DTU Library

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

Bjørn, Anders; Hauschild, Michael Zwicky

Published in:
International Journal of Life Cycle Assessment

Link to article, DOI:
10.1007/s11367-015-0899-2

Publication date:
2015

Document Version
Peer reviewed version

LIFE CYCLE SUSTAINABILITY ASSESSMENT

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

Anders Bjørn • Michael Zwicky Hauschild

Received: 18 November 2014 / Accepted: 30 April 2015

Responsible editor: Jeroen Guinée

A. Bjørn (✉) • M. Z. Hauschild

DTU Management Engineering, Quantitative Sustainability Assessment, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark

(✉) **Corresponding author:**

Anders Bjørn

e-mail: anbjo@dtu.dk

Abstract

Purpose: There is currently a weak or no link between the indicator scores quantified in life cycle assessment (LCA) and the carrying capacity of the affected ecosystems. Such a link must be established if LCA is to support assessments of environmental sustainability and it may be done by developing carrying capacity-based normalisation references. The purpose of this article is to present a framework for normalisation against carrying capacity-based references and to develop average normalisation references (NR) for Europe and the world for all those midpoint impact categories commonly included in LCA that link to the area of protection Natural environment.

Methods: Carrying capacity was in this context defined as *the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert.* A literature review was carried out to identify scientifically sound thresholds for each impact category. Carrying capacities were then calculated from these thresholds and expressed in metrics identical to midpoint indicators giving priority to those recommended by ILCD. NR was expressed as the carrying capacity of a reference region divided by its population and thus describes the annual personal share of the carrying capacity.

Results and discussion: The developed references can be applied to indicator results obtained using commonly applied characterisation models in LCIA. The European references are generally lower than the global references, mainly due to a relatively high population density in Europe. The references were compared to conventional normalisation references (NR') which represent the current level of intervention for Europe or the world. For both scales the current level of intervention for climate change, photochemical ozone formation and soil quality were found to exceed carrying capacities several times.

Conclusions: The developed carrying capacity-based normalisation references offer relevant supplementary reference information to the currently applied references based on society's background interventions by supporting an evaluation of the environmental sustainability of product systems on an absolute scale.

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

Keywords Carrying capacity • Impact assessment • Midpoint • Normalisation • Severity • Single score • Sustainability conditions • Threshold

1 Introduction

Recent years have seen an increasing focus on environmental sustainability of products and technologies and a growing use of LCA and life cycle thinking in industry and the public sector. Still, the state of the environment is deteriorating globally by and large (Steffen et al. 2004; MEA 2005). This trend reflects that increases in eco-efficiency, achieved with the aid of LCA, are generally insufficient to offset the effects of an increasing global population that is achieving a higher material affluence. With many environmental impacts on the rise globally, the end goal of eco-efficiency improvements becomes increasingly important, namely that ecological impacts and resource intensities of product life cycles should be reduced to "…a level at least in line with the Earth's estimated carrying capacity" (WBCSD 2000). This end goal can be seen as a condition for environmental sustainability, originally defined as "…seek[ing] to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans" (Goodland 1995). Attempts to quantify carrying capacities have been made for decades most recently at the global scale through the introduction of the planetary boundaries concept (Rockström et al. 2009; Steffen et al. 2015).

Carrying capacity is currently considered in some LCA indicators, for instance in the form of critical loads for terrestrial acidification in Posch et al. (2008). In such indicators only interventions above carrying capacities are accounted for, meaning that resource uses and emissions that push a natural system closer to carrying capacity exceedance get a free ride. If LCA is to support a development towards environmental sustainability, understood as the non-exceedance of carrying capacities, measures of how much environmental intervention change the level of carrying capacity exceedance are not sufficient for decision support. In other words the path to environmental sustainability cannot be illuminated solely by indicators designed to measure environmental unsustainability. Existing LCA indicators must therefore be supplemented by measures that quantify the share of carrying capacity occupied by environmental interventions of a studied product system. Such measures can be established by using carrying capacity as environmental sustainability reference in LCA. A first step was taken by Hauschild and Wenzel (1998) who derived carrying capacity based distance-to-target weighting factors, albeit using varying definitions of carrying capacity across life cycle impact categories. Tuomisto et al. (2012) recently attempted to adapt initial planetary boundaries of Rockström et al. (2009) as weighting factors for 8 impact categories. Following the suggestion of Sala et al. (2013) in the context of life cycle sustainability assessment we here propose to use carrying capacity as consistent environmental sustainability reference in the normalisation step of LCA to facilitate the comparison of indicator scores to sustainable levels of interventions. According to ISO 14044, normalisation is "the calculation of the magnitude of the category indicator results relative to some reference information. The aim of the normalisation is to understand better the relative magnitude for each indicator result of the product system under study" (ISO 2006). In existing normalisation practice the reference information is commonly the sum of all characterized environmental interventions taking place in a specified year within a specified region, often scaled per capita (Laurent et al. 2011a). Normalisation thus allows for the translation of interventions in person equivalents (or person years) and facilitates some level of comparison across impact categories. However since common references are solely based on activities within the technosphere they cannot be used to compare and aggregate the severity of different types of interventions in the ecosphere. The subsequent weighting step is designed to capture the severity of characterized interventions, but as weighting is often based on personal perspectives on the prioritization of problems or policy goals, this expression of severity has a strong subjective element, which is also why ISO 14044 does not allow weighting in "LCA studies intended to be used in comparative assertions intended to be disclosed to the public" (ISO 2006). Without weighting the user of the LCA results is left with the normalized results. When understanding carrying capacity occupation as a measure of severity normalizing according to carrying capacity instead of total characterized interventions can improve the representation of the severity of different interventions.

