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Auteurs: Authors:	Anders Bjørn, Chanjief Chandrakumar, Anne-Marie Boulay, Gabor Doka, Kai Fang, Natacha Gondran, Michael Zwicky Hauschild, Annemarie Kerkhof, Henry King, Manuele Margni, Sarah McLaren, Carina Mueller, Mikołaj Owsianiak, Greg Peters, Sandra Roos, Serenella Sala, Gustav Sandin, Sarah Sim, Marcial Vargas-Gonzalez, & Morten Ryberg
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Supplementary material to:

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

Anders Bjørn^{1,2*}, Chanjief Chandrakumar^{3,4}, Anne-Marie Boulay¹, Gabor Doka⁵, Kai Fang^{6.7}, Natacha Gondran⁸, Michael Zwicky Hauschild⁹, Annemarie Kerkhof¹⁰, Henry King¹¹, Manuele Margni¹, Sarah McLaren^{3,4}, Carina Mueller¹², Mikołaj Owsianiak⁹, Greg Peters¹³, Sandra Roos¹⁴, Serenella Sala¹⁵, Gustav Sandin¹⁶, Sarah Sim¹¹, Marcial Vargas-Gonzalez¹⁷, Morten Ryberg^Y

¹CIRAIG, Polytechnique Montréal, 3333 Chemin Queen-Mary, Montréal, QC, Canada

²Department of Management, John Molson School of Business, Concordia University, 1450 Guy, Montréal, QC, Canada

³New Zealand Life Cycle Management Centre, c/o Massey University, Private Bag 11222, Palmerston North 4442, New Zealand

⁴School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand

⁵Doka Life Cycle Assessments, Stationsstrasse 32, CH-8003 Zurich, Switzerland

⁶School of Public Affairs, Zhejiang University, 310058 Hangzhou, China

⁷Center of Social Welfare and Governance, Zhejiang University, 310058 Hangzhou, China

⁸Mines 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

⁹Quantitative Sustainability Assessment, Department of Technology, Management and Economics,

Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark

¹⁰Navigant, a Guidehouse company, Stadsplateau 15, 3521 AZ Utrecht, the Netherlands

¹¹Unilever Safety and Environmental Assurance Centre, Unilever R&D, Colworth Science Park, Sharnbrook MK44 1LQ, UK

¹²Stockholm Environment Institute York, Department of Environment and Geography, University of York, York YO10 5NG, UK

¹³Division of Environmental Systems Analysis, Chalmers University of Technology, 41296 Gothenburg, Sweden

¹⁴RISE Research Institutes of Sweden, Division Materials & Production, Box 104, 431 22 Mölndal, Sweden
¹⁵European Commission, Joint Research Centre, Via E. Fermi, 2749, Ispra (VA), Italy

¹⁶IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 411 33 Gothenburg, Sweden

¹⁷Quantis, 15 Rue de Cléry, Paris, France

*Corresponding author: <u>anders.bjoern@concordia.ca</u>

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.

	Climat change	e	Stratospl ozone depletior	neric n	Photoche ozone formatior	mical 1	Acidifica	ation	Eutrophi	cation	Ecotoxi	city	Land	use	Water	use	Non- renewa resourc use	ible ce
Study	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Ρ	Ν	Р	Ν	Р	Ν
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		

	Climat change	e	Change biosphe integrit	e in ere Sy	Stratos ozone depletic	oheric	Ocean acidifica	ation	Biogeoch flows	nemical	Land- system change		Freshwater use		r Atmospheric aerosol loading		Introd of nov entitie	uction el es
Study	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν	Р	Ν
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.					1.000		750/		700/						500/			
(2018)	81%	32		_	13%	16	75%	16	72%	32	40%	48	20%	64	50%	16		
Algunaibet et	750/	4.2			470/		670/		500/	12	001		0.204					
ai. (2019)	/5%	12			1/%	6	6/%	6	50%	12	0%	6	83%	6				
Koy and																		
Pramanick (2019)													100%	1				

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.



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.

Aspect	Examples of multiple alternative methodological choices within one case study
Anthropogenic	Six different ways of producing 1 kWh electricity (Kerkhof et al., 2015b).
system	
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	Three different indicators for the <i>Eutrophication</i> impact of a retailer's food portfolio in
indicator	soil, freshwater and ocean environmental compartments, respectively (Wolff et al.,
	2017).
Sharing principle (or	Four different combinations of sharing principles to assign carrying capacity to
combination of	horticulture industries (Chanjief Chandrakumar et al., 2019).
principles)	
Parameter	A confidence interval around impact (considering propagated parameter uncertainties)
uncertainty	and a minimum and maximum assigned carrying capacity for laundry washing
management	(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.

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

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

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	Anthropoge nic system	System bounda ry	Time perio d	Spatial resoluti on	Environmen tal indicator	Sharing principle (or combinati on of principles)	Parameter uncertaint y manageme nt
LCIA-	Climate							
related	change	54%	40%	40%	100%	100%	33%	43%
	Stratospheric							
	ozone	0%	00/	00/				00/
	Destection	0%	0%	0%	-	-	-	0%
	Photochemic							
	formation	0%	0%	100%		100%		0%
	Acidification	0%	0%	100%	-	100%	-	0%
	Eutrophicati	0%	0%	0%	-	-		070
	eutrophicati	100%	100%	0%		100%		0%
	Ecotoxicity	0%	0%	0%	-	100%	-	0%
	Land use	0%	100%			100%	_	0%
	Water use	33%	0%	- 0%	50%	-	_	0%
	Non-	5570	070	070	5070			070
	renewable							
	resource use	100%	-	100%	_	100%	-	-
PB-	Climate							
related	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%
	Biogeochemi							
	cal flows	67%	50%	-	-	71%	100%	67%
	Land-system							
	change	71%	100%	-	100%	100%	100%	75%
	Freshwater	1000/	4000/		4000/		40000	1000/
	use Atmospheric	100%	100%	-	100%	-	100%	100%
	Atmospheric							
	aerosol	100%					100%	100%
	Introduction	100%	-	-	-	-	100%	100%
	of novel							
	entities	_	_	_	_	_	_	_
	Weighted							
	average	60%	43%	36%	86%	83%	79%	54%

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