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TOPICAL REVIEW

Review of life-cycle based methods for absolute environmental sustainability assessment and their applications

Anders Bjørn[1,2], Chanjief Chandrakumar[3,4], Anne-Marie Boulay[1], Gabor Doka[5], Kai Fang[6,7], Natacha Gondran[8], Michael Zwicky Hauschild[9], Annemarie Kerkhof[10], Henry King[11], Manuele Margni[1], Sarah McLaren[3,4], Carina Mueller[12], Mikołaj Owsianiak[9], Greg Peters[13], Sandra Roos[14], Serenella Sala[15], Gustav Sandin[16], Sarah Sim[11], Marcial Vargas-Gonzalez[17] and Morten Ryberg[9]

1 CIRAIG, Polytechnique Montréal, 3333 Chemin Queen-Mary, Montréal, QC, Canada
2 Department of Management, John Molson School of Business, Concordia University, 1450 Guy, Montréal, QC, Canada
3 New Zealand Life Cycle Management Centre, c/o Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
4 School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
5 Doka Life Cycle Assessments, Stationsstrasse 32, CH-8003 Zurich, Switzerland
6 School of Public Affairs, Zhejiang University, 310058 Hangzhou, People's Republic of China
7 Center of Social Welfare and Governance, Zhejiang University, 310058 Hangzhou, People's Republic of China
8 Mines Saint-Etienne, Univ Lyon, Univ Jean Moulin, Univ Lumière, Univ Jean Monnet, ENTPE, INSA Lyon, ENS Lyon, CNRS, UMR 5600 EVS, Institut Henri Fayol, F-42023 Saint-Etienne, France
9 Quantitative Sustainability Assessment, Department of Technology, Management and Economics, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs Lyngby, Denmark
10 Navigant, a Guidehouse company, Stadsplateau 15, 3521 AZ Utrecht, The Netherlands
11 Unilever Safety and Environmental Assurance Centre, Unilever R&D, Colworth Science Park, Sharnbrook MK44 1LQ, United Kingdom
12 Stockholm Environment Institute York, Department of Environment and Geography, University of York, York YO10 5NG, United Kingdom
13 Division of Environmental Systems Analysis, Chalmers University of Technology, 41296 Gothenburg, Sweden
14 RISE Research Institutes of Sweden, Division Materials & Production, Box 104, 431 22 Mölndal, Sweden
15 European Commission, Joint Research Centre, Via E. Fermi, 2749 Ispra, VA, Italy
16 IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 411 33 Gothenburg, Sweden
17 Quantis, 15 Rue de Cléry, Paris, France

E-mail: anders.bjoern@concordia.ca

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Abstract

In many regions and at the planetary scale, human pressures on the environment exceed levels that natural systems can sustain. These pressures are caused by networks of human activities, which often extend across countries and continents due to global trade. This has led to an increasing requirement for methods that enable absolute environmental sustainability assessment (AESA) of anthropogenic systems and which have a basis in life cycle assessment (LCA). Such methods enable the comparison of environmental impacts of products, companies, nations, etc, with an assigned share of environmental carrying capacity for various impact categories. This study is the first systematic review of LCA-based AESA methods and their applications. After developing a framework for LCA-based AESA methods, we identified 45 relevant studies through an initial survey, database searches and citation analysis. We characterized these studies according to their intended application, impact categories, basis of carrying capacity estimates, spatial differentiation of environmental model and principles for assigning carrying capacity. We then characterized all method applications and synthesized their results. Based on this assessment, we present recommendations to practitioners on the selection and use of existing LCA-based AESA methods, as well as ways to perform assessments and communicate results to decision-makers. Furthermore, we identify future research priorities intended to extend coverage of all components of the proposed method framework, improve modeling and increase the applicability of methods.

1. Introduction

Life cycle assessment (LCA) is a method for estimating the environmental impacts of anthropogenic systems, such as products, companies and nations, from a 'cradle-to-grave' perspective. It covers multiple categories of environmental impact (ISO 2006a, 2006b, 2014). LCA is often used to inform decisions aimed at reducing environmental impacts, e.g. by comparing alternative products to determine which one has the better overall performance, considering, ideally, all life cycle stages (such as manufacturing and use) and impact categories (such as *Climate change* and *Freshwater use*). This has probably contributed to the globally observed incremental increase in economic value generation per unit of environmental impact (Dahmus 2014, PwC 2018). However, this increase in eco-efficiency has largely been slower than economic growth, as evidenced by the upward global trends in many indicators of environmental impact (Steffen *et al* 2015a), which threaten to exceed levels that natural systems can sustain at regional and planetary scales (Steffen *et al* 2015b). While this conclusion is not entirely new (Jevons 1866, Meadows *et al* 1972, Downing *et al* 2020), it is receiving increasing attention: a large body of academic literature related to the planetary boundaries concept has recently emerged (Downing *et al* 2019); the concept of climatic tipping points has strongly informed the setting of global climate targets in policy (UNFCCC 2015, IPCC 2018); companies are increasingly translating such global climate targets to the organizational level (SBT 2020); a similar approach to target-setting for other impact categories has been called for (SBTN 2020); and popular movements are demanding drastic action to avoid the near-term depletion of a global carbon budget for the 21st century (FFF 2020) and the increasing potential for the collapse of ecosystems related to species extinction (ER 2020).

The increased focus on the finite nature of the environment has led to the emergence of several LCA-based methods for absolute environmental sustainability assessment (AESA). The core purpose of LCA-based AESA is to evaluate whether an anthropogenic system can be considered environmentally sustainable in an absolute sense for a comprehensive set of impact categories. In this context, an 'anthropogenic system' is a concept that can range in scale from a single consumer product to the global economy and comprises several interconnected anthropogenic production and/or consumption activities (Steffen *et al* 2015b). If this system is found to be environmentally unsustainable, absolute sustainability targets may then be calculated for future years. The word 'absolute' signals that AESA involves a comparison between the impacts of an anthropogenic system and the regional or global limits of the environment, in contrast to relative (or comparative) assessments promoted by classical LCA approaches (Bjørn *et al* 2015). Box 1 contrasts relative and absolute LCA-based assessments using an illustrative example. LCA-based AESA methods are a subset of the broader category of AESA methods, some of which focus on a limited number of resources or emissions within a specific territory (Muñoz and Gladek 2017, Bjørn *et al* 2019a).

Box 1. Illustrative example of a relative and absolute environmental sustainability assessment.

Relative environmental sustainability assessment: A diesel car and an electric train may be compared on the basis of the life-cycle impacts they cause while transporting a person 6000 km throughout a year, using a comprehensive list of impact categories. If transportation using electric train turns out to have the best environmental performance overall (for example, based on a weighted sum of impacts), it can then be identified as being more environmentally sustainable than transportation using a diesel car. The outcome of a relative assessment greatly depends on the choice of reference. For example, the electric train would perhaps not be the superior option if a bicycle was also considered in the assessment. Also, a relative assessment cannot evaluate whether any of the transportation modes performs 'well enough' to be part of an environmentally sustainable economy.

Absolute environmental sustainability assessment: Instead of comparing the environmental impacts of different modes of transport to each other, an absolute assessment compares them to an external list of environmental carrying capacities. For example, the life-cycle climate impacts of a person's annual commuting generated by using a diesel car, an electric train and a bicycle could be compared to a share of a carrying capacity derived from the 1.5 degree climate goal of the Paris Agreement (UNFCCC 2015). This carrying capacity share could be calculated using one or more sharing principles. For example, an 'equal per capita'-principle could initially be used to assign a carrying capacity share to an individual, followed by another principle that captures the value of commuting relative to the other consumption activities in which that individual engages. It may then turn out that the bicycle is the only mode of transport whose climate impact does not exceed its assigned carrying capacity. Note that the ranking of performance between modes of transport is likely to be similar in a relative and absolute assessment (e.g. diesel car worst and bike best).

With an increasing number of LCA-based AESA methods, developers and users alike require a common framework and vocabulary as well as a

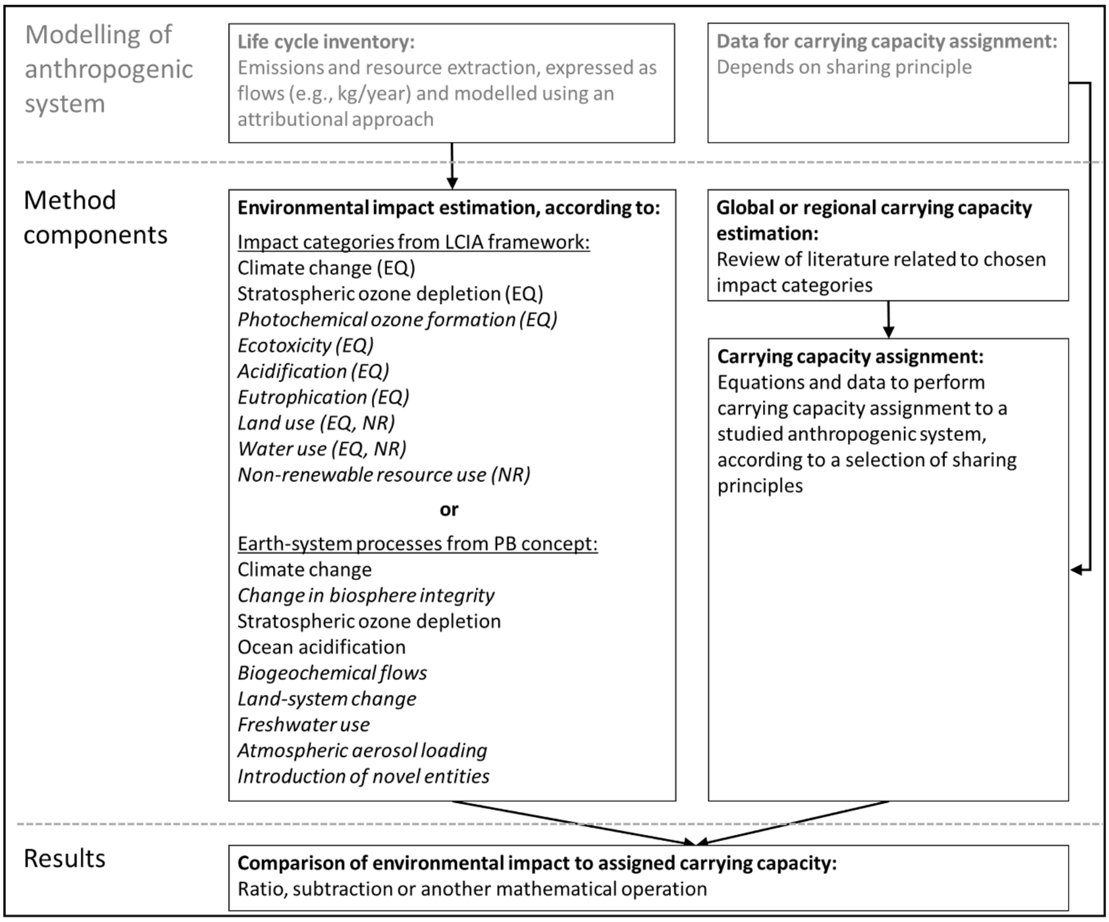

Figure 1. Framework for LCA-based AESA methods. LCIA = life cycle impact assessment. EQ = ecosystem quality. NR = natural resources. PB = planetary boundaries. Impact categories in italics are of a regional nature and the remaining are of a global nature. Boxes in grey represent assessment steps before the use of a specific method. An LCA-based AESA may also contain steps not shown in figure 1, such as goal and scope definition and interpretation of results.

comprehensive overview of existing methods and their intended use, scope, normative aspects and insights from their applications (Bjørn *et al* 2019a). Two recent reviews partially responded to these needs (Muñoz and Gladek 2017, Faria and Labutong 2019). However, Muñoz and Gladek (2017) did not have a specific focus on methods related to LCA and several new LCA-based AESA methods have been published in the meantime, while Faria and Labutong (2019) only considered methods for the setting of future corporate greenhouse gas (GHG) emission targets. With this context, our study has four objectives: (1) to propose a framework for LCA-based AESA methods, (2) to systematically review existing methods and their applications, (3) to provide recommendations to practitioners on the use of existing methods, and (4) to identify methodological improvement needs. The remainder of this paper is structured according to these four objectives.

