



## Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level

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1 LIFE CYCLE SUSTAINABILITY ASSESSMENT

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**Introducing carrying capacity based normalisation in LCA: framework and development of references at midpoint level**

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1 **Abstract**

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3 *Purpose:* There is currently a weak or no link between the indicator scores quantified in life cycle  
4 assessment (LCA) and the carrying capacity of the affected ecosystems. Such a link must be established if  
5 LCA is to support assessments of environmental sustainability and it may be done by developing carrying  
6 capacity-based normalisation references. The purpose of this article is to present a framework for  
7 normalisation against carrying capacity-based references and to develop average normalisation references  
8 (NR) for Europe and the world for all those midpoint impact categories commonly included in LCA that link  
9 to the area of protection Natural environment.  
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11  
12 *Methods:* Carrying capacity was in this context defined as *the maximum sustained environmental*  
13 *intervention a natural system can withstand without experiencing negative changes in structure or*  
14 *functioning that are difficult or impossible to revert.* A literature review was carried out to identify  
15 scientifically sound thresholds for each impact category. Carrying capacities were then calculated from  
16 these thresholds and expressed in metrics identical to midpoint indicators giving priority to those  
17 recommended by ILCD. NR was expressed as the carrying capacity of a reference region divided by its  
18 population and thus describes the annual personal share of the carrying capacity.  
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20  
21 *Results and discussion:* The developed references can be applied to indicator results obtained using  
22 commonly applied characterisation models in LCIA. The European references are generally lower than the  
23 global references, mainly due to a relatively high population density in Europe. The references were  
24 compared to conventional normalisation references (NR') which represent the current level of intervention  
25 for Europe or the world. For both scales the current level of intervention for climate change, photochemical  
26 ozone formation and soil quality were found to exceed carrying capacities several times.  
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28  
29 *Conclusions:* The developed carrying capacity-based normalisation references offer relevant supplementary  
30 reference information to the currently applied references based on society's background interventions by  
31 supporting an evaluation of the environmental sustainability of product systems on an absolute scale.  
32

33  
34 *Recommendations:* Challenges remain with respect to spatial variations to increase the relevance of the  
35 normalisation references for impact categories that function at the local or regional scale. For complete  
36 coverage of the midpoint impact categories, normalisation references based on sustainability conditions  
37 should be developed for those categories that link to the areas of protection Human health and Natural  
38 resources.  
39

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41  
42 **Keywords** Carrying capacity • Impact assessment • Midpoint • Normalisation • Severity • Single score •  
43 Sustainability conditions • Threshold  
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1 **1 Introduction**

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3 Recent years have seen an increasing focus on environmental sustainability of products and technologies  
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5 and a growing use of LCA and life cycle thinking in industry and the public sector. Still, the state of the  
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7 environment is deteriorating globally by and large (Steffen et al. 2004; MEA 2005). This trend reflects that  
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9 increases in eco-efficiency, achieved with the aid of LCA, are generally insufficient to offset the effects of an  
10  
11 increasing global population that is achieving a higher material affluence. With many environmental  
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13 impacts on the rise globally, the end goal of eco-efficiency improvements becomes increasingly important,  
14  
15 namely that ecological impacts and resource intensities of product life cycles should be reduced to "...a  
16  
17 level at least in line with the Earth's estimated carrying capacity" (WBCSD 2000). This end goal can be seen  
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19 as a condition for environmental sustainability, originally defined as "...seek[ing] to improve human welfare  
20  
21 by protecting the sources of raw materials used for human needs and ensuring that the sinks for human  
22  
23 wastes are not exceeded, in order to prevent harm to humans" (Goodland 1995). Attempts to quantify  
24  
25 carrying capacities have been made for decades most recently at the global scale through the introduction  
26  
27 of the planetary boundaries concept (Rockström et al. 2009; Steffen et al. 2015).  
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32  
33 Carrying capacity is currently considered in some LCA indicators, for instance in the form of critical loads for  
34  
35 terrestrial acidification in Posch et al. (2008). In such indicators only interventions above carrying capacities  
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37 are accounted for, meaning that resource uses and emissions that push a natural system closer to carrying  
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39 capacity exceedance get a free ride. If LCA is to support a development towards environmental  
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41 sustainability, understood as the non-exceedance of carrying capacities, measures of how much  
42  
43 environmental intervention change the level of carrying capacity exceedance are not sufficient for decision  
44  
45 support. In other words the path to environmental sustainability cannot be illuminated solely by indicators  
46  
47 designed to measure environmental unsustainability. Existing LCA indicators must therefore be  
48  
49 supplemented by measures that quantify the share of carrying capacity occupied by environmental  
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51 interventions of a studied product system. Such measures can be established by using carrying capacity as  
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53 environmental sustainability reference in LCA. A first step was taken by Hauschild and Wenzel (1998) who  
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1 derived carrying capacity based distance-to-target weighting factors, albeit using varying definitions of  
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3 carrying capacity across life cycle impact categories. Tuomisto et al. (2012) recently attempted to adapt  
4  
5 initial planetary boundaries of Rockström et al. (2009) as weighting factors for 8 impact categories.  
6  
7 Following the suggestion of Sala et al. (2013) in the context of life cycle sustainability assessment we here  
8  
9 propose to use carrying capacity as consistent environmental sustainability reference in the normalisation  
10  
11 step of LCA to facilitate the comparison of indicator scores to sustainable levels of interventions. According  
12  
13 to ISO 14044, normalisation is “the calculation of the magnitude of the category indicator results relative to  
14  
15 some reference information. The aim of the normalisation is to understand better the relative magnitude  
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17 for each indicator result of the product system under study” (ISO 2006). In existing normalisation practice  
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19 the reference information is commonly the sum of all characterized environmental interventions taking  
20  
21 place in a specified year within a specified region, often scaled per capita (Laurent et al. 2011a).  
22  
23 Normalisation thus allows for the translation of interventions in person equivalents (or person years) and  
24  
25 facilitates some level of comparison across impact categories. However since common references are solely  
26  
27 based on activities within the technosphere they cannot be used to compare and aggregate the severity of  
28  
29 different types of interventions in the ecosphere. The subsequent weighting step is designed to capture the  
30  
31 severity of characterized interventions, but as weighting is often based on personal perspectives on the  
32  
33 prioritization of problems or policy goals, this expression of severity has a strong subjective element, which  
34  
35 is also why ISO 14044 does not allow weighting in “LCA studies intended to be used in comparative  
36  
37 assertions intended to be disclosed to the public” (ISO 2006). Without weighting the user of the LCA results  
38  
39 is left with the normalized results. When understanding carrying capacity occupation as a measure of  
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41 severity normalizing according to carrying capacity instead of total characterized interventions can improve  
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43 the representation of the severity of different interventions.  
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52 The purpose of this article is to present a framework of carrying capacity-based normalisation references in  
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54 LCA and to develop European and global carrying capacity-based normalisation references compatible with  
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56 characterised indicator scores at midpoint for impact categories that link to the area of protection Natural  
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1 environment. After presenting definition and framework, the concept of carrying capacity is made  
2  
3 operational for Life Cycle Impact Assessment (LCIA), and European and global carrying capacity based  
4  
5 normalisation references for each midpoint indicator are developed. The new references are analysed by  
6  
7 internal comparison and comparison to traditional normalisation references and their implications are  
8  
9 discussed followed by an outlook.  
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## 15 **2 Methods**