The purpose of this article is to present a framework of carrying capacity-based normalisation references in LCA and to develop European and global carrying capacity-based normalisation references compatible with characterised indicator scores at midpoint for impact categories that link to the area of protection Natural environment. After presenting definition and framework, the concept of carrying capacity is made operational for Life Cycle Impact Assessment (LCIA), and European and global carrying capacity based normalisation references s for each midpoint indicator are developed. The new references are analysed by internal comparison and comparison to traditional normalisation references and their implications are discussed followed by an outlook.

2 Methods

2.1 Definition and operationalization

Carrying capacity generally refers to a certain quantity of X that some encompassing Y is able to carry (Sayre 2008). X and Y can refer to different entities depending on the discipline in which carrying capacity is applied.[1] In all applications carrying capacity aspires to idealism, stasis, and numerical expression (Sayre 2008). In ecology, for instance, carrying capacity describes the maximum equilibrium number of organisms of a species (X) that a given environment (Y) in theory can support indefinitely (Odum 1971). In the common definition of eco-efficiency (WBCSD 2000) X is impacts of unspecified environmental interventions and Y is the planet. In this form carrying capacity thus acts as the boundary between global environmental sustainability and unsustainability. Following this use of the term we define carrying capacity as *the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert.* Here a natural system may refer to ecosystems or, more broadly, Earth´s interacting physical, chemical, and biological processes, which for instance make up the climate system. By considering both functioning and structure our carrying capacity definition aims for a balanced approach: Whereas the concept of ecosystem functioning may have an anthropocentric bias, in that it tends to focus on functions valuable to humans, the concept of

[1] Wildlife management, chemistry, medicine, economics, anthropology, engineering, and population biology are listed as examples by Sayre (2008).

ecosystem structure is eco-centric because no judgement is made on the relative inherent value of organisms.[2]

We calculated carrying capacities from science based thresholds identified in the literature. Thresholds are numerical values of control variables, which in turn are numerical indicators of the structure and/or functioning of natural systems (Scheffer et al. 2001; Carpenter et al. 2001; Steffen et al. 2015). In the example of aquatic eutrophication a threshold can be expressed as a specific nutrient concentration (the control variable), which demarcates an oligotrophic (clear water) stable state from a eutrophic (turbid water) stable state, both characterized by distinct ecosystem structure and functioning. When thresholds are crossed, reverting the natural system to the original state can require a considerable amount of time with reduced interventions due to the initiation of feedback mechanisms stabilising the natural system in the new state after the threshold crossing. Here we characterize an interaction between humans and natural systems that does not lead to the exceeding of thresholds as environmentally sustainable.

Fig. 1a shows the impact pathway for the example of how demand for food drives a chain of events that ultimately leads to increased risk of threshold exceedance for nutrients, which would entail significant impacts on structure and functioning of the affected aquatic ecosystem(s). Fig. 1b shows the elements of an LCA that are used as indicators for and mechanistic translators between the points of the impact pathway in Fig. 1a and shows conceptual cause/effect curves for the translation between points. Here we use "environmental interference" as a generic term for anthropogenic changes to any point in the impact pathway. Here we expressed carrying capacity at the point in the impact pathway where the concerned midpoint indicator expresses environmental interference. A translation from threshold to carrying capacity therefore involved different LCA elements depending on the point of the impact pathway, marked with a cross in Fig. 1c, where the concerned midpoint indicator is expressed (see Section 3). For instance for