2. Framework for LCA-based AESA methods

Figure 1 displays the framework we developed for LCA-based AESA methods and sections 2.1–2.3 describe the three method components. The framework and its terminology were developed iteratively through discussions between us, considering the literature reviewed in section 3. Overall, we adopted terms that have often been used in the broader AESA literature (i.e. beyond LCA-based AESA) and that have not already been used to describe other concepts with different meanings in the LCA literature. Table 1 shows the terms resulting from this process, their definitions and similar terms identified through the LCA-based AESA literature review (see section 3). We propose to follow the standardized LCA terminology (ISO 2006a, 2006b) for the elements of an AESA that also form part of classical LCA.

2.1. Estimating environmental impact

An environmental impact estimate is the modeled environmental impact of one or more elementary flows (i.e. a resource use or an emission) occurring somewhere in the life cycle of a studied anthropogenic system. An environmental impact is always quantified with the same measure and unit as the carrying capacity to which it is compared. Such a measure may describe environmental processes at the beginning

Table 1. Terminology for LCA-based AESA and similar terms used in the literature.

Term	Definition	Similar terms
Life cycle assessment-based absolute environmental sustainability assessment (LCA-based AESA)	An assessment that evaluates the absolute environmental sustainability of an anthropogenic system by comparing its estimated environmental impact to its assigned carrying capacity, taking a life cycle perspective and, ideally, having complete coverage of impact categories	Context-based sustainability assessment; Planetary boundaries-based life cycle assessment (PB-LCA); Planetary accounting
Anthropogenic system	A system of linked anthropogenic processes that serves a production or consumption activity	Object of study, anthropogenic activity, human activity
Anthropogenic process	A single process in an anthropogenic system	Unit process
Environmental impact	The environmental impact of one or more elementary flows (a resource use or an emission), quantified with the same measure and unit as the carrying capacity	Footprint, impact score, impact potential, indicator score, environmental pressure, environmental interference
Carrying capacity	The maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems or, in the case of non-renewable resource use, that corresponds to the rate at which renewable substitutes can be developed	Safe operating space (for a planetary boundary), sustainable level of impact, environmental space, impact space, emission/impact budget, critical load/value
Assigned carrying capacity	The carrying capacity assigned to an anthropogenic system or process	Allocated carrying capacity, apportioned carrying capacity, entitled carrying capacity, fair share of carrying capacity
Sharing principle	A principle used to assign carrying capacity to an anthropogenic system or process	Assignment principle, allocation principle, effort-sharing principle or approach

of the environmental impact cause-effect chain (for *Climate change*, this would be a CO_2 emission equivalent) or further towards the end of this chain (an atmospheric temperature increase, in this example). As in classical LCA, the elementary flows of a studied anthropogenic system (i.e. the life cycle inventory result) are linked to their environmental impacts using the output of environmental models in the form of characterization factors (Bjørn *et al* 2019a). Depending on the nature of the impact category, characterization factors may be global or spatially differentiated (see figure 1). For example, characterization factors for *Climate change* are global, since the emission location is irrelevant for the impact, while characterization factors for *Water use* should generally be spatially differentiated (e.g. to the watershed level).

We note that LCA-based AESA methods tend to contain a composition of impact categories that reflect the desire to protect one or two types of values. The first type is the *inherent value* of species and ecosystems and underpins the impact categories that relate to Ecosystem quality in the existing life cycle impact assessment (LCIA) framework (Verones *et al* 2017). The second type is the *instrumental value* of natural resources and ecosystem services more widely. This second type underpins the impact categories that relate to Natural resources in the existing life cycle impact assessment (LCIA) framework (Verones *et al* 2017). Likewise, in the planetary boundaries concept (Rockström *et al* 2009, Steffen *et al* 2015b) the environment is protected due to its *instrumental* role in maintaining a Holocene-like Earth system, which is considered beneficial for humanity (Rockström *et al* 2009, Steffen *et al* 2015b). Acknowledging these different, but overlapping, types of values and goals underlying the two frameworks, we propose that a comprehensive AESA method should either (1) contain a set of environmental indicators that cover the impact categories related to Ecosystem quality and Natural resources in the existing LCIA framework (Verones *et al* 2017) or (2) contain a set of environmental indicators that cover the Earth-system processes of the planetary boundaries framework (Steffen *et al* 2015b, Ryberg *et al* 2016, Chandrakumar and McLaren 2018).

Figure 1 shows these two lists of impact categories. Some impact categories appear in both lists. For example, *Climate change* is both a concern for the stability of the Earth system and for the inherent value of species. Other impact categories in the two lists are related, but not identical. For example, the *Biogeochemical flows* category in the PB framework is similar to *Acidification* and *Eutrophication* in the LCIA framework, but is concerned with perturbation of natural cycles of chemical elements (nitrogen, phosphorous, silicon, etc) rather than the protection of species from those two specific environmental effects. Other impact categories only appear in one list. For example, *Non-renewable resource use* may negatively impact the instrumental value of resource reserves to humans, but resource depletion does not directly threaten the stability of the Earth system (Steffen *et al* 2020). Note that impact categories related to human health, commonly covered in LCA (Verones *et al* 2017), are not relevant for AESA. This is because AESA is concerned with the potential transgression of environmental carrying capacities and not with direct human health impacts from resource use and emissions. The two lists of impact categories in figure 1 reflect the state of current scientific and methodological development and are therefore subjects to future revisions.

2.2. Quantifying carrying capacities

We define carrying capacity as: *the maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems or, in the case of non-renewable resource use, that corresponds to the rate at which renewable substitutes can be developed.* The part of the definition relating to natural systems was largely adopted from Bjørn *et al* (2019a) (based on earlier definitions, e.g. Rees 1996, Fang *et al* 2015b), while the part relating to non-renewable resource use was inspired by Daly's (1995) 'input rules' for an environmentally sustainable society. Note that in the field of population biology, carrying capacity refers to the number of individuals in a species that an environment can sustain (Sayre 2008). By comparison, a sustainable number of humans is not only dependent on the environment, but also on the average consumption and eco-efficiencies of production technologies (Chertow 2001). The carrying capacity in AESA therefore relates to the maximum sustainable total anthropogenic impact instead of the maximum number of humans.

Carrying capacity can often be expressed as a rate of emission or resource use (e.g. a fixed elementary flow equivalent per year). However, for long-lived elementary flows, such as CO_2, and for the consumption of non-renewable resources, a time-integrated flow (e.g. between the years 2020 and 2100) may be more suitable (Rogelj *et al* 2019). The carrying capacity concept applies to different natural systems and at various spatial and temporal scales. For example, it can apply to the aquatic ecosystem of a particular watershed and month, or to the global climate system in the 21st century (see classification of impact categories in figure 1 as 'global' or 'regional'). Carrying capacity is an inherently normative concept, since 'perceived unacceptable impairment' and 'rate at which renewable substitutes can be developed' depend on human judgement, which can involve different ethical norms and approaches to uncertainty management (Sayre 2008, Leach 2014, Saunders 2015, Weidema and Brandão 2015). Regarding uncertainty management, the 'safe operating space' determined by a planetary boundary (Steffen *et al* 2015b) may be understood as a precautionary type of carrying capacity, since it is defined at a 'safe' distance from an estimated environmental threshold.

2.3. Assigning carrying capacity to an anthropogenic system

The total environmental impacts from all anthropogenic systems can be directly compared to carrying capacities in order to understand if they are environmentally sustainable or not in aggregate. When assessing a single anthropogenic system, it is necessary to assign a share of carrying capacity based on one or more sharing principles (see box 1 for an illustrative example). The choice of sharing principle is normative and different ethical norms underlie different principles. An operational AESA method allows its users to apply one or more sharing principles by formalizing it in an equation and making a link to the required data. The comparison of an anthropogenic system's environmental impact to its assigned carrying capacity allows for a judgement about the environmental sustainability of the system with respect to the impact categories considered. If the system is judged to be environmentally unsustainable (impact higher than assigned carrying capacity), methods may allow users to calculate assigned carrying capacity targets for future years. Note that the comparison of environmental impact to assigned carrying capacity is done for each environmental indicator. Aggregation of environmental impacts into a single score (e.g. through normalization and weighting steps, as per classical LCA, ISO 2006a, 2006b), is not made, as it could lead to overlooking exceedance of assigned carrying capacity for individual environmental indicators (Doka 2016, Ryberg *et al* 2016).

3. Review of AESA methods and their applications

3.1. Identification of studies

We identified studies that present new LCA-based AESA methods and case studies applying existing methods. As LCA-based AESA is an emergent field, we considered both comprehensive methods and methods focusing on specific components of the framework in figure 1. We considered literature written in English in the form of peer-reviewed academic articles, conference proceedings and reports (excluding theses and dissertations). For studies presented in multiple formats (e.g. a conference paper followed by a peer-reviewed publication), only the latest version was included. The inclusion criteria were as follows:

- The study must have a life cycle perspective, i.e. linking a production or consumption activity to the anthropogenic processes supporting it. This excludes studies focusing on emissions and resource use at a specific location, such as Cole *et al* (2014) or Dearing *et al* (2014).
- The study must have a link from carrying capacity to elementary flows of a life cycle inventory. This excludes many methods belonging to the 'environmental footprint family', whose links to carrying capacity and planetary boundaries have been discussed elsewhere (Li *et al* 2019, Vanham *et al* 2019).
- The study must include one or more carrying capacity estimates and these must have a clear scientific basis. This excludes studies using policy targets which had no clear link to climate science, such as a GHG emission reduction target of the European Union (Heijungs *et al* 2014). The criterion also excludes studies presenting conceptual or mathematical frameworks, but no carrying capacity estimates, such as Sacramento-Rivero (2012).
- The study must include carrying capacity estimates for the purpose of AESA. This excludes LCA-related studies that use the carrying capacity concept for other purposes, such as for translating elementary flows to area equivalents (Sandholzer and Narodoslawsky 2007, Peters *et al* 2008) or for calculating weighting factors used to aggregate environmental impacts for multiple impact categories to a single score (which is incompatible with AESA, see section 2.3) (Tuomisto *et al* 2012, Castellani *et al* 2016, Vargas-Gonzalez *et al* 2019).
- Studies presenting a new method must cover at least the environmental impact and carrying capacity components of the AESA framework (see figure 1).
- Studies that apply an existing method (i.e. without modifying it in ways that have broad implications) must include a full LCA-based AESA, i.e. compare environmental impacts of one or more anthropogenic systems to assigned carrying capacities. This excludes case studies that compare the environmental impact of an anthropogenic system to unassigned carrying capacity, such as Wang *et al* (2019) and case studies that assign carrying capacity to an anthropogenic system without estimating its environmental impact, such as Zimmermann *et al* (2005).