### 16 **2.1 Definition and operationalization**

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18 Carrying capacity generally refers to a certain quantity of X that some encompassing Y is able to carry  
19  
20 (Sayre 2008). X and Y can refer to different entities depending on the discipline in which carrying capacity is  
21  
22 applied.<sup>1</sup> In all applications carrying capacity aspires to idealism, stasis, and numerical expression (Sayre  
23  
24 2008). In ecology, for instance, carrying capacity describes the maximum equilibrium number of organisms  
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26 of a species (X) that a given environment (Y) in theory can support indefinitely (Odum 1971). In the  
27  
28 common definition of eco-efficiency (WBCSD 2000) X is impacts of unspecified environmental interventions  
29  
30 and Y is the planet. In this form carrying capacity thus acts as the boundary between global environmental  
31  
32 sustainability and unsustainability. Following this use of the term we define carrying capacity as *the*  
33  
34 *maximum sustained environmental intervention a natural system can withstand without experiencing*  
35  
36 *negative changes in structure or functioning that are difficult or impossible to revert.* Here a natural system  
37  
38 may refer to ecosystems or, more broadly, Earth's interacting physical, chemical, and biological processes,  
39  
40 which for instance make up the climate system. By considering both functioning and structure our carrying  
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42 capacity definition aims for a balanced approach: Whereas the concept of ecosystem functioning may have  
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44 an anthropocentric bias, in that it tends to focus on functions valuable to humans, the concept of  
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58 <sup>1</sup> Wildlife management, chemistry, medicine, economics, anthropology, engineering, and population biology are listed  
59 as examples by Sayre (2008).  
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1 ecosystem structure is eco-centric because no judgement is made on the relative inherent value of  
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3 organisms.<sup>2</sup>  
4

5 We calculated carrying capacities from science based thresholds identified in the literature. Thresholds are  
6  
7 numerical values of control variables, which in turn are numerical indicators of the structure and/or  
8  
9 functioning of natural systems (Scheffer et al. 2001; Carpenter et al. 2001; Steffen et al. 2015). In the  
10  
11 example of aquatic eutrophication a threshold can be expressed as a specific nutrient concentration (the  
12  
13 control variable), which demarcates an oligotrophic (clear water) stable state from a eutrophic (turbid  
14  
15 water) stable state, both characterized by distinct ecosystem structure and functioning. When thresholds  
16  
17 are crossed, reverting the natural system to the original state can require a considerable amount of time  
18  
19 with reduced interventions due to the initiation of feedback mechanisms stabilising the natural system in  
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21 the new state after the threshold crossing. Here we characterize an interaction between humans and  
22  
23 natural systems that does not lead to the exceeding of thresholds as environmentally sustainable.  
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29 Fig. 1a shows the impact pathway for the example of how demand for food drives a chain of events that  
30  
31 ultimately leads to increased risk of threshold exceedance for nutrients, which would entail significant  
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33 impacts on structure and functioning of the affected aquatic ecosystem(s). Fig. 1b shows the elements of  
34  
35 an LCA that are used as indicators for and mechanistic translators between the points of the impact  
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37 pathway in Fig. 1a and shows conceptual cause/effect curves for the translation between points. Here we  
38  
39 use “environmental interference” as a generic term for anthropogenic changes to any point in the impact  
40  
41 pathway. Here we expressed carrying capacity at the point in the impact pathway where the concerned  
42  
43 midpoint indicator expresses environmental interference. A translation from threshold to carrying capacity  
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45 therefore involved different LCA elements depending on the point of the impact pathway, marked with a  
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47 cross in Fig. 1c, where the concerned midpoint indicator is expressed (see Section 3). For instance for  
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55 <sup>2</sup> The concept of resilience may offer a bridge between anthropocentric and eco-centric approaches to environmental  
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57 management since studies generally show that ecosystems with high genotype- and species diversity has a high  
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59 resilience, meaning in general terms, that they are better at adapting to sudden changes in conditions than  
60  
61 ecosystems with lower diversity (Scheffer et al., 2001; Carpenter et al. 2001). Thus the protection of ecosystem  
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63 structure can be seen both as eco-centric and as being in the enlightened self-interest of man.  
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1 indicators expressed at the pressure point the translation from threshold to carrying capacity involved a  
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3 fate factor. For impact categories where LCIA models did not model the control variable for which the  
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5 science based threshold was expressed, alternative approaches were taken in translating threshold to  
6  
7 carrying capacity (see Section 3).  
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10 Our carrying capacity definition is concerned with environmental sustainability and we therefore only  
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12 derived carrying capacities for midpoint impact categories linking to the area of protection Natural  
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14 environment. References based on sustainability conditions for impact categories linking to the areas of  
15  
16 protection Human health and Natural resources may also be developed, but this falls outside the scope of  
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18 this article. Carrying capacities were hence quantified for the following ten midpoint categories from the EU  
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20 Commission's ILCD methodology (Hauschild et al. 2013): climate change, ozone depletion, photochemical  
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22 ozone formation, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication, marine  
23  
24 eutrophication, ecotoxicity, land use and water depletion.<sup>3</sup> Several LCIA models exist for calculating  
25  
26 indicator scores within each of these impact categories. When possible we followed the recommendations  
27  
28 for best existing practice by Hauschild et al. (2013) when choosing the characterisation model and factors  
29  
30 with which NR should be compatible. Exceptions were made when recommended models were of a  
31  
32 marginal nature. Marginal characterization models base translations between points in the impact pathway  
33  
34 on the derivative at the estimated current level of environmental interference. Because carrying capacities  
35  
36 should ideally be calculated without considering background interference (see below) marginal  
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38 characterization models were replaced by characterization models using a linear approach (i.e. using the  
39  
40 same factors to translate between points in the impact pathway no matter the current level of  
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42 interferences) when these were available. This procedure led to the replacement of ILCD recommended  
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44 models for terrestrial acidification, terrestrial eutrophication, land use and water depletion by models using  
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46 a linear approach.  
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58 <sup>3</sup> Ionizing radiation effects on the natural environment was excluded since the recommended LCIA model was  
59 classified as interim by Hauschild et al. (2013).  
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## 2.2 Derivation of normalisation references

Normalisation references (NR) were calculated as the carrying capacity (CC, indicator score/year) for impact category  $i$  in region  $j$ , divided by the population in the region ( $P$ ):

$$NR_{i,j} = \frac{CC_{i,j}}{P_j}$$

When dividing characterised LCIA results by NR they are converted into normalized results expressed in units of person equivalents (or person years). Here 1 person equivalent can be interpreted as a level of environmental intervention equivalent to the annual personal share of the carrying capacity for impact category  $i$ . This normalisation replaces the traditional normalisation, where indicator scores of a product system is compared to those of society's background interventions (Laurent et al. 2011a). If  $NR'_{i,j}$  denotes the traditional normalisation reference,  $\frac{NR'_{i,j}}{NR_{i,j}}$  can be interpreted as a distance-to-target indicator, where a value above 1 means that the current per capita interventions exceed the carrying capacity and are hence environmentally unsustainable (Seppälä and Hämäläinen 2001).

## 2.3 Spatial and temporal concerns

The choice of reference region for the normalisation inventory depends on the spatial extent of the impact category. Local and regional scale impact categories such as freshwater depletion and aquatic eutrophication should ideally be related to carrying capacities of relevant local and regional territories corresponding to the spatial information of the LCI. On the contrary global scale impact categories such as climate change and ozone depletion should be related to a single global carrying capacity. As a first step we here developed European (the continent, not the union) and global average carrying capacities for each impact category. Issues related to spatial variation are further discussed in Section 4.