[2] The concept of resilience may offer a bridge between anthropocentric and eco-centric approaches to environmental management since studies generally show that ecosystems with high genotype- and species diversity has a high resilience, meaning in general terms, that they are better at adapting to sudden changes in conditions than ecosystems with lower diversity (Scheffer et al., 2001; Carpenter et al. 2001). Thus the protection of ecosystem structure can be seen both as eco-centric and as being in the enlightened self-interest of man.

indicators expressed at the pressure point the translation from threshold to carrying capacity involved a fate factor. For impact categories where LCIA models did not model the control variable for which the science based threshold was expressed, alternative approaches were taken in translating threshold to carrying capacity (see Section 3).

Our carrying capacity definition is concerned with environmental sustainability and we therefore only derived carrying capacities for midpoint impact categories linking to the area of protection Natural environment. References based on sustainability conditions for impact categories linking to the areas of protection Human health and Natural resources may also be developed, but this falls outside the scope of this article. Carrying capacities were hence quantified for the following ten midpoint categories from the EU Commission's ILCD methodology (Hauschild et al. 2013): climate change, ozone depletion, photochemical ozone formation, terrestrial acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, ecotoxicity, land use and water depletion.[3] Several LCIA models exist for calculating indicator scores within each of these impact categories. When possible we followed the recommendations for best existing practice by Hauschild et al. (2013) when choosing the characterisation model and factors with which NR should be compatible. Exceptions were made when recommended models were of a marginal nature. Marginal characterization models base translations between points in the impact pathway on the derivative at the estimated current level of environmental interference. Because carrying capacities should ideally be calculated without considering background interference (see below) marginal characterization models were replaced by characterization models using a linear approach (i.e. using the same factors to translate between points in the impact pathway no matter the current level of interferences) when these were available. This procedure led to the replacement of ILCD recommended models for terrestrial acidification, terrestrial eutrophication, land use and water depletion by models using a linear approach.

[3] Ionizing radiation effects on the natural environment was excluded since the recommended LCIA model was classified as interim by Hauschild et al. (2013).

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 reproductive threshold for a fish stock is exceeded, its carrying capacity expressed as a maximum sustainable yield (kg fish caught per year) will decrease temporarily. Likewise if the threshold of a natural system has been exceeded the original carrying capacity could in theory decrease if parts of the natural system, such as bacteria capable of metabolising pollutants, have been weakened or entirely eliminated due to the threshold exceedance. Here we did not consider the effects on carrying capacity caused by natural dynamics because it would involve complex dynamic modelling and because the short time scale of some natural dynamics, often hours to months, is incompatible with the limited time information of typical LCIs. For impact categories of a dynamic nature, such as photochemical ozone formation, we instead expressed thresholds at a form compatible with the time constraints of relevant LCIA models. We also did not consider dynamics in carrying capacity caused by human interventions because carrying capacities were calculated from ideal scenarios where interactions between natural and humans systems are at a steady state characterized by numerical values of control variables being below threshold values. In summary, calculated carrying capacities were treated as static in this work, which is in line with the general understanding of carrying capacity as a static concept (Sayre 2008).

In calculating NR we applied the populations of 2010 (6.916 billion globally and 740 million for continental Europe (UNDESA 2012)).We do however note that NR can be considered time dependent because the human population, the denominator of formula 1, is changing in most regions and increasing globally. Practitioners may therefore choose a projected population for the median year of the time horizon considered in a study. For instance an LCA of a system that will be operating from 2015 to 2035 would then use the projected population in 2025 as P.