We applied four techniques to identify studies complying with these inclusion criteria:

(a) A survey of this study's authors was used to identify an initial, tentative list of studies.
(b) Additional studies were identified from a literature search carried out on August 15th 2019 using the Web of Science database, version 5.31 (Clarivate 2020). The search query (see Box 2) was constructed from a combination of terms for carrying capacity and LCA appearing in the titles and keywords of the tentative list of studies.
(c) The reference lists of identified studies were reviewed for additional relevant studies.
(d) Additional relevant studies which cite the identified studies were found using Google Scholar (Google 2020) up until September 1st 2019.

Box 2. Search query used in Web of Science literature search. The NEAR function was used to specify the maximum distance between two search terms in a study's title or abstract.

> carrying capacity OR planetary boundaries OR planetary limits OR planetary accounting OR safe operating space OR safe and just operating space OR entitlement OR sustainability preconditions OR threshold OR absolute NEAR/4 sustainability OR context-based sustainability OR context based sustainability OR ecological threshold OR sustainability target method OR ecological anthropogenic intervention OR biocapacity OR bio-capacity OR resource accounting OR sustainability gap OR environmental sustainability ratio OR doughnut economy
>
> AND
>
> life-cycle NEAR/2 assessment OR life cycle NEAR/2 assessment OR life cycle analysis OR life-cycle analysis OR LCA OR life cycle interpretation OR life cycle engineering OR life-cycle engineering OR life cycle management OR life-cycle management OR environmental sustainability assessment OR environmental input output analysis OR environmental input-output analysis

The procedure led to the identification of 45 studies published between 2002 and 2019, most of which were published since 2015 (see figure 2). We expect that these studies make up the vast majority of relevant studies published in peer reviewed journals and conference proceedings. Our coverage of reports outside the peer-reviewed literature may be somewhat lower, due to non-standardized indexing in literature databases and confidentiality.

3.2. Assessment of studies

Table 2 presents the 45 identified studies ordered according to their year of publication and the last name of the first author. Of the 45 studies, 34 present a new method and 20 of these also present a case study applying the new method. The remaining 11 studies (45–34) apply an existing method to a case study, meaning that a total of 31 case studies (11 + 20) were

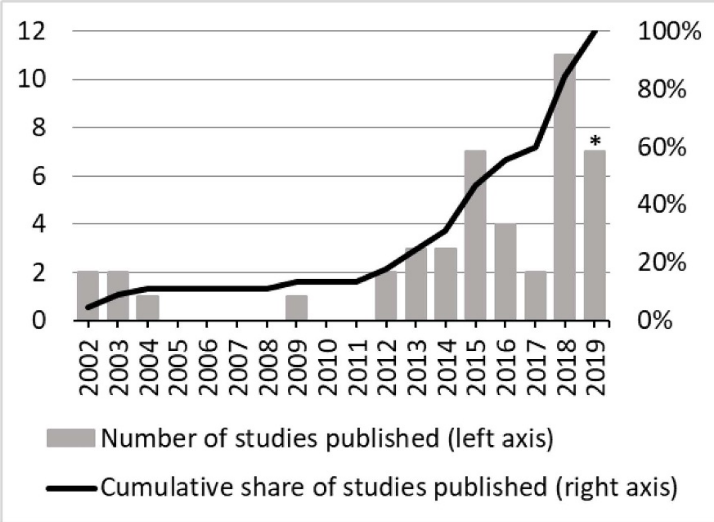

Figure 2. Distribution of 45 studies according to publication year. *Additional studies may have been published in 2019 after this review was carried out.

covered by this review. Figure 3 maps the coverage of impact categories by the 34 studies that present a new method.

3.2.1. Intended applications

Ten of the 34 methods are intended for application on any anthropogenic system whilst the remaining methods are intended for specific types of systems, such as companies (9 methods), nations (7 methods) and buildings (3 methods). Most methods are intended for current conditions. This involves comparing an anthropogenic system to its assigned share of carrying capacity today. Other methods also enable, or strictly focus on, the calculation of future targets for sustainable environmental impacts. A future target can be compared to the environmental impact of a current system to understand if and how much future impact reductions are needed. Due to the long atmospheric lifetime of many GHGs, including CO_2, methods for *Climate change* tend to derive future environmental impact targets from a 'peak and decline' global emission scenario that is consistent with a long-term climate goal, e.g. Rogelj *et al* (2018), instead of using a constant emission rate as carrying capacity. Three methods (Bendewald and Zhai 2013, Ryberg *et al* 2018c, Chandrakumar *et al* 2019a) focus on target calculation in the form of cumulative GHG emissions for long-lived systems, such as buildings.

3.2.2. Coverage of impact categories

Figure 3 shows that methods published before 2013 were based on the LCIA framework with 2015 being the year by which all nine LCIA impact categories (figure 1) had been addressed. Since 2015, most methods published have been PB-based and 2018 was the year in which all 9 PB-related impact categories had been collectively addressed by AESA methods. Considering all 34 methods, *Climate change* was the most frequently covered impact category, followed by *Water use*, *Land-system change* and *Biogeochemical flows* (see figure 3). The popularity of these four impact categories may be related to the fact that half of the PB-based methods are intended for studying the consumption of nations (see table 2), for which life cycle inventories are often restricted to elementary flows related to these categories (Stadler *et al* 2018). Most methods cover just one or two impact categories (see figure 3) and are thus far from comprehensive with respect to the framework in figure 1.

3.2.3. Basis of carrying capacity estimates

The carrying capacity estimates of LCIA-based methods are generally based on reviews of different literature sources, since there is no single comprehensive source that covers all impact categories. Some LCIA-based methods (such as Bjørn and Hauschild 2015) use planetary boundaries for the three impact categories covered in both the LCIA and PB-based frameworks (see figure 3). Early PB-based methods were based on Rockström *et al* (2009) whilst more recent ones refer to Steffen *et al* (2015b). Most PB-based methods modify one or more of the environmental indicators and boundaries proposed in the PB literature. For example, several methods use the temperature goal of the Paris Agreement (1.5–2 degrees of global warming, UNFCCC 2015) instead of the stricter PB for *Climate change* (1 W m^{-2} or 350 ppm atmospheric CO_2, Steffen *et al* 2015b). Likewise, the methods of Butz *et al* (2018) and Meyer and Newman (2018) use 'homemade' environmental indicators with interim carrying capacities for *Introduction of novel entities*, for which no boundary have yet been defined in the PB science.

Table 2. Presentation of the 45 identified studies. The 11 studies applying an existing method are in italics. EPC = equal per capita, CR = capability to reduce, HD = historical debt, EVA = economic value added, PO = physical output, LA = land area, CE = cost efficiency, FCE = final consumption expenditure, CC = calorific content, GF = Grandfathering. See table 3 for a description of sharing principles. *The three studies were considered as a single study here due to their similarities.

Study reference	Intended application	Basis of carrying capacity estimates	Spatially differentiated components	Sharing principle	Case study
Dickinson et al (2002)	Products under current conditions	Literature review, following Yossapoll *et al* (2002)	Carrying capacity	EVA	Production of various materials and energy generation
Yossapoll *et al* (2002)	Companies and products under current and future conditions	Literature review	Carrying capacity	EVA	No case study
Dickinson and Caudill (2003)	End-of-life management under current conditions	Literature review, following Yossapoll *et al* (2002)	None	EVA	Multiple end-of-life options for various materials
Dickinson et al (2003)	Integrated circuit manufacturing under current conditions	Literature review, following Yossapoll *et al* (2002)	Carrying capacity	EVA	Multiple production facilities of a manufacturer
Caudill and Dickinson (2004)	Collection scenarios under current conditions	Literature review, following Yossapoll *et al* (2002)	None	EVA	Multiple scenarios for collection of e-waste
Stewart and Deodhar (2009)	Future targets for companies	2 degree climate goal	None	EVA combined with HD and GF	A tech company
Randers (2012)	Future targets for companies	2 degree climate goal	None	EVA combined with GF	Multiple companies
Wright *et al* (2012)	Energy technologies under current conditions	Literature review	Carrying capacity	EVA	Multiple energy technologies
Bendewald and Zhai (2013)	Buildings during their lifetime (cumulative emission perspective)	Long-term near zero GHG emission goal	None	None	A research facility
Girod et al (2013)	Future targets for product categories	2 degree climate goal	None	GF or CE	Multiple product categories
Nykvist *et al* (2013), Hoff *et al* (2014, 2017)*	Nations under current conditions	Rockström *et al* (2009) with some modifications	Environmental impact and carrying capacity	EPC	The production and consumption of multiple countries

Table 2. (Continued)

Study reference	Intended application	Basis of carrying capacity estimates	Spatially differentiated components	Sharing principle	Case study
Bjørn *et al* (2014)	Flexible under current conditions	Literature review	Carrying capacity	None	No life-cycle based case study
Girod et al (2014)	Products under future conditions	2 degree climate goal, following Girod *et al* (2013)	None	EPC combined with GF	Multiple consumer products
Zijp *et al* (2014)	Flexible under current conditions	Literature review	Environmental impact and carrying capacity	None	No life-cycle based case study
Bijloo and Kerkhof (2015)	Future targets for companies	Literature review	None	GF combined with PO	An electricity utility
Bjørn and Hauschild (2015)	Flexible under current conditions	Literature review	Carrying capacity	EPC	No life-cycle based case study
Doka (2015)	Flexible under future peak population conditions	Rockström *et al* (2009)	None	EPC	No case study
Fang *et al* (2015a)	Nations under current conditions	Rockström *et al* (2009) with some modifications	Carrying capacity	EPC	The production and consumption of multiple countries
Kerkhof *et al* (2015)	Future targets for companies	2 degree climate goal	None	CE combined with PO	An electricity utility
Krabbe *et al* (2015)	Future targets for companies	2 degree climate goal	None	CE	Steel production by six hypothetical companies
Sandin *et al* (2015)	Future targets for products	Steffen *et al* (2015a)	None	GF and/or EPC	No case study with environmental impact estimation
Bjørn *et al* (2016)	Flexible under current conditions	Literature review	Environmental impact and carrying capacity	EVA or GF	No life-cycle based case study
Doka (2016)	Flexible under future peak population conditions	Steffen *et al* (2015a)	None	EPC	No case study
Fanning and O'Neill (2016)	Nations and sub-national regions under current conditions	Steffen *et al* (2015a)	None	EPC combined with LA	The consumption of multiple regions
Roos et al (2016)	Products under future conditions	Steffen *et al* (2015a), following Sandin *et al* (2015)	None	GF combined with EPC	The Swedish apparel sector

Table 2. (Continued)

Study reference	Intended application	Basis of carrying capacity estimates	Spatially differentiated components	Sharing principle	Case study
Brejnrod et al (2017)	Buildings under current conditions	Literature review, following Bjørn and Hauschild (2015)	None	EPC combined with FCE or GF	Two building archetypes
Wolff *et al* (2017)	Retailers under current conditions	Literature review, following Bjørn and Hauschild (2015) and Doka (2016)	Carrying capacity	EPC combined with GF and PO	Food portfolio of mass-market retailer
Bjørn *et al* (2018)	Future targets for consumption categories	1.5–2 degree climate goal	None	EPC combined with GF	Multiple consumption categories in Denmark
Butz *et al* (2018)	Companies under current conditions	Steffen *et al* (2015a) with some modifications	None	EVA	No case study
Chandrakumar et al (2018)	Sectors of a national economy under current conditions	2 degree climate goal, following Doka (2016)	None	GF or EVA or FCE	New Zealand's agri-food sector
Dao *et al* (2018)	Nations under current conditions	Steffen *et al* (2015a) with some modifications	None	EPC	The consumption of Switzerland
Lucas and Wilting (2018a, 2018b)	Nations under current and future conditions	Steffen *et al* (2015a) with some modifications	None	GF or EPC possibly combined with CR and LA	The production and consumption of the Netherlands
McElroy (2018)	Future targets for companies, municipalities and higher education	1.5–2 degree climate goal	None	GF and EVA (for companies); GF and EPC (for municipalities and higher education)	No case study
Meyer and Newman (2018)	Flexible under current conditions	Steffen *et al* (2015a) with some modifications	None	EPC	No case study
O'Neill *et al* (2018)	Nations under current conditions	Steffen *et al* (2015a) with some modifications	None	EPC	The consumption of multiple countries
Ryberg et al (2018a)	Products under current conditions	Steffen *et al* (2015a), following Ryberg *et al* (2018b)	Environmental impact and carrying capacity	GF, FCE or EPC combined with FCE or with EVA	Laundry washing in Europe

