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Supplementary material to:

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

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1. Detailed count of comparisons of impact and assigned carrying capacity in the 31 case studies and synthesis of results

Table S1 and S2 present the number of comparisons of impact and assigned carrying capacity and the proportion of these comparisons in which impact exceeds assigned carrying capacity, according to our count, for case studies related to the LCIA- and PB-framework, respectively. Figure S1 presents a cumulative frequency chart of the studies according to proportion of comparisons in which impact exceeds assigned carrying capacity, based on the data in Table S1 and S2.

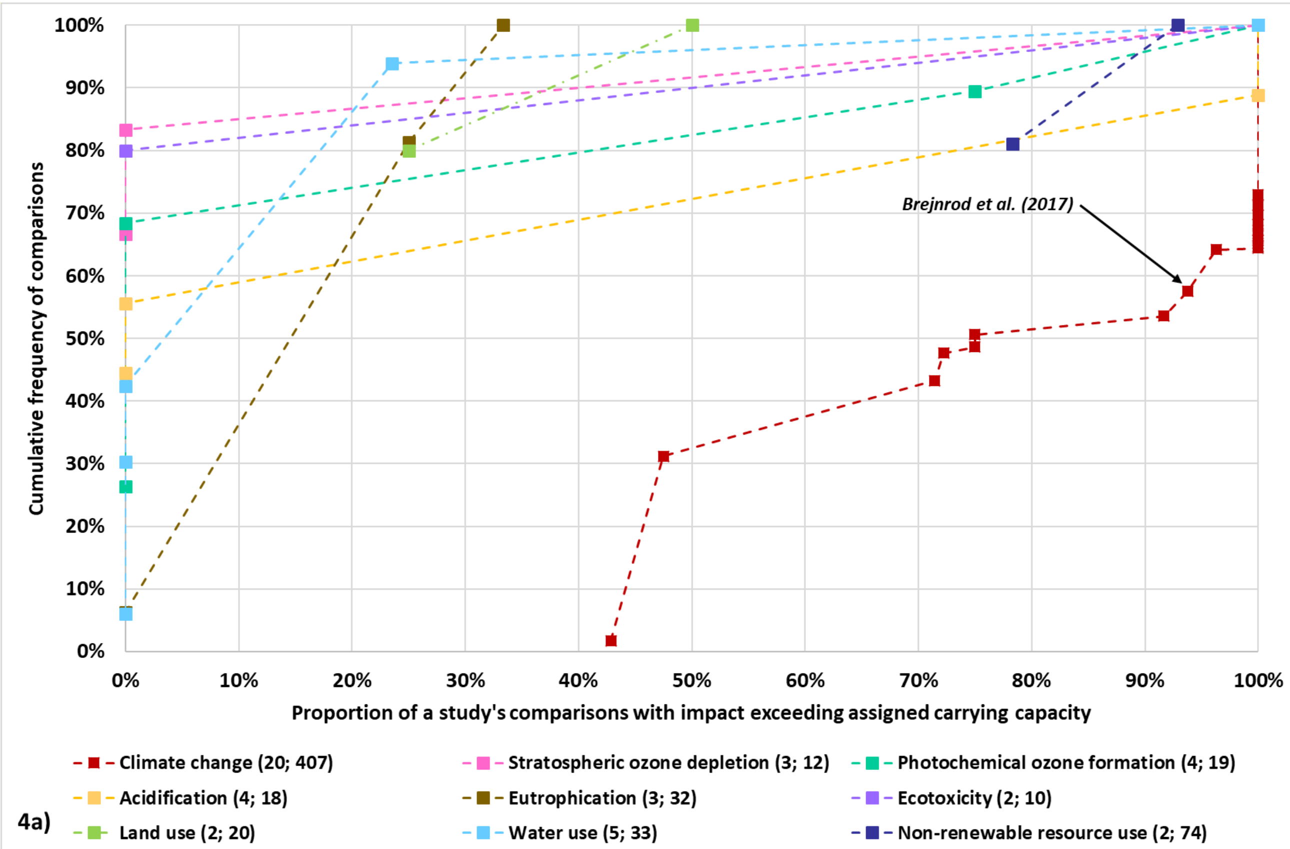
Table S1: Number of comparisons (N) and proportion of comparisons (P) in which impact exceeds assigned carrying capacity for case studies related to the LCIA-framework.