2.4 Choice of precaution

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

3 Results

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

3.1 Climate change

There is evidence of several thresholds in the climate system expressed as average temperature increases above pre-industrial levels. These include disintegration of the Greenland ice sheet (1-1.5 °C), widespread bleaching of coral reefs (>1 °C), broad ecosystem impacts with limited adaptive capacity (1-2 °C), complete melting of the Greenland ice sheet, (3 °C) and shutdown of thermohaline circulation (3 °C) (Haines-Young et al. 2006). In comparison the current temperature increase is around 0.8 °C (IPCC 2013). The crossing of each of these thresholds can lead to irreversible changes in the functioning of the climate system with cascading effects on functioning and structure of various eco-systems. Here we propose one carrying capacity based on the 2 °C target, which aims to limit global warming to 2 degrees above pre-industrial levels, and another more precautionary carrying capacity based on reducing current radiative forcing from greenhouse gases to 1 W/m^2 (corresponding to a steady state temperature increase of 1.06 degrees above pre-industrial levels, see S1) as proposed by Rockström et al. (2009). The 2 °C threshold has highest acceptance as a policy target, while the 1 W/m^2 threshold is most in line with our definition of carrying capacity, since a temperature increase of 2 °C will possibly lead to irreversible changes in functioning and structure of the climate system (Rockström et al. 2009). These thresholds were converted into carrying capacities, expressed at the pressure point of the impact pathway as GWP100 based kg CO_2-eq/year. This conversion was made using the GEOCARB model for CO_2 (Berner and Kothavala 2001) and the model of Shine et al. (2005) for other greenhouse gases, from which we calculated the sustained level of emissions that for each greenhouse gas alone would lead to a steady state concentration corresponding to each of the two proposed thresholds.[4] The carrying capacity was then calculated as the average of the GWP100-based indicators of all gasses, weighted according to their contribution to the total climate change indicator score in 2010, and this lead to a NR_{Global} of 985 kg CO_2-eq/pers/year for the 2 °C threshold and 522 kg CO_2-eq/pers/year for the 1W/m^2 threshold (see S1 for details). The calculation of a weighted average was required due to the 100 year time scale of the GWP100 indicator and high variation of atmospheric life time of greenhouse gases. Had the time scale of the characterisation model instead been infinite, specific carrying capacities of the different gasses would be identical. The hidden variance of gas specific carrying capacities in the derived normalisation references is important to communicate to practitioners and decision makers. Specifically for CO_2 (having a very long atmospheric life time) the per capita carrying capacity is just 4-8 kg/year depending on the chosen threshold (see Electronic Supplementary Material).[5]

3.2 Stratospheric ozone depletion

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

[5] Note that this carrying capacity is much lower than the 2050 goal of 2 tons per capita often mentioned in the climate change debate. The 2 tons per capita target was derived from the RCP2.6 reduction pathway designed to stay below the 2 °C threshold by 2100 (van Vuuren et al. 2011; IPCC, 2013). In the year 2100 of the RCP2.6 reduction pathway CO_2 emissions are nearly zero, which is consistent with our low carrying capacity figures for CO_2.

Rockström et al. (2009) proposed a planetary boundary of 5-10 % decrease in column ozone levels for any particular latitude with respect to 1964–1980 values. The threshold was not based on a single well-established threshold in the climate system, but rather on the precautionary principle to acknowledge the complexity of the system of which knowledge is currently incomplete. Stratospheric ozone provides the regulatory function of filtering harmful ultraviolet radiation from the sun. Due to the long life time of many ozone depleting substances, ozone degradation in the stratosphere takes decades to recover. The threshold of 7.5 % decrease in ozone levels (medium value) was converted to a carrying capacity expressed at the pressure point of the impact pathway in ozone depletion potential (ODP) based kg CFC-11-eq/year of Montzka and Fraser (1999). This conversion was based on the model of Velders and Daniel (2013), which was used to calculate the sustained CFC-11-eq emissions that would lead to this decrease in ozone levels at steady state.[6] This resulted in a NR_{Global} of 0.078 kg CFC-11-eq/pers/year.

3.3 Photochemical ozone formation

We could not find a globally applicable threshold for this impact category and therefore based the carrying capacity on a time integrated ozone concentration threshold of 3 ppm*hour AOT40 for daylight hours during May-July which is applied in European regulation. AOT40 is an effect measure calculated as the accumulated ozone exposure during daylight hours above a threshold value of 40 ppb (EEA 1998).

We here outline the derivation of the European carrying capacity and refer to the Electronic Supplementary Material for details and approximation at the global scale. The threshold, which was developed by WHO and adopted as a policy target by the European Environmental Agency (EEA 1998), was designed to prevent negative effects on growth and/or seed production for (semi-) natural sensitive perennial and annual species (Umweltbundesamt 2004).

[6] We could not use the FF of CFC-11 of the ODP model because it is expressed relative to a reference substance (CFC-11) and not as an absolute steady-state ozone response to changes in emission.

We converted the time integrated threshold into an average concentration threshold of 44ppb ozone which applies to the 8 consecutive daily hours[7] with the highest ozone concentrations of May-July. This threshold was back calculated to a carrying capacity expressed at the pressure point of the impact pathway as kg NMVOC-eq/year applying the fate factor of the recommended indicator of Van Zelm et al. (2008) modified to calculate a change in maximum daily 8-h average ozone concentrations in Europe during May-July as a function of a change in emission. This resulted in a NR_{Europe} of 2.5 kg NMVOC-eq/pers/year.