Table 2. (Continued)

Study reference	Intended application	Basis of carrying capacity estimates	Spatially differentiated components	Sharing principle	Case study
Ryberg *et al* (2018b)	Flexible under current conditions	Steffen *et al* (2015a)	Environmental impact and carrying capacity	None	No case study
Ryberg *et al* (2018c)	Manufacturing under current and future conditions (cumulative emission perspective)	Steffen *et al* (2015a)	None	None	No case study that includes carrying capacity assignment
Algunaibet et al (2019)	Energy systems under current and future conditions	Steffen *et al* (2015a), following Ryberg *et al* (2018b)	None	EPC combined with EVA	The US energy sector
Bjørn *et al* (2020) (published in 2019)	Flexible under current conditions	Steffen *et al* (2015a)	Environmental impact and carrying capacity	EPC or EVA	No life-cycle based case study
Chandrakumar *et al* (2019a)	Buildings during their lifetime (cumulative emission perspective)	2 degree climate goal	None	EPC combined with HD and GF	A detached house
Chandrakumar et al (2019b)	Products, industries and sectors under current conditions	2 degree climate goal, following Doka (2016)	None	GF and PO combined with CC, LA or EVA	Agri-food sector, horticulture industries and horticulture products in New Zealand
Faria and Labutong (2019)	Future targets for companies	2 degree climate goal	None	GF	An electricity utility
Liu and Bakshi (2019)	Flexible under current conditions	Literature review	Environmental impact and carrying capacity	GF	Corn ethanol consumption in cars
Roy and Pramanick (2019)	Nations under current and future conditions	Steffen *et al* (2015a)	None	EPC	Production and consumption in India

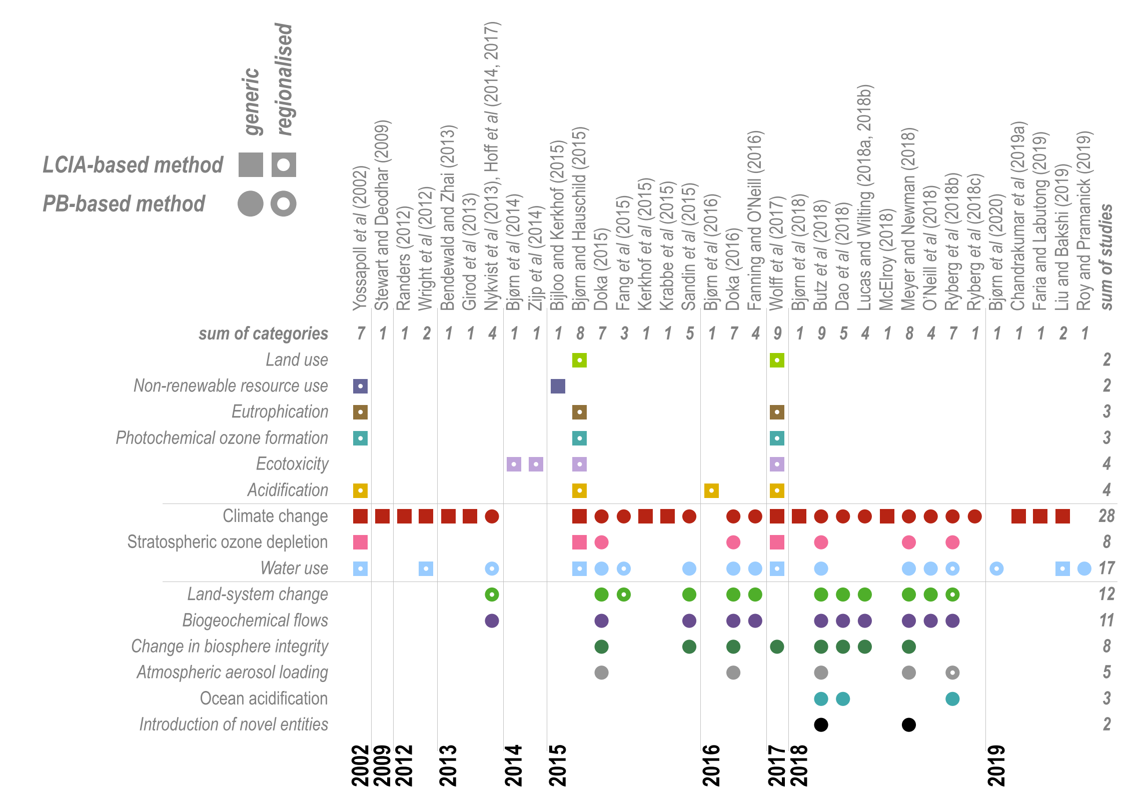

Figure 3. Coverage of impact categories by the 34 methods. The categories are ordered in three groups: LCIA-based only (top), LCIA- and PB-based (middle), PB-based only (bottom). Impact categories in italics are of a regional nature and the remaining are of a global nature. The study of Bjørn *et al* (2020) was grouped under 2019, as it was published that year, while assigned to a journal issue in 2020.

3.2.4. Spatial differentiation

Of the 34 methods, 12 allow for spatially differentiated impact assessment and/or contain spatially differentiated carrying capacity values for regional impact categories (see table 2 and figure 3). Some of these methods are restricted to a certain region (such as the United States in Yossapoll *et al* 2002), while others can be applied to different regions by choosing between characterization factors and carrying capacities matching the location of elementary flows. For example, the PB-based method of Bjørn *et al* (2020) for *Freshwater use* contains a characterization factor and carrying capacity estimate for each of 11 050 watersheds. Note that many methods are spatially generic with respect to impact categories of a regional nature (in italics in figure 3). This is especially the case for methods originating in the PB framework, to which regional boundaries were introduced in 2015 (Steffen *et al* 2015b). None of these methods are spatially differentiated for *Biogeochemical flows, Change in biosphere integrity*, or *Introduction of novel entities* (see figure 3).

3.2.5. Sharing principles

The 45 reviewed studies refer to individual sharing principles with a variety of names and sometimes use a similar name for different principles. By comparing the underlying calculations, we identified a total of 10 distinct sharing principles. Table 3 gives a short description of each principle, its applicability to different types of anthropogenic systems and the number of reviewed studies applying it. The table also tentatively identifies the ethical norm underlying each principle.

The first five principles of table 2 are equally applicable to individual products, companies and sectors and to the total consumption of products by one or more individuals (e.g. during a year). These five principles span ethical norms that are egalitarian (in short: treating all people as equal), inegalitarian (in short: considering some inequalities as just) and prioritarian (in short: allowing positive discrimination for the disadvantaged) (Grasso 2012). On the other hand, the last five principles are only applicable to individual products, companies and sectors and are all based on a utilitarian ethic (in short: maximizing well-being in society) (Roemer 1996, Paavola 2001). Some principles have specific constraints in their application; for instance, *Calorific content* is only applicable to food products and *Grandfathering* is only applicable to anthropogenic systems whose existence goes back to an appropriate reference year. In many cases a principle cannot be applied alone. For example, the *Equal per capita* principle must be combined with another principle to be applicable to individual products, companies and sectors. This was demonstrated in the case study of Ryberg *et al* (2018a), who used

Table 3. Description of the 10 sharing principles identified in the reviewed literature.

Name	Description	Ethical norm (tentative)	Type of anthropogenic system applicable to: Individual products, companies and sectors	Type of anthropogenic system applicable to: Total consumption of products by one or more individuals	Number of studies applying the principle
Equal per capita (EPC)	Assigned share is the same for all individuals	Egalitarian	Yes, for products to final consumption and when combined with another principle	Yes	21
Capability to reduce (CR)	Assigned share is negatively correlated with a region's gross domestic product per capita	Prioritarian	Yes, for systems confined within a single region and when combined with another principle	Yes, when combined with another principle	1
Historical debt (HD)	Assigned share is negatively correlated with a region's cumulative environmental impact per capita	Prioritarian	Yes, for systems confined within a single region and when combined with another principle	Yes, when combined with another principle	2
Grandfathering (GF)	Assigned share is proportional with environmental impact in a reference year	Inegalitarian	Yes, for systems that existed in the reference year	Yes, for systems that existed in the reference year	20
Land area (LA)	Assigned share is proportional with area of possessed land	Inegalitarian	Yes	Yes	3
Economic value added (EVA)	Assigned share is proportional to economic value added	Utilitarian	Yes	No	17
Cost efficiency (CE)	Assigned share is inversely proportional with the cost of reducing environmental impact of production	Utilitarian	Yes	No	3
Final consumption expenditure (FCE)	Assigned share is proportional with final consumption expenditure	Utilitarian	Yes, for products to final consumption	No	3
Calorific content (CC)	Assigned share is proportional with calorific content	Utilitarian	Yes, for food products and when combined with another principle	No	1
Physical production output (PO)	Assigned share is proportional with physical production output	Utilitarian	Yes, when combined with another principle	No	5