	Climate change		**Stratospheric ozone depletion**		**Photochemical ozone formation**		**Acidification**		**Eutrophication**		**Ecotoxicity**		**Land use**		**Water use**		**Non-renewable resource use**	
Study	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Dickinson et al. (2002)	100%	6			0%	5	100%	6									93%	14
Dickinson and Caudill (2003)	75%	4																
Dickinson et al. (2003)	100%	2	100%	2	75%	4	100%	2	0%	2					0%	2		
Caudill and Dickinson (2004)	96%	27																
Stewart and Deodhar (2009)	100%	1																
Randers (2012)	100%	3																
Wright et al. (2012)	43%	7													24%	17		
Bendewald and Zhai (2013)	100%	1																
Girod et al. (2013)	100%	110																
Girod et al. (2014)	48%	120																

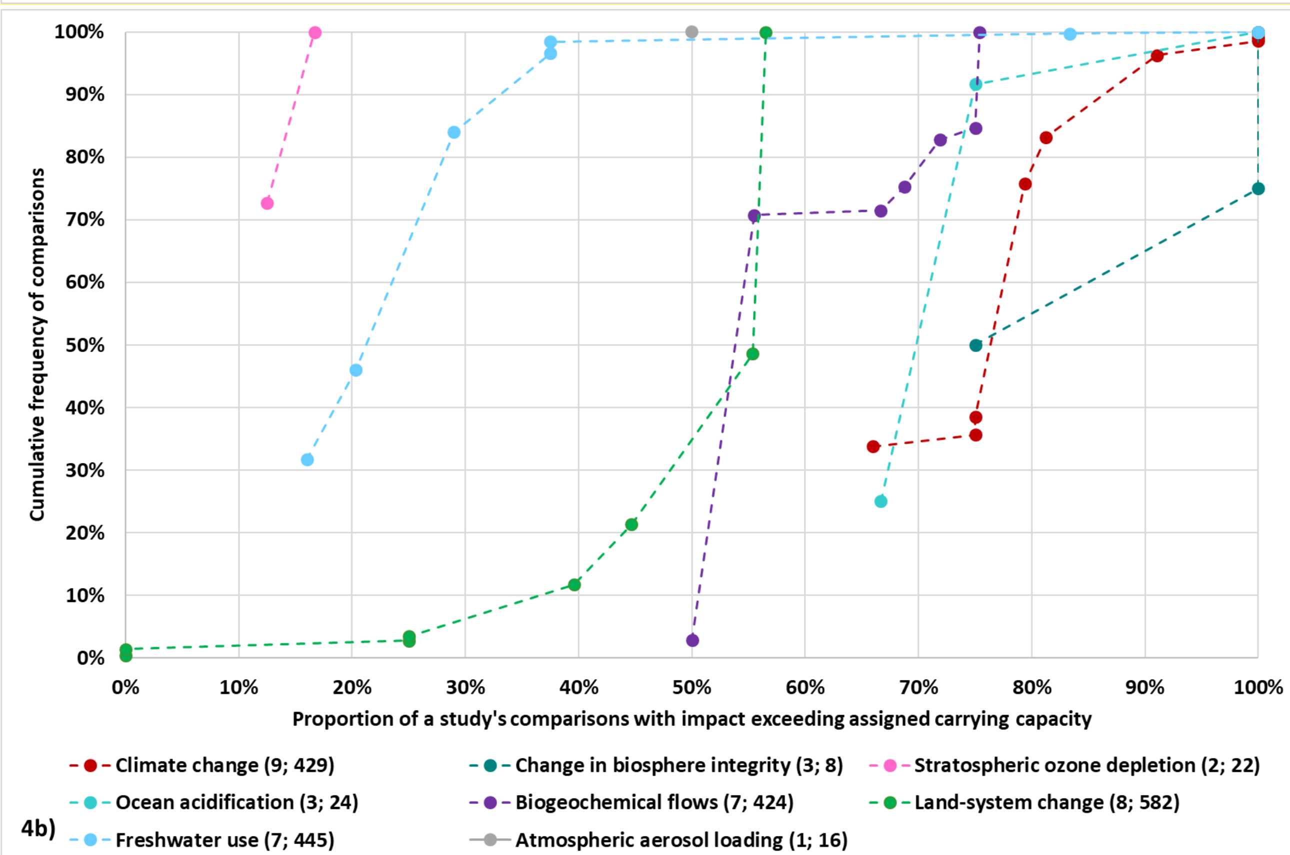
Bijloo and Kerkhof (2015)																	78%	60
Kerkhof et al. (2015)	92%	12																
Krabbe et al. (2015)	100%	6																
Brejnrod et al. (2017)	94%	16	0%	8	0%	8	0%	8	25%	24	0%	8	25%	16	0%	8		
Wolff et al. (2017)	100%	2	0%	2	100%	2	0%	2	33%	6	100%	2	50%	4	100%	2		
Bjørn et al. (2018)	72%	18																
Chandrakumar et al. (2018)	100%	4																
Chandrakumar et al. (2019a)	100%	7																
Chandrakumar et al. (2019b)	71%	49																
Faria and Labutong (2019)	100%	4																
Liu and Bakshi (2019)	75%	8														0%	4		

Table S2: Number of comparisons (N) and proportion of comparisons (P) in which impact exceeds assigned carrying capacity for case studies related to the PB-framework.