Carrying capacities are in practice dynamic due to: 1) Natural dynamics related to for instance the diurnal and seasonal cycles and stochastic weather events. 2) Anthropogenic interventions that can lead to temporary or permanent carrying capacity reductions if thresholds are exceeded. For instance if a

1 reproductive threshold for a fish stock is exceeded, its carrying capacity expressed as a maximum  
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3 sustainable yield (kg fish caught per year) will decrease temporarily. Likewise if the threshold of a natural  
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5 system has been exceeded the original carrying capacity could in theory decrease if parts of the natural  
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7 system, such as bacteria capable of metabolising pollutants, have been weakened or entirely eliminated  
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9 due to the threshold exceedance. Here we did not consider the effects on carrying capacity caused by  
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11 natural dynamics because it would involve complex dynamic modelling and because the short time scale of  
12  
13 some natural dynamics, often hours to months, is incompatible with the limited time information of typical  
14  
15 LCIs. For impact categories of a dynamic nature, such as photochemical ozone formation, we instead  
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17 expressed thresholds at a form compatible with the time constraints of relevant LCIA models. We also did  
18  
19 not consider dynamics in carrying capacity caused by human interventions because carrying capacities were  
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21 calculated from ideal scenarios where interactions between natural and humans systems are at a steady  
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23 state characterized by numerical values of control variables being below threshold values. In summary,  
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25 calculated carrying capacities were treated as static in this work, which is in line with the general  
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27 understanding of carrying capacity as a static concept (Sayre 2008).  
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34 In calculating NR we applied the populations of 2010 (6.916 billion globally and 740 million for continental  
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36 Europe (UNDESA 2012)). We do however note that NR can be considered time dependent because the  
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38 human population, the denominator of formula 1, is changing in most regions and increasing globally.  
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40 Practitioners may therefore choose a projected population for the median year of the time horizon  
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42 considered in a study. For instance an LCA of a system that will be operating from 2015 to 2035 would then  
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44 use the projected population in 2025 as P.  
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## 50 2.4 Choice of precaution

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52 In our carrying capacity quantifications we adhered to the consensus within LCA modelling to aim for best  
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54 estimates. Therefore whenever an uncertainty range or confidence interval was given for an identified  
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56 threshold and parameters used to translate this threshold to a carrying capacity, the medium or average  
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1 value was chosen, corresponding to a medium level of precaution. A best estimate approach is suitable in  
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3 LCA where the purpose is to compare indicator scores across assessed product systems and impact  
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5 categories. A more precautionary approach to quantifying carrying capacities, as e.g. taken by Rockström et  
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7 al. (2009) and Steffen et al. (2015), may be more appropriate in other decision support contexts, e.g. the  
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9 design of emission standards in a specified jurisdiction.  
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### 15 **3 Results**

16  
17 The following sections present the principles behind the derivations of global average carrying capacity  
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19 based normalisation references for each impact category and the choice of characterisation model in cases  
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21 where the recommendation of ILCD on best existing practice for characterisation modelling were not  
22  
23 followed. See Table 1 for a summary, S1 for a detailed description including derivations of European  
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25 references, which were calculated in much the same way as global references, and S2 for calculations in a  
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27 spreadsheet.  
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#### 34 **3.1 Climate change**

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36 There is evidence of several thresholds in the climate system expressed as average temperature increases  
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38 above pre-industrial levels. These include disintegration of the Greenland ice sheet (1-1.5 °C), widespread  
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40 bleaching of coral reefs (>1 °C), broad ecosystem impacts with limited adaptive capacity (1-2 °C), complete  
41  
42 melting of the Greenland ice sheet, (3 °C) and shutdown of thermohaline circulation (3 °C) (Haines-Young et  
43  
44 al. 2006). In comparison the current temperature increase is around 0.8 °C (IPCC 2013). The crossing of  
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46 each of these thresholds can lead to irreversible changes in the functioning of the climate system with  
47  
48 cascading effects on functioning and structure of various eco-systems. Here we propose one carrying  
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50 capacity based on the 2 °C target, which aims to limit global warming to 2 degrees above pre-industrial  
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52 levels, and another more precautionary carrying capacity based on reducing current radiative forcing from  
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54 greenhouse gases to 1 W/m<sup>2</sup> (corresponding to a steady state temperature increase of 1.06 degrees above  
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1 pre-industrial levels, see S1) as proposed by Rockström et al. (2009). The 2 °C threshold has highest  
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3 acceptance as a policy target, while the 1 W/m<sup>2</sup> threshold is most in line with our definition of carrying  
4  
5 capacity, since a temperature increase of 2 °C will possibly lead to irreversible changes in functioning and  
6  
7 structure of the climate system (Rockström et al. 2009). These thresholds were converted into carrying  
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9 capacities, expressed at the pressure point of the impact pathway as GWP100 based kg CO<sub>2</sub>-eq/year. This  
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11 conversion was made using the GEOCARB model for CO<sub>2</sub> (Bernier and Kothavala 2001) and the model of  
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13 Shine et al. (2005) for other greenhouse gases, from which we calculated the sustained level of emissions  
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15 that for each greenhouse gas alone would lead to a steady state concentration corresponding to each of  
16  
17 the two proposed thresholds.<sup>4</sup> The carrying capacity was then calculated as the average of the GWP100-  
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19 based indicators of all gasses, weighted according to their contribution to the total climate change indicator  
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21 score in 2010, and this lead to a NR<sub>Global</sub> of 985 kg CO<sub>2</sub>-eq/pers/year for the 2 °C threshold and 522 kg CO<sub>2</sub>-  
22  
23 eq/pers/year for the 1W/m<sup>2</sup> threshold (see S1 for details). The calculation of a weighted average was  
24  
25 required due to the 100 year time scale of the GWP100 indicator and high variation of atmospheric life time  
26  
27 of greenhouse gases. Had the time scale of the characterisation model instead been infinite, specific  
28  
29 carrying capacities of the different gasses would be identical. The hidden variance of gas specific carrying  
30  
31 capacities in the derived normalisation references is important to communicate to practitioners and  
32  
33 decision makers. Specifically for CO<sub>2</sub> (having a very long atmospheric life time) the per capita carrying  
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35 capacity is just 4-8 kg/year depending on the chosen threshold (see Electronic Supplementary Material).<sup>5</sup>  
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### 46 3.2 Stratospheric ozone depletion

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52 <sup>4</sup> The reason we could not use the FF of the GWP100 model to make the conversion is that the FF calculates a time  
53 integrated increase in radioactive forcing caused by an emission rather than the steady state increase in radioactive  
54 forcing or temperature required to convert the two thresholds (1 W/m<sup>2</sup> and 2 °C) into carrying capacities according to  
55 our definition.

56 <sup>5</sup> Note that this carrying capacity is much lower than the 2050 goal of 2 tons per capita often mentioned in the climate  
57 change debate. The 2 tons per capita target was derived from the RCP2.6 reduction pathway designed to stay below  
58 the 2 °C threshold by 2100 (van Vuuren et al. 2011; IPCC, 2013). In the year 2100 of the RCP2.6 reduction pathway CO<sub>2</sub>  
59 emissions are nearly zero, which is consistent with our low carrying capacity figures for CO<sub>2</sub>.  
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1 Rockström et al. (2009) proposed a planetary boundary of 5-10 % decrease in column ozone levels for any  
2  
3 particular latitude with respect to 1964–1980 values. The threshold was not based on a single well-  
4  
5 established threshold in the climate system, but rather on the precautionary principle to acknowledge the  
6  
7 complexity of the system of which knowledge is currently incomplete. Stratospheric ozone provides the  
8  
9 regulatory function of filtering harmful ultraviolet radiation from the sun. Due to the long life time of many  
10  
11 ozone depleting substances, ozone degradation in the stratosphere takes decades to recover. The  
12  
13 threshold of 7.5 % decrease in ozone levels (medium value) was converted to a carrying capacity expressed  
14  
15 at the pressure point of the impact pathway in ozone depletion potential (ODP) based kg CFC-11-eq/year of  
16  
17 Montzka and Fraser (1999). This conversion was based on the model of Velders and Daniel (2013), which  
18  
19 was used to calculate the sustained CFC-11-eq emissions that would lead to this decrease in ozone levels at  
20  
21 steady state.<sup>6</sup> This resulted in a  $NR_{Global}$  of 0.078 kg CFC-11-eq/pers/year.  
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### 29 3.3 Photochemical ozone formation 30