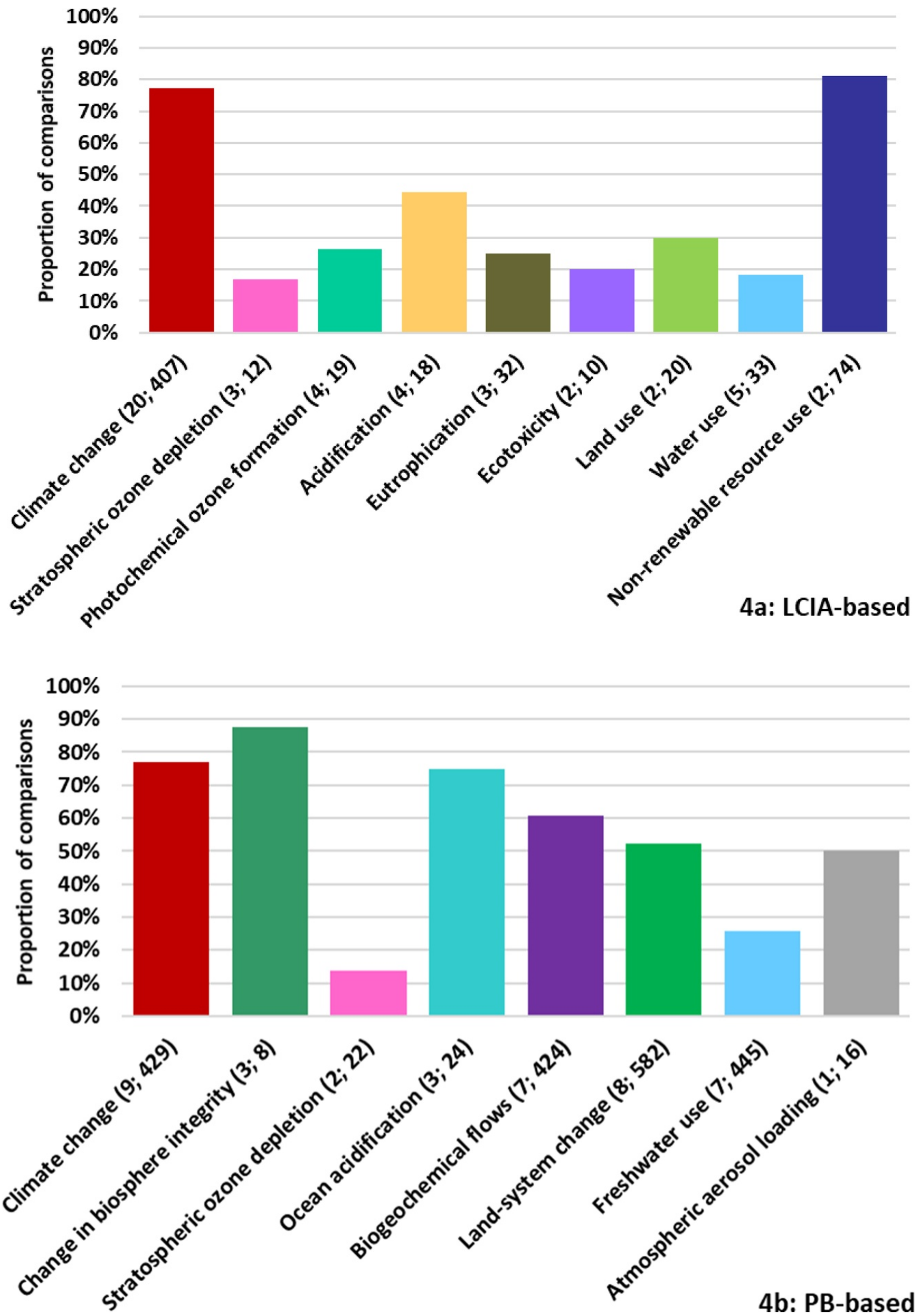

Figure 4. Proportion of comparisons in which impact exceeds assigned carrying capacity in all 31 case studies. Figures (a) and (b) cover studies that are based on the LCIA- and PB framework, respectively. In the legend, the number of studies is given in parenthesis after each impact category, followed by the total number of comparisons of impact and assigned carrying capacity across these studies.

that principle to first assign carrying capacity to the total consumption of the European Union during one year and subsequently used *Final consumption expenditure* to arrive at an assigned share for the subset of products involved in laundry washing. All 10 principles can be applied to assess an anthropogenic system under current conditions and to define future targets. When applying principles for future target setting, parameters such as population and economic value added in the target year are often required, see Faria and Labutong (2019).

Nearly half of the 45 reviewed studies applied the *Equal per capita, Grandfathering* and *Economic value added* principles, whereas the remaining seven principle were only applied in 1–5 studies. Few studies explicitly justified their choice of sharing principles (beyond referring to older studies having applied the same principles). The difference in rate of use may reflect a combination of ease of application (e.g. in terms of required data) and perceived societal acceptability.

3.2.6. Case studies.

The 31 case studies identified span a wide variety of anthropogenic systems, from specific products and companies to the total consumption of nations. Most case studies can be characterized as proofs of concept, but some studies were commissioned by government entities, such as the Dutch or European environment agencies (Hoff *et al* 2014, Lucas and Wilting 2018a, 2018b), presumably intended to inform policy. Most of the case studies cover several comparisons of anthropogenic systems and assigned carrying capacity for each of the impact categories considered. For example, the study of Brejnrod *et al* (2017) contains 24 comparisons for the *Eutrophication* impact category, due to the inclusion of (1) four anthropogenic systems (a short-life and a long-life version of two building archetypes), (2) two system boundaries (including vs. excluding energy consumption in the use phase) and (3) three environmental indicators related to impacts on soil, freshwater and ocean environmental compartments, respectively ($4^*2^*3 = 24$). The anthropogenic system has a higher impact than the assigned carrying capacity in six of that study's 24 comparisons for *Eutrophication*. Figure 4 shows the proportion of the aggregated number of comparisons in the 31 case studies in which impact exceeds assigned carrying capacity for the different impact categories. Supplementary material (SM) 1 (available online at stacks.iop.org/ERL/15/083001/mmedia) contains a detailed count for each study and a related cumulative frequency chart.

Several patterns can be observed in figure 4. There is a large difference between the proportions of comparisons in which impact exceeds assigned carrying capacity across impact categories. These differences are, overall, consistent with studies comparing total anthropogenic impacts to global carrying capacities (Bjørn and Hauschild 2015, Steffen *et al* 2015b). For example, since global GHG emissions exceed the carrying capacity for *Climate change*, while global ozone depleting emissions by many measures are within the carrying capacity for *Stratospheric ozone*, it is more likely that individual anthropogenic systems are judged to be environmentally sustainable with respect to the latter impact category. There is a good agreement between the results for the three identical impact categories within the LCIA- and PB-frameworks (*Climate change* > *Water use* > *Stratospheric ozone depletion*). Considering impact categories that are similar, but not identical, the agreement is lower: e.g. the proportions of comparisons with impacts exceeding assigned carrying capacity is substantially higher for *Land-system change* (PB-related) than for *Land-use* (LCIA-related).

The definition of planetary and regional boundaries reflect the precautionary principle (Steffen *et al* 2015b), which may partially explain why the scores in figure 4(b) are overall higher than the scores in figure 4(a). By contrast, the list of carrying capacities created for methods based on the LCIA framework commonly reflects a 'best estimate' approach (Bjørn and Hauschild 2015), using average parameter values and only considering scientifically well-established impact mechanisms.

We assessed the importance of methodological choices in determining case study results (SM 2). This assessment was based on observing, within each case study, whether different methodological choices (e.g. of sharing principle) are associated with different numbers of comparisons in which impact exceeds assigned carrying capacity. In this way we found that the choice of environmental indicator (for a given impact category), sharing principle (or combination of principles) and spatial resolution appear to be most important for AESA results.

As mentioned in section 3.2.1, some AESA methods enable the calculation of future environmental impact targets. Such methods were used by 13 of the 31 case studies, in which assigned carrying capacity was calculated in one or more specific future years, most commonly for *Climate change*. Five of these 13 studies compare the estimated future environmental impact of one or more anthropogenic systems to future assigned carrying capacity (Girod *et al* 2013, 2014, Roos *et al* 2016, Bjørn *et al* 2018, Algunaibet *et al* 2019). These future impact scenarios were generally based on assumed specific technological innovations and behavioral changes (Girod *et al* 2014, Roos *et al* 2016) or on projections of eco-efficiency and consumer demand based on historic trends (Girod *et al* 2013, Bjørn *et al* 2018). Only Algunaibet *et al* (2019) took an integrated approach and used assigned carrying capacities for the year 2030 as constraints in a cost-optimization model applied to the US energy system. They found a solution that only involves exceedance of the assigned carrying capacity for one of eight environmental indicators (there was no solution with no exceedance of any assigned carrying capacity), compared to a 'business as usual' scenario in which assigned carrying capacity was exceeded for six environmental indicators.

4. Recommendations to practitioners on the use of existing AESA methods

This section is organized in three parts, sequenced chronologically from the perspective of a practitioner: (1) Choosing an LCA-based AESA method, (2) Performing the AESA and (3) Communicating the AESA.

4.1. Choosing a method

Below, we present four aspects that a practitioner should consider when selecting a method. These considerations are relevant for the 34 methods identified in this review (see table 2 and figure 3) as well as for future methods.

4.1.1. Basis in LCIA- or PB framework?

Practitioners should first consider if they need a method relating to the LCIA- or the PB framework. This decision can be based on which of the two frameworks' embedded sets of values (variants of *intrinsic* and *instrumental* values, see section 2.1) best matches the goal of the study. The decision can also be based on the more pragmatic question of whether the audience of the study is already more familiar with one framework or the other.

4.1.2. Coverage of impact categories, spatial differentiation and scientific robustness

Next, the practitioner should consider the coverage of impact categories and degree of spatial differentiation that best suit the study's needs, while also taking the scientific robustness of available methods into account. As in classical LCA, general good practice dictates inclusion of as many impact categories as possible to minimize the risk of 'burden shifting' (i.e. a decision leading to an increased impact in another impact category) (ISO 2006b). An exhaustive coverage of either of the two lists of impact categories in the LCA-based AESA framework (see figure 1) is currently rarely observed (see figure 3). This is due to limitations in the underlying environmental science, such as lack of environmental models for certain impact categories or unquantified planetary and regional boundaries for some Earth-system processes. When confronted with these current limitations, practitioners may restrict their choice to methods that are consistent with the goal of their study and, if needed, adapt this goal. For example, in a study of bio-based products, impact categories typically of concern in the agricultural production (such as *Land use, Eutrophication* and *Climate Change*) could be prioritized.

The review of case studies (section 3.2.6) showed that spatial differentiation can be decisive for a study's results (see SM2). In practice, application of spatially differentiated methods may depend, in part, on the resources available for constructing a spatially differentiated life cycle inventory, i.e. collecting spatial data on elementary flows contributing to regional impact categories (see figure 1). Consideration of the share of life-cycle elementary flows known to take place in regions where the carrying capacity and/or characterization factors are much higher or lower than for an average region may also be relevant. For example, a spatially differentiated assessment may be preferable for water-intensive anthropogenic systems, where most of the water consumption is known to take place in watersheds experiencing high water scarcity. However, note that many existing methods covering regional impact categories are spatially generic, e.g. eight of the 17 methods for *Water use* identified in this review (see figure 3).

In addition to the question of impact category coverage and spatial differentiation, the scientific robustness of these aspects is also important. Currently, a systematic comparative assessment of the scientific robustness of LCA-based AESA methods is lacking. Until this becomes available (see section 5.4), practitioners may try to judge on their own, e.g. by considering whether characterization factors have been calculated from state-of-the-art LCIA model components and whether carrying capacity estimates are well-founded in environmental science or of a more interim nature.

4.1.3. Sharing principle

Having chosen a method that covers environmental impact estimation and carrying capacity (see figure 1), the choice of one or more sharing principles for assigning carrying capacity to the studied anthropogenic system must be made. Many of the reviewed methods were found to apply one or more specific principles (see table 2). However, all 10 principles identified in table 3 are applicable to any of the methods. Practitioners can use table 3 to identify sharing principles that are technically applicable to the anthropogenic system they are assessing (depending, for example, on whether the system is a single product or the total consumption of an individual). In most cases, multiple sharing principles are technically applicable. In the reviewed case studies the choice of sharing principle was found to have a high influence on the results (see section 3.2.6 and SM 3). As there is generally a lack of consensus on the most appropriate principle to use, given the diversity of stakeholder perspectives, results should be calculated for multiple sharing principles.

4.1.4. Broader considerations

In addition to the three specific considerations above, practitioners can use method selection criteria from the broader sustainability assessment literature (Pintér *et al* 2012, Hauschild *et al* 2013, Sala *et al* 2015, Zijp *et al* 2015), for example related to: stakeholder acceptance of method; quality of method documentation; whether a method is integrated in software (which can save time for the practitioner) and whether a method will be updated in the future, thus allowing for future studies that reflect increasing scientific maturity.