	Climate change		Change in biosphere integrity		Stratospheric ozone depletion		Ocean acidification		Biogeochemical flows		Land-system change		Freshwater use		Atmospheric aerosol loading		Introduction of novel entities	
Study	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**	**P**	**N**
Nykvist et al. (2013), Hoff et al. (2014), Hoff et al. (2017)	79%	160							75%	65	55%	159	29%	169				
Fang et al. (2015)	91%	56									45%	56	38%	56				
Fanning and O'Neill (2016)	75%	8							69%	16	25%	8	38%	8				
Roos et al. (2016)	100%	10																
Wolff et al. (2017)			100%	2														
Dao et al. (2018)	100%	2	100%	2			100%	2	67%	3	0%	2						
Lucas and Wilting (2018a; 2018b)	100%	4	75%	4					75%	8	25%	4						
O'Neill et al. (2018)	66%	145							55.5%	288	57%	299	16%	141				
Ryberg et al. (2018)	81%	32			13%	16	75%	16	72%	32	40%	48	20%	64	50%	16		
Algunaibet et al. (2019)	75%	12			17%	6	67%	6	50%	12	0%	6	83%	6				
Roy and Pramanick (2019)													100%	1				



100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Cumulative frequency of comparisons
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Proportion of a study's comparisons with impact exceeding assigned carrying capacity
Brejnrod et al. (2017)
Climate change (20; 407)
Stratospheric ozone depletion (3; 12)
Photochemical ozone formation (4; 19)
Acidification (4; 18)
Eutrophication (3; 32)
Ecotoxicity (2; 10)
Land use (2; 20)
Water use (5; 33)
Non-renewable resource use (2; 74)
4a)



100%
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Cumulative frequency of comparisons
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Proportion of a study's comparisons with impact exceeding assigned carrying capacity
Climate change (9; 429)
Change in biosphere integrity (3; 8)
Stratospheric ozone depletion (2; 22)
Ocean acidification (3; 24)
Biogeochemical flows (7; 424)
Land-system change (8; 582)
Freshwater use (7; 445)
Atmospheric aerosol loading (1; 16)
4b)

Figure S1: Cumulative frequency of the 31 case studies according to proportion of comparisons in which impact exceeds assigned carrying capacity. Each point represent a study and Figures 4a and 4b 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. For example, in the study of Brejnrod et al. (2017), highlighted for *Climate change* in Figure S1a, the anthropogenic system (a building archetype) has a higher impact than the carrying capacity assigned to it in 15 of 16 comparisons, giving a score of 94% on the horizontal axis. Since seven studies (squares in Figure S1a) have a lower score on the horizontal axis, impacts exceed assigned carrying capacity in no more than than 94% of comparisons in eight of the 20 studies that include *Climate change*. Moreover, the vertical axis shows that these eight studies comprise 57% of all the 407 comparisons across the 20 studies that include *Climate change*.

2. **Assessment of the importance of methodological choices for AESA results**

Table S3 presents seven identified common aspects for which methodological choices are made in the 31 case studies. The table also gives examples of multiple alternative methodological choices within one case study for each of the aspects.

Table S3: Seven common aspects for which methodological choices are made in the 31 case studies

Aspect	**Examples of multiple alternative methodological choices within one case study**
Anthropogenic system	Six different ways of producing 1 kWh electricity (Kerkhof et al., 2015b).
System boundary	Including or excluding energy consumption in use phase of buildings (Brejnrod et al., 2017).
Time period	Two different years of integrated circuit manufacturing (Dickinson et al., 2003).
Spatial resolution	Global average or regional carrying capacities for *Water use* and *Land-system change* in the study of nations (Hoff et al., 2014).
Environmental indicator	Three different indicators for the *Eutrophication* impact of a retailer's food portfolio in soil, freshwater and ocean environmental compartments, respectively (Wolff et al., 2017).
Sharing principle (or combination of principles)	Four different combinations of sharing principles to assign carrying capacity to horticulture industries (Chanjief Chandrakumar et al., 2019).
Parameter uncertainty management	A confidence interval around impact (considering propagated parameter uncertainties) and a minimum and maximum assigned carrying capacity for laundry washing (considering carrying capacity uncertainty) (Ryberg et al., 2018). From these results, a "best case" comparison (lowest impact and highest assigned carrying capacity) and a "worst case" comparison (highest impact and lowest assigned carrying capacity) can be constructed.