31 We could not find a globally applicable threshold for this impact category and therefore based the carrying  
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33 capacity on a time integrated ozone concentration threshold of 3 ppm\*hour AOT40 for daylight hours  
34  
35 during May-July which is applied in European regulation. AOT40 is an effect measure calculated as the  
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37 accumulated ozone exposure during daylight hours above a threshold value of 40 ppb (EEA 1998).  
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40 We here outline the derivation of the European carrying capacity and refer to the Electronic Supplementary  
41  
42 Material for details and approximation at the global scale. The threshold, which was developed by WHO  
43  
44 and adopted as a policy target by the European Environmental Agency (EEA 1998), was designed to prevent  
45  
46 negative effects on growth and/or seed production for (semi-) natural sensitive perennial and annual  
47  
48 species (Umweltbundesamt 2004).  
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58 <sup>6</sup> We could not use the FF of CFC-11 of the ODP model because it is expressed relative to a reference substance (CFC-  
59 11) and not as an absolute steady-state ozone response to changes in emission.  
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1 We converted the time integrated threshold into an average concentration threshold of 44ppb ozone  
2  
3 which applies to the 8 consecutive daily hours<sup>7</sup> with the highest ozone concentrations of May-July. This  
4  
5 threshold was back calculated to a carrying capacity expressed at the pressure point of the impact pathway  
6  
7 as kg NMVOC-eq/year applying the fate factor of the recommended indicator of Van Zelm et al. (2008)  
8  
9 modified to calculate a change in maximum daily 8-h average ozone concentrations in Europe during May-  
10  
11 July as a function of a change in emission. This resulted in a  $NR_{\text{Europe}}$  of 2.5 kg NMVOC-eq/pers/year.  
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### 17 3.4 Terrestrial acidification

18  
19  
20 Thresholds were here based on the critical load concept, for which acidification is defined as the highest  
21  
22 deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful  
23  
24 effects on ecosystem structure and function (Umweltbundesamt 2004)<sup>8</sup>. Exceeding critical loads can lead to  
25  
26 the reductions in crop and forest yields, which can take decades to recover (Hettelingh et al. 2007). We  
27  
28 calculated a world average critical load of 1170 mole  $H^+$  eq/ha/year based on Bouwman et al. (2002), who  
29  
30 developed a global map of critical loads based on acid buffering capacity of soils. From this critical load we  
31  
32 subtracted global average natural depositions of 90 mole  $H^+$  eq/ha/year. We converted the threshold  
33  
34 (critical load) to a carrying capacity expressed at the state point of the impact pathway as mole  $H^+$  eq  
35  
36 deposition/year to be aligned with the OT indicator of Posch et al. (2008) based on average European  
37  
38 conditions. This indicator was chosen instead of the indicator recommended by ILCD, Accumulated  
39  
40 exceedance of Posch et al. (2008), because that indicator is of a marginal nature as it accounts for the share  
41  
42 of emissions depositing on soils for which critical loads are modelled to be exceeded by background  
43  
44 depositions. For this impact category the carrying capacity was to be expressed at the same point in the  
45  
46 impact pathway as the threshold (the state point). Therefore the carrying capacity was simply calculated by  
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53  
54 <sup>7</sup> Although the number of daylight hours exceed 8 per day during May-July at all latitudes within Europe, we chose a  
55  
56 time frame of 8 hours per day for the translation of the time integrated concentration threshold (3 ppm\*hour AOT40)  
57  
58 to a concentration threshold (44ppb) to be compatible with the time frame of the recommended indicator of Van  
59  
60 Zelm et al. (2008). Had we chosen a longer time frame, e.g. 12 hours per day, the concentration threshold would have  
61  
62 been only slightly lower (43ppb instead of 44ppb) and so would the resulting carrying capacity calculated.  
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1 multiplying the global average critical load with the global terrestrial area ( $1.49 \cdot 10^{10}$  ha) This resulted in a  
2  
3  $NR_{Global}$  of  $2.3 \cdot 10^3$  mole  $H^+$  eq/pers/year.  
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### 8 3.5 Terrestrial eutrophication 9

10 Again thresholds were based on the critical load concept, which for terrestrial eutrophication is defined as  
11 the highest deposition of nitrogen as  $NH_x$  and/or  $NO_y$  below which harmful effects in ecosystem structure  
12 and function do not occur according to present knowledge (Umweltbundesamt 2004). Exceeding critical  
13 loads can reduce crop and forest yields and changes in species compositions (disappearance of species  
14 adapted to nutrient poor conditions), which may be practically irreversible (Bobbink et al. 2010). We  
15 calculated a world average critical load based on the global critical load map of Bouwman et al. (2002),  
16 which was constructed by extrapolations from a study covering critical loads of natural and semi-natural  
17 vegetation in Europe. From this estimate we subtracted estimated global average natural depositions which  
18 gave a global threshold of 1340 mole N eq/ha/year. As for terrestrial acidification we converted the  
19 threshold to a carrying capacity expressed at the state point of the impact pathway as mole N eq  
20 deposition/year based on the OT indicator of Posch et al. (2008) which is based on average European  
21 conditions. This indicator was chosen instead of the one recommended by ILCD for the reason given for  
22 terrestrial acidification above. Again the carrying capacity was calculated by multiplying the global average  
23 critical load with global terrestrial area. This resulted in a  $NR_{Global}$  of  $2.7 \cdot 10^3$  mole N eq/pers/year.  
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### 46 3.6 Freshwater and marine eutrophication 47

48 For freshwater and marine eutrophication a threshold demarcates oligotrophic (clear water) from  
49 eutrophic (turbid water) states (Carpenter et al. 2001). Thresholds may vary spatially, depending on e.g.  
50 temperature, salinity and depth. We chose 0.3 mg  $P_{tot}$ /L as a generic threshold for freshwater (usually P-  
51 limited) based on Struijs et al. (2011) who stated that concentrations above this value are considered a  
52 potential cause of encroachment of aquatic life due to nutrient enrichment. For marine environments  
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1 (usually N-limited), we chose 1.75 mg N<sub>tot</sub>/L as the medium of the concentration limit range proposed by de  
2  
3 Vries et al. (2013) in their development of planetary boundaries for nitrogen emissions. The concentration  
4  
5 threshold was converted to a carrying capacity expressed at the pressure point of the impact pathway as  
6  
7 increase in P (freshwater) and N (marine) concentrations to be compatible with the midpoint indicators of  
8  
9 Struijs et al. (2009) based on average European conditions. For the conversion we used FFs of P and N of  
10  
11 Struijs et al. (2009), which links a marginal emissions increase (kg/year) to a steady state concentration  
12  
13 increase (kg P or N per m<sup>3</sup>). After a linear scaling to account for global water volumes and the subtractions  
14  
15 of natural flows of N and P, NR<sub>Global</sub> was calculated as 0.84 kg P eq/pers/yr for freshwater and 29 kg N  
16  
17 eq/p/yr for marine waters.  
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### 25 3.7 Freshwater ecotoxicity

26  
27 The carrying capacity calculation was based on the threshold HC5(NOEC), which has been adopted as a  
28  
29 quality target in several regulatory frameworks, such as the EU Water Framework Directive (EC 2011).  
30  
31 HC5(NOEC) is the concentration at which maximum 5 % of species in an ecosystem are affected and it is  
32  
33 derived from species sensitivity distributions, which are probabilistic models of the variation in sensitivity of  
34  
35 all species in a model ecosystem to a particular stressor (Posthuma et al. 2002). The HC5(NOEC) threshold  
36  
37 was converted to a carrying capacity expressed at the impact point of the impact pathway as  
38  
39 [PAF]\*m<sup>3</sup>\*day/year to be compatible with the spatially generic USEtox indicator (Rosenbaum et al. 2008).  
40  
41  
42 The conversion was carried out by modifying the effect factor of USEtox from being based on the  
43  
44 HC50(EC50) effect level to being based on HC5(NOEC) following Bjørn et al. (2014). In accordance with  
45  
46 USEtox full concentration addition was assumed, i.e. if two chemicals are each present at their HC5(NOEC)  
47  
48 in the same freshwater volume then the carrying capacity of the compartment is assumed to be exceeded  
49  
50  
51 by 100 %. The procedure resulted in a NR<sub>Global</sub> of 1.9\*10<sup>4</sup> [PAF]\*m<sup>3</sup>\*day/pers/year.  
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### 58 3.8 Land use