4.2. Performing the LCA-based AESA

The practitioner should, as a general rule, adhere to best practice in classical LCA (ISO 2006a, 2006b). However, it is important to diverge from the predominant inventory analysis practice of expressing elementary flows in mass (or, occasionally, volume) and instead express them as an actual flowrate, i.e. a mass (or volume) per unit of time. This is necessary, since the carrying capacity in most cases relates to a rate of emissions or resource use (see section 2.2). There are different ways of incorporating time information in life cycle inventories. For example, Ryberg *et al* (2018a) studied the continuous activity of laundry washing in Europe and expressed all elementary flows in kg (or m^3) per year. Recent developments in dynamic life cycle inventory databases may also be utilized (Pigné *et al* 2019). Time also plays an important role in the assignment of carrying capacity, which tends to depend on variables that change on a yearly basis. Therefore, when using methods that present carrying capacity estimates per capita (e.g. Bjørn and Hauschild 2015) or per unit of global economic value added (e.g. Butz *et al* 2018), practitioners should check that the reference year used in these calculations match the reference year of the study, recalculating if necessary.

4.3. Communication to decision-makers

Since LCA-based AESA is an emerging approach within the field of environmental sustainability assessment, it is important to explain to decision-makers how it differs from other types of assessments. For decision-makers who are familiar with classical LCA and its application for relative environmental sustainability assessment (see box 1), the focus could be on explaining the absolute nature of the assessment. This includes the ability to estimate future targets for sustainable environmental impacts (see section 3.2.6), allowing for the development of appropriate action plans.

In all cases, it is important to communicate uncertainties. For example, 11 of the 31 reviewed case studies (see table S4 in SM 2) used uncertainty propagation to evaluate the robustness of case study results. At the same time, it is important to acknowledge that some uncertainties in our understanding of natural systems, including 'unknown unknowns', are difficult to quantify (Herrmann *et al* 2014, Lade *et al* 2020) (see section 5.2). Hence, care should be taken when interpreting AESA results. Moreover, if a study involves estimating future assigned carrying capacity, it is especially important to communicate any assumptions related to future global production and consumption. For example, if the analyst assumes a high growth rate for the global economy, this will lead to a lower assigned carrying capacity to an individual product in the future than a low, zero or negative assumed growth rate would. Also, if the analyst uses a method involving interim carrying capacity estimates or which is spatially generic for impact categories of a regional nature (see figure 3), the implications of this for the robustness of results should be addressed. As in classical LCA, it is useful to distinguish uncertainties related to engineering- and environmental science (e.g. inventory and impact assessment modeling) from those related to value judgement (e.g. the selection of a set of impact categories and the choice of sharing principle). The former can be reduced as the science matures (see section 5), while it takes societal consensus on values to manage the latter (see section 5.3).

5. Research needs

5.1. Coverage of all framework components

The framework and related terminology presented in section 2 was the result of a comprehensive literature review (section 3) and in-depth discussions between the 20 authors of this paper; we represent a large proportion of the people currently working in the field of LCA-based AESA. We recommend that method developers use the framework and its terminology for planning, carrying out and communicating their research. For clarity and comparability, it would be helpful if method developers indicate which components of the framework (e.g. in terms of impact categories and sharing principles) are addressed by their work, as well as the components that fall out of scope. It should also be clear if a new method is intended for stand-alone use by practitioners or could be combined with one or more other existing methods.

The literature review (section 3.2) showed that there are several parts of the framework that require more attention in future LCA-based AESA method development. In terms of impact categories, figure 3 suggests that future method development could be directed to achieve a broader coverage of impact categories like *Land use, Non-renewable resource use* (LCIA-based) and *Introduction of novel entities* (PB-based). Future methods could also give greater focus to regionalization (i.e. covering spatially differentiated characterization factors and/or carrying capacities). Regionalization has the potential to identify any regional occurrences of environmental unsustainability that would be overlooked through global assessment, given the spatially uneven distribution of carrying capacity as well as environmental impacts of many elementary flows. For example, the case study of Nykvist *et al* (2013) found that the total land use for the production of goods and services consumed in Bangladesh was much lower than the assigned share of the global carrying capacity for *Land-system change* (based on the *Equal per capita principle*, see table 3), while total land use within

Bangladesh was much higher than the carrying capacity of that region. In regionalized AESA, environmental impacts of each anthropogenic process should ideally be compared to a set of assigned carrying capacities for the region(s) affected by its elementary flows. However, the practicalities and added value to decision-makers of such assessments require exploration (Bjørn *et al* 2020). In terms of assignment of carrying capacity, method developers may consider the principles identified in table 3 and their applicability as a starting point when choosing what principles to make available in a method, but should note that additional principles may be developed.

5.2. Modeling improvements

Aside from better coverage of components of the LCA-based AESA framework (section 2), the quality of the coverage should also be considered. Each component of the framework may be characterized by parameter and model uncertainty. In general, more accurate representation of a system leads to lower model uncertainty, but at the cost of increased parameter uncertainty, due to the higher number of parameters required (van Zelm and Huijbregts 2013).

State of the art LCIA methods have commonly been developed with the aim of minimizing total uncertainty by achieving a suitable compromise between model and parameter uncertainty, and LCA-based AESA can build on this in various ways: (1) characterization factors developed by classical state of the art LCIA models may be directly used in LCA-based AESA (Bjørn and Hauschild 2015). (2) For methods based on the PB framework, some impact categories do not exist in the classical LCA literature and new LCIA models must be developed for calculating characterization factors (Ryberg *et al* 2016, 2018b, Doka 2016). In such cases, method developers could, to the extent possible, use the same data (e.g. related to climatic conditions or physical and chemical properties of emitted substances) that underlie classical LCIA models and individual model components (such as a multimedia environmental fate model) may also be adopted. In some cases, a reduction in uncertainty may also be achieved by using other environmental indicators than those proposed in PB literature (aka 'control variables'). For example, Bjørn *et al* (2019b) argued that, in the context of LCA-based AESA, the changes in precipitation and surface air temperature are more suitable environmental indicators for *Land-system change* than the area of forested land remaining is. (3) Uncertainties related to different parameters and modeling steps are not equally important. Developers of LCA-based AESA methods may be inspired by techniques widely used in the LCIA community to determine priorities in the quest of overall uncertainty minimization (van Zelm and Huijbregts 2013, Wender *et al* 2018).

Specifically for carrying capacity, it is important for method developers to be aware that carrying capacities originating in different literature sources have been estimated in response to different research questions and by using different techniques (for example, based on an understanding of a system's threshold behavior, the highest stress leading to zero (measurable) effect, or a maximum deviation from a pre-industrial reference). Hence, carrying capacities are context dependent, to some extent, and not objective qualities of the environment. Also, some methods, such as Butz *et al* (2018), cover interim carrying capacity estimates that are in great need of further improvement. To ensure that AESA results are comparable across impact categories, method developers should aim to assemble an internally consistent list of carrying capacities, for example by developing inclusion criteria for literature estimates of carrying capacity. A related challenge is that the size of one carrying capacity may depend on whether another carrying capacity has been exceeded (Steffen *et al* 2015b, Lade *et al* 2020). For example, the exceedance of a carrying capacity for *Climate change* is expected to lead to significant changes in precipitation patterns, causing a change in the carrying capacity for *Freshwater use* due to the effect on blue water availability (Bjørn *et al* 2019b). The handling of such feedbacks may require an approach that integrates the modeling for several impact categories rather than modeling each cause-effect pathway in isolation.

Regarding the sharing of carrying capacity, methods intended for future target setting must deal with the challenge that the economy is evolving. Prospective economic modeling should therefore be explored. Integrated assessment models may be of particular relevance, since they can be used to develop production- and consumption scenarios constrained by carrying capacities (Randers *et al* 2018, Rogelj *et al* 2018), as was partially done in the case study of Algunaibet *et al* (2019) (see section 3.2.6).

5.3. Applicability for decision-support

The fundamental characteristics of LCA-based AESA, compared to classical LCA used for relative environmental sustainability assessment (see box 1), offer two key motivations for decision-makers to use the approach. First, AESA can be used to evaluate whether an anthropogenic system can be considered environmentally sustainable, in an absolute sense. Second, if this is found not to be the case (as in a large proportion of the reviewed case studies, see figure 4), assigned carrying capacity can be calculated for the future and adopted as targets, e.g. in corporations (Faria and Labutong 2019, Walenta 2020).

On a practical level, several actions need to be taken to make LCA-based AESA feasible for decision-support. Currently, AESA methods and case studies are typically only documented in the academic literature and can be hard to find, due to the historic lack of a common language. We encourage the creation of teaching materials to facilitate consistent usage of methods and sensible interpretation of results by LCA practitioners in industry, consultancy and policy settings. Likewise, a library of case studies, including any not identified in this review, could be established and maintained. In addition to being a resource for practitioners, this would form the basis of future case study reviews that build on our initial findings (section 3.2.6). It is also important for method developers to better understand the needs and experiences of potential method users. We therefore encourage the creation of a digital platform for knowledge sharing between researchers and practitioners in related fields. This would be particularly useful for method developers to better understand emergent consensus amongst stakeholders in the sharing of carrying capacity. To further qualify discussions around the use of various sharing principles, social scientists studying approaches to sharing scarce resources and the degree of societal support should be invited to join the platform.

Integration of LCA-based AESA in software is important to make its application easier. Compared to existing LCA software, LCA-based AESA requires a number of additional features: (1) management of time information for processes or elementary flows (see section 4.2), (2) spatially differentiated calculations of environmental impacts for regional categories (also a requirement for state of the art classical LCA, Mutel *et al* 2019), (3) spatially differentiated calculations of assigned carrying capacity for regional impact categories, and (4) links to potential databases on carrying capacities and assigned shares of carrying capacity, according to different sharing principles (elaborated in section 5.4).

5.4. Method harmonization and potential consensus building

LCA-based AESA is a new and rapidly developing field. It can be difficult for method developers to keep up with the various developments and for practitioners to identify the methods best serving their needs. The framework we propose in section 2 provides a first attempt at structuring and categorizing LCA-based AESA approaches and methods. We also align terminology encountered in the literature to bring clarity and inform harmonization efforts. The naming and characterization of sharing principles (section 3) may also contribute to near-term consensus building. In addition, the review of methods in section 3 may form the basis of a quantitative comparison of the scientific robustness of different methods, which can be used to inform method selection (see section 4.1).

As a medium-term ambition, consistency and ease of application would be improved upon the creation of complete AESA methods, developed by combining components (such as impact categories and sharing principles) of individual methods. Such an undertaking could follow the historical practice in the LCA community of creating uniform 'LCIA methodologies', such as ReCiPe (Huijbregts *et al* 2017) and IMPACT World+ (Bulle *et al* 2019), from a selection of individual LCIA models that fulfill some common criteria. An integrated and comprehensive method often requires harmonization of its components, for example, with respect to spatial differentiation, reference conditions in LCIA modeling and naming of elementary flows.

In the longer term, more in-depth forms of method integration may be devised, inspired by the evolution of the field of classical LCA: data inputs for calculations of environmental impact, carrying capacities and assigned shares may be harmonized, for example, inspired by the processes leading to the USEtox (Rosenbaum *et al* 2008) or the AWARE (Boulay *et al* 2018) LCIA models. Also, a consensus on best practice for different methodological aspects may be sought, inspired by consensus processes for LCIA modeling, such as the one initiated by the Joint Research Centre of the European Commission (Hauschild *et al* 2013). This may be particularly important if agreement is to be sought on the underlying ethical norms, equations, data inputs and appropriate application for the various sharing principles ideally involving collaboration with social scientists. This could lead to the construction of databases of assigned shares of carrying capacity for different principles (expressed, for example, per unit of production), spatially and temporally differentiated where needed. As alternative to seeking a consensus on best practice, Huijbregts' (2014) proposal of using a multi-model mean for default parameter values and allowing practitioners to incorporate variance between model outputs in uncertainty analysis could also be explored.

