10/yr, 6952 t PM2.5/yr, 5048 t PM2.5-10/yr	<u>Target:</u> <i>Pesticides:</i> 0.5 µg/l or 96% reduction	<u>Target:</u> 60% reduction	<u>Target:</u> tox.-eq ≤ 2.5*10 ⁷ or 80% reduction	<u>Target:</u> no release without adequate safety testing
	<u>Target:</u> <i>Lead emissions to air:</i> 58 t Pb/yr	<u>Target:</u> <i>Heavy metals in air:</i> Pb ≤ 0.5-1 µg/m ³ or 80% reduction			
	<u>Target:</u> <i>Cadmium emissions to air:</i> 2.08 t Cd/yr	<u>Target:</u> <i>Heavy metals in water:</i> 80% reduction of Cd			

	<u>Target:</u> <i>Carcinogenic substances:</i> 0.1 µg PAH/l,	<u>Target:</u> <i>Carcinogenic substances:</i> 0.01 ng/ m³ or 90% reduction			
	<u>Criteria:</u> ambient limit values defined within the Swiss Federal Air Pollution Control Ordinance, PAHs' target within the International Commission for the Protection of the Rhine	<u>Criteria:</u> <i>Pesticides:</i> groundwater contamination, 5% system impairment	<u>Criteria:</u> Policy target for year 1995	<u>Criteria:</u> critical load of deposition of Mercury	<u>Criteria:</u> 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 years without yet having undergone a safety assessment (Richardson et al., 2023)
		<u>Criteria:</u> <i>Heavy metals in air:</i> lead levels in children's blood, limited life expectancy and learning ability in an unknown number of people			
		<u>Criteria:</u> <i>Heavy metals in water:</i> cadmium content in rivers, ultimately also effect on people			
		<u>Criteria:</u> <i>Carcinogenic substances:</i> probability of 1 death per year per million people			