To assess the importance of each of the seven aspects of Table S3 systematically, we analysed whether different methodological choices for a single aspect are associated with a different numbers of comparisons in which impact exceeds assigned carrying capacity. For example, in the study of agri-food systems by Chandrakumar et al. (2019), only including *Climate change*, the four choices of sharing principles (*Grandfathering*, *Economic value added*, *Land area* and *Calorific content*) were associated with different numbers of exceedance comparisons, whereas the two choices of parameter uncertainty management ("best case" and "worst case") were associated with the same number of exceedance comparisons. Table S4 shows the outcome of this analysis for each impact category included in each of the 31 case studies. Below, we refer to comparisons in which impact exceeds assigned carrying capacity as "exceedance comparisons".

Table S5 gives the share of all case studies (see Table S4) in which different methodological choices are associated with a different number of exceedance comparisons for each aspect (see Table S3) and impact category. The last row contains the average score across all impact categories, weighted by the number of studies that the score for each impact category is based on. The choices of environmental indicator (for a given impact category), sharing principle (or combination of principles) and spatial resolution have the highest score (79-86%). According to our approach, these three types of methodological choices are, hence, the ones most likely to be decisive for whether an impact is found to exceed a carrying capacity.

A limitation of this approach to evaluating the importance of methodological choices is that it is more likely that different methodological choices are associated with different numbers of exceedance comparisons in studies with a high number of comparisons than in studies with a low number of comparisons. Differences in numbers of comparisons across studies, hence, represents a potential bias in the assessment. To evaluate the implications of this potential bias, we repeated the procedure described above three times, applying three different study filters each time: 1) Removing all studies containing more than 50 comparisons, 2) Removing all studies containing more than 25 comparisons, 3) Removing all studies containing more than 10 comparisons. The original results (last row of Table S5) were found to be consistent with the new results: environmental indicator, sharing principle (or combination of principles) and spatial resolution continued to have the highest scores amongst all seven aspects, regardless of the filter applied.

Table S4: Impact categories for which different methodological choices are (in green) or are not (in red) associated with different numbers of exceedance comparisons.

Study	Number of comparisons	Anthropogenic system	System boundary	Time period	Spatial resolution	Environmental indicator	Sharing principle (or combination of principles)	Parameter uncertainty management
Dickinson et al. (2002)	5-14	Climate change Photochemical ozone formation Acidification Non-renewable resource use	-	-	-	Non-renewable resource use	-	-
Dickinson and Caudill (2003)	4	Climate change	-	-	-	-	-	-
Dickinson et al. (2003)	2-4	-	-	Climate change Ozone depletion Photochemical ozone formation Acidification Eutrophication Water use	-	Photochemical ozone formation	-	-
Caudill and Dickinson (2004)	27	Climate change	-	-	-	-	-	Climate change
Stewart and Deodhar (2009)	1	-	-	-	-	-	-	-
Randers (2012)	3	Climate change	Climate change	-	-	-	-	-
Wright et al. (2012)	7-17	Climate change Water use	Water use	-	Water use	-	-	-
Bendewald and Zhai (2013)	1	-	-	-	-	-	-	-
Girod et al. (2013)	110	Climate change	-	Climate change	-	-	Climate change	Climate change
Nykvist et al. (2013), Hoff et al. (2014), Hoff et al. (2017)	65-169	Climate change Biogeochemical flows Land-system change Water use	Climate change Biogeochemical flows Land-system change Water use	-	Land-system change Water use	Biogeochemical flows	-	-
Girod et al. (2014)	120	Climate change	-	Climate change	-	-	-	Climate change