6. Conclusion and outlook

This study presented the first comprehensive review of LCA-based AESA methods and their applications and proposed a method framework. These outcomes may serve as a resource for potential users to understand similarities and differences of existing methods and to choose a method and perform and communicate an assessment. Our analysis of research needs is intended to stimulate further development of the field. The study was motivated by a wish to increase the relevance of LCA for decision-support. We hope to also inspire researchers working in other fields such as Earth system science and social science to take part in ongoing efforts to improve and harmonize LCA-based AESA approaches.

The AESA approach can be used to inform action at the level of individual production and consumption activities in response to unsustainable macro-level trends. Our review of method applications found that impacts are too high in most of the covered production and consumption activities. In these cases, any historic improvement in eco-efficiency has not been large enough to decouple the environmental impacts from economic growth so that societies can operate within the regional and global limits of the environment. Building on this conclusion, it is necessary to explore what actions policymakers, the private sectors and citizens can take to drive the innovations in production and consumption that are needed to reduce impacts sufficiently.

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Data availability statement

Any data that support the findings of this study are included within the article and its supplementary material.

ORCID iD

Chanjief Chandrakumar https://orcid.org/0000-0001-8419-3708

References

Algunaibet I M, Fernández C P, Galán-Martın Á, Huijbregts M A J, Mac Dowell N and Guillén-Gosálbez G 2019 Powering sustainable development within planetary boundaries *Energy Environ. Sci.* **12** 1890–900

Bendewald M and Zhai Z J 2013 Using carrying capacity as a baseline for building sustainability assessment *Habitat Int.* **37** 22–32

Bijloo M and Kerkhof A 2015 *One Planet Thinking—Mineral Depletion* (The Netherlands: Ecofys)

Bjørn A, Diamond M, Birkved M and Hauschild M Z 2014 Chemical footprint method for improved communication of freshwater ecotoxicity impacts in the context of ecological limits *Environ. Sci. Technol.* **48** 13253–62

Bjørn A, Diamond M, Owsianiak M, Verzat B and Hauschild M Z 2015 Strengthening the link between life cycle assessment and indicators for absolute sustainability to support development within planetary boundaries *Environ. Sci. Technol.* **49** 6370–1

Bjørn A and Hauschild M Z 2015 Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level *Int. J. Life Cycle Assess.* **20** 1005–18

Bjørn A, Kalbar P, Nygaard S E, Kabins S, Jensen C L, Birkved M, Schmidt J and Hauschild M Z 2019a Pursuing necessary reductions in embedded GHG emissions of developed nations: will efficiency improvements and changes in consumption get us there? *Glob. Environ. Change* **52** 314–24

Bjørn A, Margni M, Roy P O, Bulle C and Hauschild M Z 2016 A proposal to measure absolute environmental sustainability in life cycle assessment *Ecol. Indic.* **63** 1–13

Bjørn A, Richardson K and Hauschild M Z 2019b A framework for development and communication of absolute environmental sustainability assessment methods *J. Ind. Ecol.* **23** 838–54

Bjørn A, Sim S, Boulay A-M, King H, Clavreul J, Lam W Y, Barbarossa V, Bulle C and Margni M 2020 A planetary boundary-based method for freshwater use in life cycle assessment: development and application to tomato production case study *Ecol. Indic.* **110** 105865

Bjørn A, Sim S, King H, Keys P, Wang-Erlandsson L, Cornell S, Margni M and Bulle C 2019b Challenges and opportunities towards improved application of the planetary boundary for land-system change in life cycle assessment of products *Sci. Total Environ.* **696** 133964

Bjørn A, Sim S, King H, Patouillard L, Margni M, Hauschild M Z and Ryberg M 2020 Process-based life cycle assessment applying planetary and regional boundaries: an industry case study *Int. J. Life Cycle Assess.* (submitted)

Boulay A M *et al* 2018 The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE) *Int. J. Life Cycle Assess.* **23** 368–78

Brejnrod K N, Kalbar P, Petersen S and Birkved M 2017 The absolute environmental performance of buildings *Build. Environ.* **119** 87–98

Bulle C *et al* 2019 IMPACT World+: a globally regionalized life cycle impact assessment method *Int. J. Life Cycle Assess.* **24** 1653–74

Butz C, Liechti J, Bodin J and Cornell S E 2018 Towards defining an environmental investment universe within planetary boundaries *Sustain. Sci.* **13** 1031–44

Castellani V, Benini L, Sala S and Pant R 2016 A distance-to-target weighting method for Europe 2020 *Int. J. Life Cycle Assess.* **21** 1159–69

Caudill R J and Dickinson D A 2004 Sustainability and end-of-life product management: a case study of electronics collection scenarios *IEEE Int. Symp. on Electronics and the Environment, 2004* pp 132–7

Chandrakumar C, Malik A, McLaren S J, Lenzen M, Ramilan T and Jayamaha N P 2018 New zealand agri-food sector and absolute climate impacts: an application of multi-regional input-output analysis *Conf. Proc. 11th Int. Conf. on Life Cycle Assessment of Food 2018 (LCA Food): Global Food Challenges Towards Sustainable Consumption and Production* (*Bangkok, Thailand, 17–19 October 2018*)

Chandrakumar C, McLaren S J, Dowdell D and Jaques R 2019a A top-down approach for setting climate targets for buildings: the case of a New Zealand detached house *IOP Conf. Series: Earth and Environmental Science* vol 323 p 12183

Chandrakumar C, McLaren S J, Jayamaha N P and Ramilan T 2019b Absolute sustainability-based life cycle assessment (ASLCA): a benchmarking approach to operate agri-food systems within the 2 °C global carbon budget *J. Ind. Ecol.* **23** 906–17

Chertow M R 2001 The IPAT equation and its variants: changing views of technology and environmental impact *J. Ind. Ecol.* **4** 13–29

Clarivate 2020 *Web of Science* (United States: Clarivate Analytics) (https://clarivate.com/webofsciencegroup/)

Cole M J, Bailey R M and New M G 2014 Tracking sustainable development with a national barometer for South Africa using a downscaled "safe and just space" framework *Proc. Natl Acad. Sci. USA* **111** E4399–408

Dahmus J 2014 Can efficiency improvements reduce resource consumption? *J. Ind. Ecol.* **18** 883–97

Daly H E 1995 On Wilfred Beckerman's critique of sustainable development *Environ. Values* **4** 49–55

Dao H, Peduzzi P and Friot D 2018 National environmental limits and footprints based on the planetary boundaries

framework: the case of Switzerland *Glob. Environ. Change* **52** 49–57
Dearing J A *et al* 2014 Safe and just operating spaces for regional social-ecological systems *Glob. Environ. Change* **28** 227–38
Dickinson D A and Caudill R J 2003 Sustainable product and material end-of-life management: an approach for evaluating alternatives *IEEE Int. Symp. on Electronics and the Environment, 2003* pp 153–8
Dickinson D A, Mosovsky J A, Caudill R J, Watts D J and Morabit J M 2002 Application of the sustainability target method: supply line case studies *IEEE Int. Symp. on Electronics and the Environment* pp 139–43
Dickinson D A, Mosovsky J A and Houthuysen S D 2003 Assessing integrated circuit manufacturing for environmental performance and sustainability: a full scale IC business application *IEEE Int. Symp. on Electronics and the Environment, 2003* pp 214–9
Doka G 2016 *Combining Life Cycle Inventory Results with Planetary Boundaries: The Planetary Boundary Allowance Impact Assessment Method. Update PBA'06* (Zürich: Doka LCA)
Doka G 2015 *Combining Life Cycle Inventory Results with Planetary Boundaries: The Planetary Boundary Allowance Impact Assessment Method PBA'05* (Zürich: Doka LCA)
Downing A S, Bhowmik A, Collste D, Cornell S E, Donges J, Fetzer I, Häyhä T, Hinton J, Lade S and Mooij W M 2019 Matching scope, purpose and uses of planetary boundaries science *Environ. Res. Lett.* **14** 073005
Downing A S, Chang M, Kuiper J J, Campenni M, Häyhä T, Cornell S, Svedin U and Mooij W 2020 Learning from generations of sustainability concepts *Environ. Res. Lett.* (accepted) (https://doi.org/10.1088/1748-9326/ab7766)
ER 2020 Extinction rebellion (https://rebellion.earth/)
Fang K, Heijungs R, Duan Z and De Snoo G R 2015a The environmental sustainability of nations: benchmarking the carbon, water and land footprints against allocated planetary boundaries *Sustainability* **7** 11285–305
Fang K, Heijungs R and De Snoo G R 2015b Understanding the complementary linkages between environmental footprints and planetary boundaries in a footprint–boundary environmental sustainability assessment framework *Ecol. Econ.* **114** 218–26
Fanning A L and O'Neill D W 2016 Tracking resource use relative to planetary boundaries in a steady-state framework: a case study of canada and spain *Ecol. Indic.* **69** 836–49
Faria P C S and Labutong N 2019 A description of four science-based corporate GHG target-setting methods *Sustain. Account. Manage. Policy J.* **11** 591–612
FFF 2020 Fridays for future (https://www.fridaysforfuture.org/)
Girod B, van Vuuren D P and Hertwich E G 2014 Climate policy through changing consumption choices: options and obstacles for reducing greenhouse gas emissions *Glob. Environ. Change* **25** 5–15
Girod B, Van Vuuren D P and Hertwich E G 2013 Global climate targets and future consumption level: an evaluation of the required GHG intensity *Environ. Res. Lett.* **8** 14016
Google 2020 Google Scholar (https://scholar.google.com/)
Grasso M 2012 Sharing the emission budget *Polit. Stud.* **60** 668–86
Hauschild M Z *et al* 2013 Identifying best existing practice for characterization modeling in life cycle impact assessment *Int. J. Life Cycle Assess.* **18** 683–97
Heijungs R, De Koning A and Guinée J B 2014 Maximizing affluence within the planetary boundaries *Int. J. Life Cycle Assess.* **19** 1331–5
Herrmann I T, Hauschild M Z, Sohn M D and Mckone T E 2014 Confronting uncertainty in life cycle assessment used for decision support: developing and proposing a taxonomy for LCA studies *J. Ind. Ecol.* **18** 366–79
Hoff H, Häyhä T, Cornell S and Lucas P 2017 *Bringing EU policy into line with the Planetary Boundaries* (Stockholm: SEI, PBL Netherlands: Environmental Assessment Agency and Stockholm Resilience Centre)
Hoff H, Nykvist B and Carson M 2014 *"Living Well, Within the Limits of Our Planet"? Measuring Europe's Growing External Footprint* (Stockholm: Stockholm Environment Institute)
Huijbregts M 2014 A critical view on scientific consensus building in life cycle impact assessment *Int. J. Life Cycle Assess.* **19** 477–9
Huijbregts M A J, Steinmann Z J N, Elshout P M F, Stam G, Verones F, Vieira M, Zijp M, Hollander A and van Zelm R 2017 ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level *Int. J. Life Cycle Assess.* **22** 138–47
IPCC 2018 *Global Warming of 1.5 °C. Summary for Policymakers* (Geneva: Intergovernmental Panel on Climate Change)
ISO 2006a ISO 14040:2006 Environmental management—life cycle assessment—principles and framework (Geneva: International Organization for Standardization)
ISO 2006b ISO 14044:2006 Environmental management—life cycle assessment—requirements and guidelines (Geneva: International Organization for Standardization)
ISO 2014 ISO/TS 14072: 2014 Environmental management—life cycle assessment—requirements and guidelines for organizational life cycle assessment (Geneva: International Organization for Standardization)
Jevons W S 1866 *The Coal Question* (London: Macmillan and Company) OCLC 464772008
Kerkhof A, de Boer E, Meijer G, Scheepmaker J and Blok K 2015 *Towards Companies that Perform Within the Earth's Regenerative Capacity* (The Netherlands: Ecofys)
Krabbe O, Linthorst G, Blok K, Crijns-Graus W, van Vuuren D P, Höhne N, Faria P, Aden N and Pineda A C 2015 Aligning corporate greenhouse-gas emissions targets with climate goals *Nat. Clim. Change* **5** 1057–60
Lade S J, Steffen W, de Vries W, Carpenter S R, Donges J F, Gerten D, Hoff H, Newbold T, Richardson K and Rockström J 2020 Human impacts on planetary boundaries amplified by Earth system interactions *Nat. Sustain.* **3** 119–28
Leach M 2014 Resilience 2014: limits revisited? Planetary boundaries, justice and power *Pathways to Sustainability* 9 May 2014 (avaliable at: https://steps-centre.org/blog/resilience2014-leach/)
Li M, Wiedmann T and Hadjikakou M 2019 Towards meaningful consumption-based planetary boundary indicators: the phosphorus exceedance footprint *Glob. Environ. Change* **54** 227–38
Liu X and Bakshi B R 2019 Ecosystem services in life cycle assessment while encouraging techno-ecological synergies *J. Ind. Ecol.* **23** 347–60
Lucas P and Wilting H 2018a *Towards a Safe Operating Space for the Netherlands. Policy Brief* (The Hague: PBL Netherlands Environmental Assessment Agency)
Lucas P and Wilting H 2018b *Using Planetary Boundaries to Support National Implementation of Environment-Related Sustainable Development Goals* (The Hague: PBL Netherlands Environmental Assessment Agency)
McElroy M W 2018 *Frequently Asked Questions About CSO's Context-Based Carbon Metric* (United States: The Center for Sustainable Organizations) (https://www.sustainableorganizations.org/context-based-metrics-public-domain/)
Meadows D H, Meadows D L, Randers J and Behrens W W III 1972 *The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind* (New York: Universe Books)
Meyer K and Newman P 2018 The planetary accounting framework: a novel, quota-based approach to understanding the impacts of any scale of human activity in the context of the planetary boundaries *Sustain. Earth* **1** 4
Muñoz O S and Gladek E 2017 *One Planet Approaches. Methodology Mapping and Pathways Forward* (Amsterdam: Metabolic: WWF. FOEN, Swiss Federal Office for the Environment)