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1 To reflect the multitude of functions and services of land we calculated carrying capacities based on  
2  
3 thresholds for two control variables representing different impact pathways. The first threshold concerns  
4  
5 erosion regulation and the second threshold regional scale biodiversity.  
6

7  
8 The soil erosion carrying capacity was based on Verheijen et al. (2009), who provided a threshold interval  
9  
10 for Europe of 0.3-1.4 ton/ha/year for 'tolerable soil erosion', defined as 'any actual soil erosion rate at  
11  
12 which a deterioration or loss of one or more soil functions does not occur'. The threshold range was based  
13  
14 on the estimated rate of natural soil formation caused by mineral weathering and dust deposition. We  
15  
16 chose the middle value of 0.85 ton/ha/year and converted this to a carrying capacity expressed at the state  
17  
18 point of the impact pathway as ton of eroded soil/(ha\*year) to be compatible with global average CFs of  
19  
20 the indicator for erosion resistance of Saad et al. (2013). The indicator of Saad et al. (2013) was chosen  
21  
22 instead of the one recommended by ILCD based on soil organic matter (SOM) of Milà i Canals et al. (2007),  
23  
24 because that indicator is of a marginal nature as it accounts for the change in SOM compared to an  
25  
26 alternative land use scenario reference. As for terrestrial acidification and eutrophication the carrying  
27  
28 capacity was expressed at the same point in the impact pathway as the threshold, the state point.  
29  
30 Therefore the carrying capacity was simply calculated by multiplying the threshold with the global  
31  
32 terrestrial area ( $1.49 \cdot 10^{10}$  ha). This gave a NR of 1.8 ton/pers/year.  
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39 The land use threshold for biodiversity was based on Noss et al. (2012), who meta-reviewed 13 studies that  
40  
41 reported science-based local or regional conservation targets expressed as a share of natural lands that  
42  
43 should be conserved, i.e. practically undisturbed by humans, to maintain sufficient levels of biodiversity in  
44  
45 the region in question. Such conservation targets have the inbuilt perspective that loss of local biodiversity,  
46  
47 due to e.g. intensive agriculture or infrastructure land use, is acceptable as long as regional biodiversity is  
48  
49 maintained. The relationship between land use and regional biodiversity levels show threshold behaviour  
50  
51 as ecosystems not directly affected by the land use (e.g. situated close to a clear-cut forest) are known to  
52  
53 undergo state shifts due to the effects of neighbouring land use (Barnovsky et al. 2012; Noss et al. 2012). As  
54  
55 a threshold we chose the median value, 31 %, of the data series of Noss et al. (2012) for the share of  
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1 terrestrial land that needs to be conserved as a threshold.<sup>9</sup> The threshold was converted to a carrying  
2  
3 capacity expressed at the pressure point of the impact pathway as  $\text{m}^2 \cdot \text{year}/\text{year}$  land occupation to be  
4  
5 directly compatible with any LCI. For reasons given above we did not align the carrying capacity with the  
6  
7 ILCD recommended indicator and instead chose to align it directly to any LCI since the threshold is  
8  
9 independent on types of land use (i.e. paved road counts as none-conserved land just as managed forest).  
10  
11 The conversion of the threshold to carrying capacity was carried out simply by taking 31 % of global  
12  
13 terrestrial land. This gave a  $\text{NR}_{\text{Global}}$  of  $1.5 \cdot 10^4 \text{ m}^2 \cdot \text{year}/\text{pers}/\text{year}$ . In practice a set of CFs with the value 1  
14  
15 for all relevant elementary flows could be created in LCA software to form an indicator compatible with the  
16  
17  
18  
19  
20 NR.

21  
22 Note that land transformations were not considered in the derivation of the two carrying capacities  
23  
24 because indicators of land transformation are inherently marginal as they are based on an alternative land  
25  
26 use scenario reference.  
27

### 3.9 Water depletion

31  
32 The carrying capacity was based on the so-called environmental flow requirements for good conditions  
33  
34 ( $\text{EFR}_{\text{good}}$ ), which is a threshold measure of the minimum water flow required to sustain rivers in a “good  
35  
36 ecological state” (Smakhtin et al. 2004). This threshold was supplemented by another threshold for the  
37  
38 minimum water flow required to sustain terrestrial ecosystems in the river catchment. In deriving a  
39  
40 combined threshold for aquatic and terrestrial ecosystems we followed Gerten et al. (2013), who estimated  
41  
42 the global accessible blue water resource ( $16.300 \text{ km}^3/\text{year}$ ) and subtracted a global  $\text{EFR}_{\text{good}}$  quantification  
43  
44 of 57 % of blue water and another 30 % of blue water to avoid physical water stress of terrestrial  
45  
46 ecosystems. In the impact pathway of water depletion a change in pressure, expressed in  $\text{m}^3/\text{year}$  water  
47  
48 consumed, causes a change in control variable, expressed in  $\text{m}^3/\text{year}$  water availability, of similar  
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57 <sup>9</sup> This number is in good agreement with recent conclusions that around 34 % of global terrestrial coverage should be  
58 conserved to achieve biodiversity protection goals given patterns and effects of current land conservation (Butchart et  
59 al. 2015)

1 magnitude.  $EFR_{good}$  can therefore be interpreted as a pressure based carrying capacity and no conversion  
2  
3 from threshold to carrying capacity was hence needed. As for the carrying capacity of land use related to  
4  
5 regional biodiversity the carrying capacity is aligned directly to any LCI since the  $EFR_{good}$  estimates of Gerten  
6  
7 et al. (2013) made no distinction between different types of blue water consumption such as lake or river  
8  
9 water. We deviated from the ILCD recommended water scarcity indicator of Frischknecht et al. (2008),  
10  
11 because this indicator is of a marginal nature as it models the scarcity created by background water  
12  
13 consumption. This procedure gave a  $NR_{Global}$  of 306 m<sup>3</sup>/pers/year. As for the land use impact category  
14  
15 (regional biodiversity) a set of CFs with the value 1 for all relevant elementary flows could be created in LCA  
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17 software to form an indicator compatible with the NR.  
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### 25 3.10 Comparison with traditional normalisation references and across spatial scale