3.4 Terrestrial acidification

Thresholds were here based on the critical load concept, for which acidification is defined as the highest deposition of acidifying compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function (Umweltbundesamt 2004)[8]. Exceeding critical loads can lead to the reductions in crop and forest yields, which can take decades to recover (Hettelingh et al. 2007). We calculated a world average critical load of 1170 mole H^+ eq/ha/year based on Bouwman et al. (2002), who developed a global map of critical loads based on acid buffering capacity of soils. From this critical load we subtracted global average natural depositions of 90 mole H^+ eq/ha/year. We converted the threshold (critical load) to a carrying capacity expressed at the state point of the impact pathway as mole H^+ eq deposition/year to be aligned with the OT indicator of Posch et al. (2008) based on average European conditions. This indicator was chosen instead of the indicator recommended by ILCD, Accumulated exceedance of Posch et al. (2008), because that indicator is of a marginal nature as it accounts for the share of emissions depositing on soils for which critical loads are modelled to be exceeded by background depositions. For this impact category the carrying capacity was to be expressed at the same point in the impact pathway as the threshold (the state point). Therefore the carrying capacity was simply calculated by

[7] Although the number of daylight hours exceed 8 per day during May-July at all latitudes within Europe, we chose a time frame of 8 hours per day for the translation of the time integrated concentration threshold (3 ppm*hour AOT40) to a concentration threshold (44ppb) to be compatible with the time frame of the recommended indicator of Van Zelm et al. (2008). Had we chosen a longer time frame, e.g. 12 hours per day, the concentration threshold would have been only slightly lower (43ppb instead of 44ppb) and so would the resulting carrying capacity calculated.

multiplying the global average critical load with the global terrestrial area ($1.49*10^{10}$ ha)This resulted in a NR_{Global} of $2.3*10^3$ mole H^+ eq/pers/year.

3.5 Terrestrial eutrophication

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

3.6 Freshwater and marine eutrophication

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

3.7 Freshwater ecotoxicity

The carrying capacity calculation was based on the threshold HC5(NOEC), which has been adopted as a quality target in several regulatory frameworks, such as the EU Water Framework Directive (EC 2011). HC5(NOEC) is the concentration at which maximum 5 % of species in an ecosystem are affected and it is derived from species sensitivity distributions, which are probabilistic models of the variation in sensitivity of all species in a model ecosystem to a particular stressor (Posthuma et al. 2002). The HC5(NOEC) threshold was converted to a carrying capacity expressed at the impact point of the impact pathway as [PAF]*m^3*day/year to be compatible with the spatially generic USEtox indicator (Rosenbaum et al. 2008). The conversion was carried out by modifying the effect factor of USEtox from being based on the HC50(EC50) effect level to being based on HC5(NOEC) following Bjørn et al. (2014). In accordance with USEtox full concentration addition was assumed, i.e. if two chemicals are each present at their HC5(NOEC) in the same freshwater volume then the carrying capacity of the compartment is assumed to be exceeded by 100 %. The procedure resulted in a NR_{Global} of $1.9*10^4$ [PAF]*m^3*day/pers/year.

3.8 Land use

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

The soil erosion carrying capacity was based on Verheijen et al. (2009), who provided a threshold interval for Europe of 0.3-1.4 ton/ha/year for 'tolerable soil erosion', defined as 'any actual soil erosion rate at which a deterioration or loss of one or more soil functions does not occur'. The threshold range was based on the estimated rate of natural soil formation caused by mineral weathering and dust deposition. We chose the middle value of 0.85 ton/ha/year and converted this to a carrying capacity expressed at the state point of the impact pathway as ton of eroded soil/(ha*year) to be compatible with global average CFs of the indicator for erosion resistance of Saad et al. (2013). The indicator of Saad et al. (2013) was chosen instead of the one recommended by ILCD based on soil organic matter (SOM) of Milà i Canals et al. (2007), because that indicator is of a marginal nature as it accounts for the change in SOM compared to an alternative land use scenario reference. As for terrestrial acidification and eutrophication the carrying capacity was expressed at the same point in the impact pathway as the threshold, the state point. Therefore the carrying capacity was simply calculated by multiplying the threshold with the global terrestrial area ($1.49*10^{10}$ ha).This gave a NR of 1.8 ton/pers/year.