Mutel C *et al* 2019 Overview and recommendations for regionalized life cycle impact assessment *Int. J. Life Cycle Assess.* **24** 856–65
Nykvist B, Persson Å, Moberg F, Persson L, Cornell S and Rockström J 2013 *National Environmental Performance on Planetary Boundaries—A Study for the Swedish Environmental Protection Agency—Report 6576* (Stockholm: Stockholm Environment Institute)
O'Neill D W, Fanning A L, Lamb W F and Steinberger J K 2018 A good life for all within planetary boundaries *Nat. Sustain.* **1** 88–95
Paavola J 2001 Towards sustainable consumption: economics and ethical concerns for the environment in consumer choices *Rev. Soc. Econ.* **2** 37–41
Peters G M, Sack F, Lenzen M, Lundie S and Gellego B 2008 Towards a deeper and broader ecological footprint *Proc. ICE Eng. Sustain.* **161** 31–37
Pigné Y, Gutiérrez T N, Gibon T, Schaubroeck T and Popovici E 2020 A tool to operationalize dynamic LCA, including time differentiation on the complete background database *Int. J. Life Cycle Assess.* 25 267–279
Pintér L, Hardi P, Martinuzzi A and Hall J 2012 Bellagio STAMP: principles for sustainability assessment and measurement *Ecol. Indic.* **17** 20–28
PwC 2018 *Time to Get on With it. The Low Carbon Economy Index 2018. Tracking the Progress G20 Countries Have Made to Decarbonise Their Economies* (United States: PricewaterhouseCoopers) (https://www.pwc.co.uk/services/sustainability-climate-change/insights/low-carbon-economy-index.html)
Randers J 2012 Greenhouse gas emissions per unit of value added ("GEVA")—a corporate guide to voluntary climate action *Energy Policy* **48** 46–55
Randers J, Rockström J, Stoknes P E, Golüke U, Collste D and Cornell S 2018 *Transformation is Feasible. How to Achieve the Sustainable Development Goals Within Planetary Boundaries* (Stockholm Resilience Centre and BI Norwegian Business School, Stockholm, Sweden)
Rees W E 1996 Revisiting carrying capacity: area-based indicators of sustainability *Popul. Environ.* **17** 195–215
Rockström J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32
Roemer J E 1996 *Theories of Distributive Justice* (London: Harvard University Press)
Rogelj J, Forster P M, Kriegler E, Smith C J and Séférian R 2019 Estimating and tracking the remaining carbon budget for stringent climate targets *Nature* **571** 335–42
Rogelj J *et al* 2018 Scenarios towards limiting global mean temperature increase below 1.5 °C *Nat. Clim. Change* **8** 325–32
Roos S, Zamani B, Sandin G, Peters G M and Svanström M 2016 A life cycle assessment (LCA)-based approach to guiding an industry sector towards sustainability: the case of the Swedish apparel sector *J. Clean. Prod.* **133** 691–700
Rosenbaum R K *et al* 2008 USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment *Int. J. Life Cycle Assess.* **13** 532–46
Roy A and Pramanick K 2019 Analysing progress of sustainable development goal 6 in India: past, present, and future *J. Environ. Manage.* **232** 1049–65
Ryberg M W, Owsianiak M, Clavreul J, Mueller C, Sim S, King H and Hauschild M Z 2018a How to bring absolute sustainability into decision-making: an industry case study using a planetary boundary-based methodology *Sci. Total Environ.* **634** 1406–16
Ryberg M W, Owsianiak M, Richardson K and Hauschild M Z 2016 Challenges in implementing a planetary boundaries based life-cycle impact assessment methodology *J. Clean. Prod.* **139** 450–9
Ryberg M W, Richardson K and Hauschild M Z 2018b Development of a life-cycle impact assessment methodology linked to the planetary boundaries framework *Ecol. Indic.* **88** 250–62
Ryberg M W, Wang P, Kara S and Hauschild M Z 2018c Prospective assessment of steel manufacturing relative to planetary boundaries: calling for life cycle solution *Proc. CIRP* **69** 451–6
Sacramento-Rivero J C 2012 A methodology for evaluating the sustainability of biorefineries: framework and indicators *Biofuel. Bioprod. Biorefin.* **6** 32–44
Sala S, Ciuffo B and Nijkamp P 2015 A systemic framework for sustainability assessment *Ecol. Econ.* **119** 314–25
Sandholzer D and Narodoslawsky M 2007 SPIonExcel-fast and easy calculation of the sustainable process index via computer *Resour. Conserv. Recycl.* **50** 130–42
Sandin G, Peters G M and Svanström M 2015 Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts *Int. J. Life Cycle Assess.* **20** 1684–700
Saunders F P 2015 Planetary boundaries: at the threshold… again: sustainable development ideas and politics *Environ. Dev. Sustain.* **17** 823–35
Sayre N F 2008 The genesis, history, and limits of carrying capacity *Ann. Assoc. Am. Geogr.* **98** 120–34
SBT 2020 Science based targets (http://sciencebasedtargets.org/)
SBTN 2020 Science based targets network (http://sciencebasedtargetsnetwork.org/)
Stadler K *et al* 2018 EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input–output tables *J. Ind. Ecol.* **22** 502–15
Steffen W, Broadgate W, Deutsch L, Gaffney O and Ludwig C 2015a The trajectory of the anthropocene: the great acceleration *Anthr. Rev.* **2** 81–98
Steffen W *et al* 2015b Planetary boundaries: guiding human development on a changing planet *Science (80.-)* **347** 736
Steffen W, Richardson K, Rockström J, Schellnhuber H J, Dube O P, Dutreuil S, Lenton T M and Lubchenco J 2020 The emergence and evolution of earth system science *Nat. Rev. Earth Environ.* **1** 54–63
Stewart E and Deodhar A 2009 *A corporate Finance Approach to Climate-Stabilizing Targets (C-FACT)* (Autodesk, United States)
Tuomisto H L, Hodge I D and Riordan P 2012 Exploring a safe operating approach to weighting in life cycle impact assessment—a case study of organic, conventional and integrated farming systems *J. Clean. Prod.* **37** 147
UNFCCC 2015 *Adoption of the Paris Agreement. Proposal by the President. Draft Decision-/CP.21* (United: Nations Framework Convention on Climate Change (UNFCCC), Paris, France)
Vanham D *et al* 2019 Environmental footprint family to address local to planetary sustainability and deliver on the SDGs *Sci. Total Environ.* **693** 133642
Vargas-Gonzalez M, Witte F, Martz P, Gilbert L, Humbert S, Jolliet O, van Zelm R and L'Haridon J 2019 Operational life cycle impact assessment weighting factors based on planetary boundaries: applied to cosmetic products *Ecol. Indic.* **107** 105498
Verones F *et al* 2017 LCIA framework and cross-cutting issues guidance within the UNEP-SETAC life cycle initiative *J. Clean. Prod.* **161** 957–67
Walenta J 2020 Climate risk assessments and science-based targets: A review of emerging private sector climate action tools *Wiley Interdiscip. Rev. Clim. Change* **11** e628
Wang X, Daigger G, de Vries W, Kroeze C, Yang M, Ren N Q, Liu J and Butler D 2019 Impact hotspots of reduced nutrient discharge shift across the globe with population and dietary changes *Nat. Commun.* **10** 1–12
Weidema B P and Brandão M 2015 Ethical perspectives on planetary boundaries and LCIA *Extended Abstract. Presentation at the SETAC Europe 25th Annual Meeting in Barcelona* (*3–7 May 2015*)

Wender B A, Prado V, Fantke P, Ravikumar D and Seager T P 2018 Sensitivity-based research prioritization through stochastic characterization modeling *Int. J. Life Cycle Assess.* **23** 324–32
Wolff A, Gondran N and Brodhag C 2017 Detecting unsustainable pressures exerted on biodiversity by a company. Application to the food portfolio of a retailer *J. Clean. Prod.* **166** 784–97
Wright J M, Zheng Z and Caudill R J 2012 Assessing the sustainability of renewable energy technologies *2012 IEEE Int. Symp. on Sustainable Systems and Technology (ISSST)* pp 1–6
Yossapoll C, Caudill R, Axe L, Dickinson D, Watts D and Mosovsky J 2002 Carrying capacity estimates for assessing environmental performance and sustainability *IEEE Int. Symp. on Electronics and the Environment, 2002* pp 32–37
van Zelm R and Huijbregts M A J 2013 Quantifying the trade-off between parameter and model structure uncertainty in life cycle impact assessment *Environ. Sci. Technol.* **47** 9274–80
Zijp M C, Posthuma L and van de Meent D 2014 Definition and applications of a versatile chemical pollution footprint methodology *Environ. Sci. Technol.* **48** 10588–97
Zijp M, Heijungs R, van der Voet E, van de Meent D, Huijbregts M, Hollander A and Posthuma L 2015 An identification key for selecting methods for sustainability assessments *Sustainability* **7** 2490–512
Zimmermann M, Althaus H J and Haas A 2005 Benchmarks for sustainable construction: a contribution to develop a standard *Energy Build.* **37** 1147–57