Bijloo and Kerkhof (2015)	60	Non-renewable resource use	-	Non-renewable resource use	-	Non-renewable resource use	-	-
Fang et al. (2015)	56	Climate change Land-system change Water use	-	-	-	-	-	Climate change Land-system change Water use
Kerkhof et al. (2015)	12	Climate change	-	Climate change	-	-	-	-
Krabbe et al. (2015)	6	Climate change	-	-	-	-	-	-
Fanning and O'Neill (2016)	8-16	Climate change Biogeochemical flows Land-system change Water use	-	-	-	Biogeochemical flows	-	Climate change Biogeochemical flows Land-system change Water use
Roos et al. (2016)	10	Climate change	-	-	-	-	-	-
Brejnrod et al. (2017)	8-24	Climate change Ozone depletion Photochemical ozone formation Acidification Eutrophication Ecotoxicity Land use Water use	Climate change Ozone depletion Photochemical ozone formation Acidification Eutrophication Ecotoxicity Land use Water use	-	-	Climate change Eutrophication Land use	-	-
Wolff et al. (2017)	2-6	-	-	-	-	Eutrophication Land use	-	Climate change Ozone depletion Photochemical ozone formation Acidification Eutrophication Ecotoxicity Land use Water use Change in biosphere integrity
Bjørn et al. (2018)	18	Climate change	-	-	-	-	-	Climate change

Chandrakumar et al. (2018)	4	-	Climate change	-	-	-	Climate change	-
Dao et al. (2018)	2-3	Climate change Change in biosphere integrity Ocean acidification Biogeochemical flows Land-system change	-	-	-	Biogeochemical flows	-	-
Lucas and Wilting (2018a; 2018b)	4-8	-	Climate change Change in biosphere integrity Biogeochemical flows Land-system change	-	-	Biogeochemical flows	Climate change Change in biosphere integrity Biogeochemical flows Land-system change	-
O'Neill et al. (2018)	141-299	Climate change Biogeochemical flows Land-system change Water use	-	-	-	Biogeochemical flows Land-system change	-	-
Ryberg et al. (2018)	16-64	Climate change Stratospheric ozone depletion Ocean acidification Biogeochemical flows Land-system change Water use Atmospheric aerosol loading	-	-	Land-system change Water use	Climate change Biogeochemical flows	Climate change Stratospheric ozone depletion Ocean acidification Biogeochemical flows Land-system change Water use Atmospheric aerosol loading	Climate change Stratospheric ozone depletion Ocean acidification Biogeochemical flows Land-system change Water use Atmospheric aerosol loading
Algunaibet et al. (2019)	6-12	Climate change Stratospheric ozone depletion	-	-	-	Climate change Biogeochemical flows	-	Climate change Stratospheric ozone depletion

		Ocean acidification Biogeochemical flows Land-system change Water use						Ocean acidification Biogeochemical flows Land-system change Water use
Chandrakumar et al. (2019a)	**7**	-	Climate change	-	-	-	-	-
Chandrakumar et al. (2019b)	**49**	Climate change	-	-	-	-	Climate change	Climate change
Faria and Labutong (2019)	**4**	-	-	Climate change	-	-	-	Climate change
Roy and Pramanick (2019)	**1**	-	-	-	-	-	-	-
Liu and Bakshi (2019)	**4-8**	Climate change Water use	Climate change	-	Climate change Water use	-	-	-

Table S5: Share of case studies (see Table S4) in which different methodological choices are associated with different numbers of exceedance comparisons. The last row is the weighted average of each column with respect to the number of studies that the score in each cell is based on.

	Impact category	Anthropogenic system	System boundary	Time period	Spatial resolution	Environmental indicator	Sharing principle (or combination of principles)	Parameter uncertainty management
LCIA-related	Climate change	54%	40%	40%	100%	100%	33%	43%
	Stratospheric ozone depletion	0%	0%	0%	-	-	-	0%
	Photochemical ozone formation	0%	0%	100%	-	100%	-	0%
	Acidification	0%	0%	0%	-	-		0%
	Eutrophication	100%	100%	0%	-	100%	-	0%
	Ecotoxicity	0%	0%	-	-	-	-	0%
	Land use	0%	100%	-	-	100%	-	0%
	Water use	33%	0%	0%	50%	-	-	0%
	Non-renewable resource use	100%	-	100%	-	100%	-	-
PB-related	Climate change	75%	0%	-	-	50%	50%	75%
	Change in biosphere integrity	0%	100%	-	-	-	100%	0%
	Stratospheric ozone depletion	50%	-	-	-	-	100%	100%
	Ocean acidification	67%	-	-	-	-	100%	50%
	Biogeochemical flows	67%	50%	-	-	71%	100%	67%
	Land-system change	71%	100%	-	100%	100%	100%	75%
	Freshwater use	100%	100%	-	100%	-	100%	100%
	Atmospheric aerosol loading	100%	-	-	-	-	100%	100%
	Introduction of novel entities	-	-	-	-	-	-	-
	Weighted average	**60%**	**43%**	**36%**	**86%**	**83%**	**79%**	**54%**

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