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27 Table 1 presents an overview of the developed carrying capacity-based normalisation references (NR)  
28  
29 globally and for Europe and a comparison with traditional normalisation references based on characterized  
30  
31 global background interventions (NR').  $NR'_{global}$  was based on Laurent et al. (2013) who calculated global  
32  
33 normalisation references for the ILCD methodology for the year 2010 (or 2000 for impact categories where  
34  
35 more recent data was unavailable).  $NR'_{Europe}$  was based on Benini et al. (2014) and Sala et al. (2015) who  
36  
37 calculated normalisation references for EU-27 for the ILCD methodology, also for the year 2010. When  
38  
39 comparing  $NR'_{Europe}$  to  $NR_{Europe}$  it should be noted that  $NR_{Europe}$  has a wider geographical coverage as it is  
40  
41 based on the European continent. For impact categories where our developed NR was not aligned with the  
42  
43 ILCD methodology  $NR'$  was calculated using the underlying inventories of Laurent et al. (2013) and Sala et  
44  
45 al. (2015), with the exception of water depletion for which blue water consumption could not be extracted  
46  
47 from the inventories of these two studies. More details can be found in the Electronic Supplementary  
48  
49 Material (SI1 and SI2).  
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55  $NR'/NR$ -values above 1 mean that current levels of interventions exceed the carrying capacity and that  
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57 normalized indicator scores will become higher when a traditional normalisation reference is replaced by a  
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1 carrying capacity-based one. This is the case for climate change (both thresholds), photochemical ozone  
2  
3 formation and land use (soil erosion) both at the global and European scale, for freshwater eutrophication  
4  
5 at the European scale and for water depletion at the global scale. The  $NR'/NR$  ratios for the remaining  
6  
7 impact categories are all below 1 and normalized indicator scores of these categories thus become smaller  
8  
9 when replacing traditional normalisation references with carrying capacity based ones. When comparing  
10  
11 across scale (column 6 in Table 1) it can be seen that for all impact categories except water depletion and  
12  
13 marine eutrophication  $NR_{\text{Europe}}$  is smaller than  $NR_{\text{Global}}$ , which is mainly due to Europe's relatively high  
14  
15 population density.  
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19  
20 The interpretation of results for climate change, photochemical ozone formation, land use and water  
21  
22 depletion is that humanity is globally unsustainable according to our carrying capacity definition. Global  
23  
24 degrees of unsustainability are seemingly greatest for climate change (when carrying capacity is based on  
25  
26 the  $1 \text{ W/m}^2$  threshold) and photochemical ozone formation where in both cases characterized  
27  
28 interventions need to decrease by a factor of 15, compared to those of the year 2010 and 2000  
29  
30 respectively, to reach sustainable levels characterized by no exceedance of reference thresholds on  
31  
32 average.  
33  
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35  
36 For the remaining impact categories current interventions appear environmentally sustainable when  
37  
38 averaging over the global situation because  $NR'_{\text{global}}/NR_{\text{Global}}$  is below 1. The relevance of this perspective is  
39  
40 discussed in the next section.  
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#### 46 **4 Discussion and outlook**

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48 The new normalisation references are compatible with commonly used midpoint indicators and provide  
49  
50 reference information of a different relevance than society's background interventions, giving better  
51  
52 indications of the severity of interventions compared to sustainable levels. The references can be  
53  
54 integrated in LCA software for the application in LCA studies. Practitioners should be aware of uncertainties  
55  
56 of the references discussed below and that updated references in the future may replace the ones  
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1 proposed here. Using the developed references in LCA serves mainly two purposes: 1) To provide absolute  
2  
3 references that can inform criteria for environmental sustainability of systems. 2) To provide a scientific  
4  
5 basis for aggregating indicator scores across impact categories in LCA.  
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#### 10 4.1 Criteria for environmental sustainability 11

12 Regarding the first purpose the normalisation references offer a pedagogical expression of interventions in  
13  
14 environmental sustainability person equivalents, which serves to communicate how large a share of the  
15  
16 carrying capacity a given system or activity takes up. This can help shifting the perspective of environmental  
17  
18 assessments from comparing eco-efficiencies of product systems to addressing eco-efficiency  
19  
20 improvements required to achieve environmental sustainability at a societal scale (i.e. through the NR'/NR  
21  
22 ratio). Criteria for environmental sustainability of societal subsystems are inherently subjective because  
23  
24 they involve the allocation of carrying capacity to systems that meet different human needs (and wants).  
25  
26 However it may be feasible to agree upon a moral rule that carrying capacities should be shared equally  
27  
28 amongst people living within its geographical boundaries or an alternative rule that global carrying  
29  
30 capacities should be shared equally within the global population.<sup>10</sup> Moral rules like these would not restrict  
31  
32 personal freedom by enforcing a specific consumption pattern. Instead they would translate into equal  
33  
34 personal carrying capacity budgets that could be used according to personal preferences, much like a  
35  
36 salary. As a supplement to the perspective of personal carrying capacity consensus on the allocation of  
37  
38 carrying capacity between products belonging to different sectors may be based on sector specific  
39  
40 reduction scenarios of e.g. IPCC, IEA or national and municipal environmental strategies.  
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#### 50 4.2 Aggregation of normalized indicator scores 51 52 53 54 55

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57 <sup>10</sup> The difference between these two rules is not trivial. Consider the potentially large differences between per capita  
58 domestic carrying capacities of Canada and Singapore for the many impact categories related to the availability of land  
59 and water as source or sink.  
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1 Regarding the second purpose, the developed normalisation references allows for the aggregation of  
2  
3 indicator scores expressed in carrying capacity occupation across impact categories to a single score. In this  
4  
5 process an additional weighting step is needed as the exceeding of the considered carrying capacities are  
6  
7 not necessarily equally severe for all categories of impact. Factors that influence the severity of exceeding a  
8  
9 carrying capacity include the type of damage that is caused, the social and/or economic impact, the spatial  
10  
11 extent, the time required for reversion of damage, whether a threshold is characterized by a hysteresis,<sup>11</sup>  
12  
13 and effects on other carrying capacities.<sup>12</sup> As an example it could be argued that carrying capacity  
14  
15 normalised indicator scores for climate change should have a higher weight than corresponding scores for  
16  
17 photochemical ozone formation, given for instance that effects of crossing climate system thresholds are  
18  
19 both more pervading and difficult to reverse than the effects of crossing the tropospheric ozone threshold  
20  
21 for vegetation used in this work.  
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#### 29 4.3 Uncertainties and future work 30

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32 The introduction of the carrying capacity based normalisation reference on one hand eliminates the  
33  
34 inventory-related uncertainties that accompany the classical normalisation reference (NR'), and these  
35  
36 uncertainties are large, especially for the toxicity-related impact categories (Laurent et al. 2011b). On the  
37  
38 other hand additional uncertainty related to quantification of carrying capacity is introduced. A central  
39  
40 question is whether control variables, and thus thresholds, should be located at midpoint or endpoint<sup>13</sup> in  
41  
42 the impact pathway. In this work control variables, often expressed in a concentration metric, were located  
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46 <sup>11</sup> A hysteresis is a phenomenon which causes the exceedance of a threshold to be difficult to revert because the  
47  
48 natural system has entered a new stable state characterized by stabilizing feedback mechanisms. In practice this  
49  
50 means that a reduction in environmental intervention of a similar magnitude as the increase in interventions that  
51  
52 previously caused the threshold to be exceeded is not sufficient to bring the system back to its original state.  
53  
54 Hysteresis has been observed for e.g. the response of shallow lakes to changes in phosphorous loadings (Scheffer  
55  
56 2001).

57 <sup>12</sup> For instance increased run-off due to the exceedance of the climate change carrying capacity can lead to a higher  
58  
59 loss of reactive nitrogen and phosphorous from fertilizer application, thereby increasing the risk of exceeding carrying  
60  
61 capacities for freshwater and marine eutrophication. See Steffen et al. (2015) for elaboration on this topic.

62 <sup>13</sup> Midpoint is here understood as the point at which the impact pathway of different substances converge (Hauschild  
63  
64 et al. 2013). Because this point of convergence varies the impact pathway location of the midpoint varies across  
65  
66 impact categories. In comparison the endpoint is consistently located at the of the impact pathway and typically  
67  
68 expressed in a metric related to the disappearance of species (Hauschild et al. 2013).

1 at midpoint. A control variables related to effects on species (e.g. potentially disappeared fraction of  
2 species, PDF) at endpoint could alternatively have be chosen consistently for all impact categories, along  
3 with a threshold value. Carrying capacity based normalisation references could then be calculated at either  
4 midpoint or endpoint from such an overarching threshold value. This approach is expected to lead to higher  
5 uncertainties than the approach taken here of calculating carrying capacities from thresholds at midpoint,  
6 because it would involve a translation through more processes in the impact pathway (i.e. from driver to  
7 impact in the DPSIR framework, see Fig. 1). Also, a control variable at endpoint, such as PDF, is not  
8 necessarily a good indicator of ecosystem functioning (Mace et al. 2014), although it is a direct measure of  
9 ecosystem structure. Yet, a consistently chosen threshold value at endpoint would lead to the calculation of  
10 carrying capacities that reflect the same level of species protection across impact categories, which is  
11 appealing in the comparative setting of LCA. This approach should therefore be further explored.