The land use threshold for biodiversity was based on Noss et al. (2012), who meta-reviewed 13 studies that reported science-based local or regional conservation targets expressed as a share of natural lands that should be conserved, i.e. practically undisturbed by humans, to maintain sufficient levels of biodiversity in the region in question. Such conservation targets have the inbuilt perspective that loss of local biodiversity, due to e.g. intensive agriculture or infrastructure land use, is acceptable as long as regional biodiversity is maintained. The relationship between land use and regional biodiversity levels show threshold behaviour as ecosystems not directly affected by the land use (e.g. situated close to a clear-cut forest) are known to undergo state shifts due to the effects of neighbouring land use (Barnovsky et al. 2012; Noss et al. 2012). As a threshold we chose the median value, 31 %, of the data series of Noss et al. (2012) for the share of terrestrial land that needs to be conserved as a threshold.[9] The threshold was converted to a carrying capacity expressed at the pressure point of the impact pathway as m^2*year/year land occupation to be directly compatible with any LCI. For reasons given above we did not align the carrying capacity with the ILCD recommended indicator and instead chose to align it directly to any LCI since the threshold is independent on types of land use (i.e. paved road counts as none-conserved land just as managed forest). The conversion of the threshold to carrying capacity was carried out simply by taking 31 % of global terrestrial land. This gave a NR_{Global} of $1.5*10^4$ m^2*year/pers/year. In practice a set of CFs with the value 1 for all relevant elementary flows could be created in LCA software to form an indicator compatible with the NR.

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

3.9 Water depletion

The carrying capacity was based on the so-called environmental flow requirements for good conditions (EFR_{good}), which is a threshold measure of the minimum water flow required to sustain rivers in a "good ecological state" (Smakhtin et al. 2004). This threshold was supplemented by another threshold for the minimum water flow required to sustain terrestrial ecosystems in the river catchment. In deriving a combined threshold for aquatic and terrestrial ecosystems we followed Gerten et al. (2013), who estimated the global accessible blue water resource (16.300 km^3/year) and subtracted a global EFR_{good} quantification of 57 % of blue water and another 30 % of blue water to avoid physical water stress of terrestrial ecosystems. In the impact pathway of water depletion a change in pressure, expressed in m^3/year water consumed, causes a change in control variable, expressed in m^3/year water availability, of similar

[9] This number is in good agreement with recent conclusions that around 34 % of global terrestrial coverage should be conserved to achieve biodiversity protection goals given patterns and effects of current land conservation (Butchart et al. 2015)

magnitude. EFR_{good} can therefore be interpreted as a pressure based carrying capacity and no conversion from threshold to carrying capacity was hence needed. As for the carrying capacity of land use related to regional biodiversity the carrying capacity is aligned directly to any LCI since the EFR_{good} estimates of Gerten et al. (2013) made no distinction between different types of blue water consumption such as lake or river water. We deviated from the ILCD recommended water scarcity indicator of Frischknecht et al. (2008), because this indicator is of a marginal nature as it models the scarcity created by background water consumption. This procedure gave a NR_{Global} of 306 m^3/pers/year. As for the land use impact category (regional biodiversity) a set of CFs with the value 1 for all relevant elementary flows could be created in LCA software to form an indicator compatible with the NR.

3.10 Comparison with traditional normalisation references and across spatial scale

Table 1 presents an overview of the developed carrying capacity-based normalisation references (NR) globally and for Europe and a comparison with traditional normalisation references based on characterized global background interventions (NR'). NR'_{global} was based on Laurent et al. (2013) who calculated global normalisation references for the ILCD methodology for the year 2010 (or 2000 for impact categories were more recent data was unavailable). NR'_{Europe} was based on Benini et al. (2014) and Sala et al. (2015) who calculated normalisation references for EU-27 for the ILCD methodology, also for the year 2010. When comparing NR'_{Europe} to NR_{Europe} it should be noted that NR_{Europe} has a wider geographical coverage as it is based on the European continent. For impact categories where our developed NR was not aligned with the ILCD methodology NR' was calculated using the underlying inventories of Laurent et al. (2013) and Sala et al. (2015), with the exception of water depletion for which blue water consumption could not be extracted from the inventories of these two studies. More details can be found in the Electronic Supplementary Material (SI1 and SI2).

NR'/NR-values above 1 mean that current levels of interventions exceed the carrying capacity and that normalized indicator scores will become higher when a traditional normalisation reference is replaced by a carrying capacity-based one. This is the case for climate change (both thresholds), photochemical ozone formation and land use (soil erosion) both at the global and European scale, for freshwater eutrophication at the European scale and for water depletion at the global scale. The NR'/NR ratios for the remaining impact categories are all below 1 and normalized indicator scores of these categories thus become smaller when replacing traditional normalisation references with carrying capacity based ones. When comparing across scale (column 6 in Table 1) it can be seen that for all impact categories except water depletion and marine eutrophication NR_{Europe} is smaller than NR_{Global}, which is mainly due to Europe's relatively high population density.