12 Another type of uncertainty relates to spatial variations.

13 Our derived carrying capacities reflect average conditions of Europe and the world and have been  
14 developed to fit site generic characterisation factors. This is useful in LCA, where locations of environmental  
15 interventions are often not known with great accuracy. However the spatially generic approach hides  
16 variations emission fate and carrying capacity of receiving environments, which is problematic in cases  
17 where locations of environmental interventions are in fact known and spatially derived impact assessment  
18 models exist. Our spatially generic approach, combined with the fact that emission sources are rarely  
19 homogenously distributed in space, is the reason that our method predicts that carrying capacities have not  
20 been exceeded for the majority of impact categories (see Table 1 and Bjørn et al. (2014) for an elaboration  
21 of this issue for freshwater ecotoxicity). This prediction is invalidated by observations since exceedances of  
22 carrying capacities are quite frequent for many types of environmental interferences operating at the local  
23 to regional scale (MEA 2005; Steffen et al. 2015). A pragmatic way of accounting for this bias is to subtract  
24 the carrying capacity of remote areas, classified based on e.g. a population density threshold, from the  
25 calculation of spatially aggregated carrying capacities. Thereby land, water and air in scarcely populated

1 areas would be considered unavailable as resources and for assimilating emissions, and the carrying  
2  
3 capacity estimates would consequently be reduced. This was done by Gerten et al. (2013), who estimated  
4  
5 the accessible blue water to be 40 % of global blue water resources, meaning that roughly 60 % of the  
6  
7 theoretical global carrying capacity for water use (i.e. total flow minus environmental flow requirements)  
8  
9 was considered unavailable This estimate of unavailable carrying capacity gives an impression of the extent  
10  
11 at which our derived carrying capacities may be overestimated, but it needs to be assessed for each impact  
12  
13 category since it is 0 for climate change and stratospheric ozone depletion and may be higher than 60 % for  
14  
15 other impact categories. Such a modification might change the ranking between the normalised indicator  
16  
17 scores but it would not solve the problem of spatial variability in degrees of carrying capacity occupation of  
18  
19 a given emission within the remaining non-remote areas where carrying capacity is judged available.  
20  
21 Normalisation references could be developed at finer scales than what was demonstrated in this article to  
22  
23 take into account spatial variation in carrying capacity and the spatial distribution of the processes making  
24  
25 up an LCI. However at a high resolution (e.g. 0.5°-0.5°) such references would need to take into account  
26  
27 trans-boundary emissions. Alternatively carrying capacity could be integrated in spatially differentiated  
28  
29 characterisation models rather than in the normalisation step. In this way indicator scores could be  
30  
31 expressed in hectare years, which could be compared to the availability of land, thus following the style of  
32  
33 the ecological footprint indicator (Borucke et al. 2013).

34  
35 Beyond the location of control variable in the impact pathway and the handling of spatial variations  
36  
37 additional sources of uncertainties related to quantification of carrying capacity needs consideration: the  
38  
39 selection of threshold on which to base the carrying capacity in some cases involves a choice between more  
40  
41 alternatives. For instance we aimed to base carrying capacities on scientific consensus on threshold  
42  
43 reflecting the state of natural systems that should be protected to ensure their structure and functioning.  
44  
45 Yet, a clear scientific consensus could not be identified in all cases. For example, the threshold for  
46  
47 stratospheric ozone depletion (Section 3.2) was here based on the planetary boundary of Rockström et al.  
48  
49 (2009), which is to a larger extent a precautionary first estimate than a scientific consensus, due to the  
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1 imperfect understanding of the relationship between control variable and structure and functioning of  
2 natural systems. In other cases the relationship is better understood, but may not be characterized by a  
3 single sharp threshold, but rather by a sequence of thresholds or be close to linear (Dearing et al. 2014). In  
4 such cases value judgement on what can be considered a minimum environmentally sustainable level of  
5 structure and functioning is required for the calculation of carrying capacities. Other sources of  
6 uncertainties in the calculated carrying capacity based normalisation references are: 1) choice of structure  
7 and functioning to be protected (land is, for example, associated with a multitude of functions beyond  
8 erosion resistance and host of biodiversity (Saad et al. 2013)), 2) choice of control variable (for example,  
9 total concentration of nitrogen may not be the best control variable for indicating structure and/or  
10 functioning of marine ecosystems (HELCOM 2013)), 3) choice of impact pathway model to translate  
11 threshold to carrying capacity (the translation for photochemical ozone formation in this work, for  
12 example, involved different time frames and could be improved). Identifying all sources of uncertainties,  
13 analysing their magnitudes and consequently managing and reducing them is an important future task that  
14 could take point of departure in the proposal of Bjørn et al. (2015).

15 This article only provided normalisation references for midpoint impact categories that link to the area of  
16 protection Natural environment. To increase the usefulness of the references they should be supplemented  
17 with normalisation references based on sustainability conditions for the impact categories linking to the  
18 areas of protection Human health and Natural resources, thus covering all midpoint impact categories of  
19 LCA. For midpoint impact categories such as climate change and photochemical ozone formation that link  
20 to more than one area of protection the lowest normalisation reference amongst the complete set of  
21 references should then be used. Using sustainability conditions as references in impact assessment may  
22 also be explored in life cycle sustainability assessment.

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56 Annie Levasseur (CIRAIG) for assisting with quantifying the carrying capacity for stratospheric ozone  
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1 depletion, photochemical ozone formation and climate change respectively and Tue Vissing Jensen (DTU)  
2  
3 for technical support.  
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8 **Electronic Supplementary Material** SI1 elaborates on the carrying capacity quantifications for each impact  
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10 category and SI2 contains all calculations in spread sheet format.  
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**Table 1** Developed global normalisation references based on carrying capacity, comparison across scales and with traditional normalisation references. Bold values indicate that NR'/NR fractions are above 1. Italics CF references mean compatibility with characterisation methods recommended by Hauschild et al. (2013)

Impact category	NR_Global (per person year)	$\frac{NR'_{Global}}{NR_{Global}}$	NR_Europe (per person year)	$\frac{NR'_{Europe}}{NR_{Europe}}$	$\frac{NR_{Global}}{NR_{Europe}}$	CF compatibility	Threshold
Climate change	985kg CO <sub>2</sub> -eq	<b>8.2</b>	985ton CO <sub>2</sub> -eq	<b>9.4</b>	1	<i>GWP100 (CO<sub>2</sub>-eq) (Forster et al. 2007)</i>	Temperature increase of 2°
	522 kg CO <sub>2</sub> -eq	<b>15</b>	522 kg CO <sub>2</sub> -eq	<b>18</b>			Radioactive forcing increase of 1W*m <sup>2</sup>
Ozone depletion	0.078kg CFC-11-eq	0.53	0.078kg CFC-11-eq	0.28	1	<i>ODP (Montzka and Fraser 1999)</i>	7.5 % decrease in average ozone concentration
Photochemical ozone formation	3.8 kg NMVOC-eq	<b>15</b>	2.5 kg NMVOC-eq	<b>13</b>	1.6	<i>Tropospheric ozone concentration Increase (Van Zelm et al. 2008)</i>	Tropospheric ozone concentration of 3 ppm* hour AOT40
Terrestrial acidification	2.3*10 <sup>3</sup> mole H+ eq	0.34	1.4*10 <sup>3</sup> mole H+ eq	0.53	1.7	OT method of Posch et al. (2008)	Deposition of 1170 and 1100 mole H <sup>+</sup> eq*ha <sup>-1</sup> *year <sup>-1</sup> globally and for the EU
Terrestrial eutrophication	2.8*10 <sup>3</sup> mole N eq	0.13	1.8*10 <sup>3</sup> mole N eq	0.30	1.5	OT method of Posch et al. (2008)	Deposition of 1340 and 1390 mole N eq*ha <sup>-1</sup> *year <sup>-1</sup> globally and for the EU
Freshwater eutrophication	0.84kg P eq	0.74	0.46kg P eq	<b>3.22</b>	1.8	<i>P concentration increase (Struijs et al. 2009)</i>	P concentration of 0.3mg/L
Marine eutrophication	29 kg N eq	0.32	31kg N eq	0.55	0.95	<i>N concentration increase (Struijs et al. 2009)</i>	N concentration of 1.75 mg/L
Freshwater ecotoxicity	1.9*10 <sup>4</sup> [PAF]*m <sup>3</sup> *day	0.036	1.0*10 <sup>4</sup> [PAF]*m <sup>3</sup> *day	0.85	1.8	<i>CTU (Rosenbaum et al. 2008)</i>	HC5(NOEC)
Land use, soil erosion	1.8 tons eroded soil	<b>4.9</b>	1.2 tons	<b>9.3</b>	1.6	Saad et al. (2013), land occupation CFs only	Tolerable soil erosion of 0.85 tons*ha <sup>-1</sup> *year <sup>-1</sup> )
Land use, biodiversity	1.5*10 <sup>4</sup> m <sup>2</sup> *year	0.42	9.5*10 <sup>3</sup> m <sup>2</sup> *year	0.79	1.6	LCI data, land occupation only	31 % conserved land area