The interpretation of results for climate change, photochemical ozone formation, land use and water depletion is that humanity is globally unsustainable according to our carrying capacity definition. Global degrees of unsustainability are seemingly greatest for climate change (when carrying capacity is based on the 1 W/m^2 threshold) and photochemical ozone formation where in both cases characterized interventions need to decrease by a factor of 15, compared to those of the year 2010 and 2000 respectively, to reach sustainable levels characterized by no exceedance of reference thresholds on average.

For the remaining impact categories current interventions appear environmentally sustainable when averaging over the global situation because NR'_{global}/NR_{Global} is below 1. The relevance of this perspective is discussed in the next section.

4 Discussion and outlook

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

4.1 Criteria for environmental sustainability

Regarding the first purpose the normalisation references offer a pedagogical expression of interventions in environmental sustainability person equivalents, which serves to communicate how large a share of the carrying capacity a given system or activity takes up. This can help shifting the perspective of environmental assessments from comparing eco-efficiencies of product systems to addressing eco-efficiency improvements required to achieve environmental sustainability at a societal scale (i.e. through the NR'/NR ratio). Criteria for environmental sustainability of societal subsystems are inherently subjective because they involve the allocation of carrying capacity to systems that meet different human needs (and wants). However it may be feasible to agree upon a moral rule that carrying capacities should be shared equally amongst people living within its geographical boundaries or an alternative rule that global carrying capacities should be shared equally within the global population.[10] Moral rules like these would not restrict personal freedom by enforcing a specific consumption pattern. Instead they would translate into equal personal carrying capacity budgets that could be used according to personal preferences, much like a salary. As a supplement to the perspective of personal carrying capacity consensus on the allocation of carrying capacity between products belonging to different sectors may be based on sector specific reduction scenarios of e.g. IPCC, IEA or national and municipal environmental strategies.

4.2 Aggregation of normalized indicator scores

[10] The difference between these two rules is not trivial. Consider the potentially large differences between per capita domestic carrying capacities of Canada and Singapore for the many impact categories related to the availability of land and water as source or sink.

Regarding the second purpose, the developed normalisation references allows for the aggregation of indicator scores expressed in carrying capacity occupation across impact categories to a single score. In this process an additional weighting step is needed as the exceeding of the considered carrying capacities are not necessarily equally severe for all categories of impact. Factors that influence the severity of exceeding a carrying capacity include the type of damage that is caused, the social and/or economic impact, the spatial extent, the time required for reversion of damage, whether a threshold is characterized by a hysteresis,[11] and effects on other carrying capacities.[12] As an example it could be argued that carrying capacity normalised indicator scores for climate change should have a higher weight than corresponding scores for photochemical ozone formation, given for instance that effects of crossing climate system thresholds are both more pervading and difficult to reverse than the effects of crossing the tropospheric ozone threshold for vegetation used in this work.

4.3 Uncertainties and future work

The introduction of the carrying capacity based normalisation reference on one hand eliminates the inventory-related uncertainties that accompany the classical normalisation reference (NR'), and these uncertainties are large, especially for the toxicity-related impact categories (Laurent et al. 2011b). On the other hand additional uncertainty related to quantification of carrying capacity is introduced. A central question is whether control variables, and thus thresholds, should be located at midpoint or endpoint[13] in the impact pathway. In this work control variables, often expressed in a concentration metric, were located

[11] A hysteresis is a phenomenon which causes the exceedance of a threshold to be difficult to revert because the natural system has entered a new stable state characterized by stabilizing feedback mechanisms. In practice this means that a reduction in environmental intervention of a similar magnitude as the increase in interventions that previously caused the threshold to be exceeded is not sufficient to bring the system back to its original state. Hysteresis has been observed for e.g. the response of shallow lakes to changes in phosphorous loadings (Scheffer 2001).

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

[13] Midpoint is here understood as the point at which the impact pathway of different substances converge (Hauschild et al. 2013). Because this point of convergence varies the impact pathway location of the midpoint varies across impact categories. In comparison the endpoint is consistently located at the of the impact pathway and typically expressed in a metric related to the disappearance of species (Hauschild et al. 2013).

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

Another type of uncertainty relates to spatial variations.