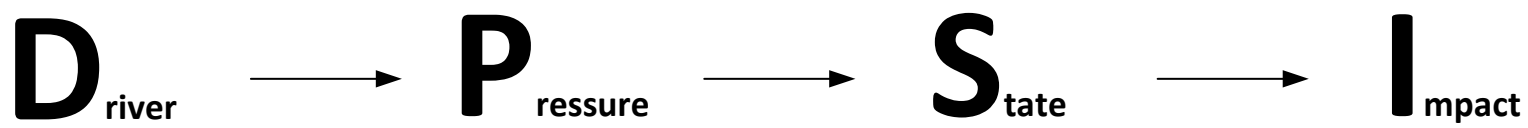
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Water depletion	306 m <sup>3</sup>	<b>1.3</b>	490 m <sup>3</sup>	0.52	0.63	LCI data classified as blue water consumption	Conservation of 57 % of river flows for aquatic ecosystems and 30 % for terrestrial
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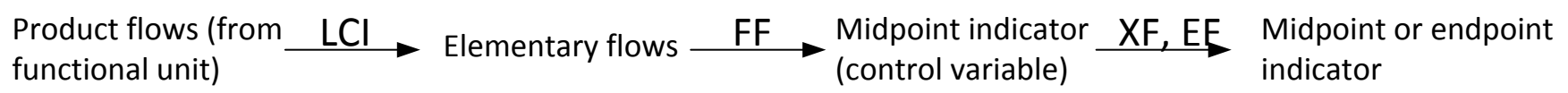
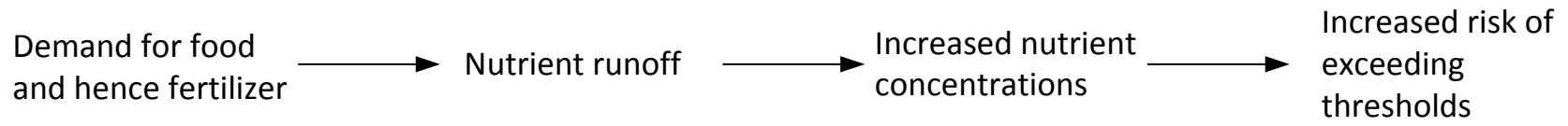
1 **Figure caption**

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4 **Fig. 1** Elements of LCA placed in the DPSIR impact pathway framework (EEA, 1999) (response category not included).  
5 Fig. 1a shows the example of an impact pathway leading to aquatic eutrophication. Fig. 1b maps elements of LCA and  
6 their interactions. The punctured frame around the cause/effect curve between the state and impact points indicate  
7 that our adopted science based thresholds are external references to LCA for impact categories where thresholds are  
8 not considered by LCIA models. Fig. 1c shows three types of midpoint indicators characterised by the point in the  
9 impact pathway where interferences are modelled (arrow) and expressed (cross)

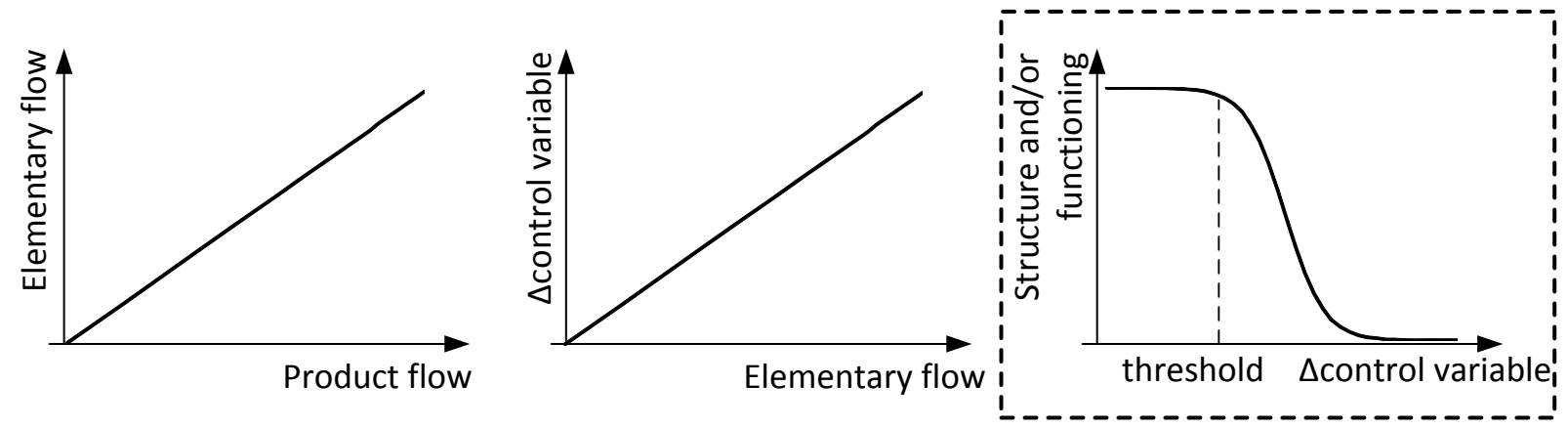
Figure 1



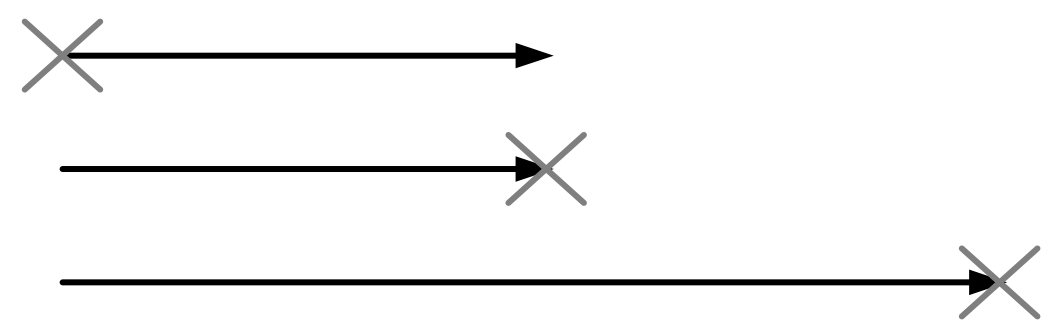
a) Example



b) LCA elements



c) 3 types of LCIA indicators



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