Our derived carrying capacities reflect average conditions of Europe and the world and have been developed to fit site generic characterisation factors. This is useful in LCA, where locations of environmental interventions are often not known with great accuracy. However the spatially generic approach hides variations emission fate and carrying capacity of receiving environments, which is problematic in cases where locations of environmental interventions are in fact known and spatially derived impact assessment models exist. Our spatially generic approach, combined with the fact that emission sources are rarely homogenously distributed in space, is the reason that our method predicts that carrying capacities have not been exceeded for the majority of impact categories (see Table 1 and Bjørn et al. (2014) for an elaboration of this issue for freshwater ecotoxicity). This prediction is invalidated by observations since exceedances of carrying capacities are quite frequent for many types of environmental interferences operating at the local to regional scale (MEA 2005; Steffen et al. 2015). A pragmatic way of accounting for this bias is to subtract the carrying capacity of remote areas, classified based on e.g. a population density threshold, from the calculation of spatially aggregated carrying capacities. Thereby land, water and air in scarcely populated areas would be considered unavailable as resources and for assimilating emissions, and the carrying capacity estimates would consequently be reduced. This was done by Gerten et al. (2013), who estimated the accessible blue water to be 40 % of global blue water resources, meaning that roughly 60 % of the theoretical global carrying capacity for water use (i.e. total flow minus environmental flow requirements) was considered unavailable This estimate of unavailable carrying capacity gives an impression of the extent at which our derived carrying capacities may be overestimated, but it needs to be assessed for each impact category since it is 0 for climate change and stratospheric ozone depletion and may be higher than 60 % for other impact categories. Such a modification might change the ranking between the normalised indicator scores but it would not solve the problem of spatial variability in degrees of carrying capacity occupation of a given emission within the remaining non-remote areas where carrying capacity is judged available. Normalisation references could be developed at finer scales than what was demonstrated in this article to take into account spatial variation in carrying capacity and the spatial distribution of the processes making up an LCI. However at a high resolution (e.g. 0.5°·0.5°) such references would need to take into account trans-boundary emissions. Alternatively carrying capacity could be integrated in spatially differentiated characterisation models rather than in the normalisation step. In this way indicator scores could be expressed in hectare years, which could be compared to the availability of land, thus following the style of the ecological footprint indicator (Borucke et al. 2013).

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

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

Acknowledgements We thank Guus Velders (RIVM), Rosalie van Zelm (Radboud University Nijmegen) and Annie Levasseur (CIRAIG) for assisting with quantifying the carrying capacity for stratospheric ozone depletion, photochemical ozone formation and climate change respectively and Tue Vissing Jensen (DTU) for technical support.

Electronic Supplementary Material SI1 elaborates on the carrying capacity quantifications for each impact category and SI2 contains all calculations in spread sheet format.

References

Barnosky AD, Hadly EA, Bascompte J (2012) Approaching a state shift in Earth's biosphere. Nature 486:52–58

Benini L, Mancini L, Sala S, Manfredi S, Schau EM, Pant R (2014) Normalisation method and data for Environmental Footprints. Report EUR 26842 EN. Joint Research Centre. Institute for Environment and Sustainability. European Commission

Berner RA, Kothavala Z (2001) GEOCARB III: A revised model of atmospheric CO2 over phanerozoic time. Am J Sci 301:182–204

Bjørn A, Richardson K, Hauschild MZ (2015) Environmentally sustainable or not? Managing and reducing indicator uncertainties. Ecological Indicators. Submitted.

Bjørn A, Diamond M, Birkved M, Hauschild MZ (2014) Chemical Footprint Method for Improved Communication of Freshwater Ecotoxicity Impacts in the Context of Ecological Limits. Environ Sci Technol 48:13253–13262

Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, Bustamante M, Cinderby S, Davidson E, Dentener F, Emmett B, Erisman JW, Fenn M, Gilliam F, Nordin A, Pardo L, De Vries W (2010) Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecol Appl 20:30–59

Borucke M, Moore D, Cranston G et al (2013) Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. Ecol Ind 24:518–533

Bouwman AF, Van Vuuren DP, Derwent RG, Posch M (2002) A Global Analysis of Acidification and Eutrophication of Terrestrial Ecosystems. Water Air Soil Pollut 141:349–382

Butchart SHM, Clarke M, Smith RJ et al (2015) Shortfalls and Solutions for Meeting National and Global Conservation Area Targets. Conservation Letters. doi: 10.1111/conl.12158.

Carpenter S, Walker B, Anderies JM, Abel N (2001) From Metaphor to Measurement: Resilience of What to What? Ecosystems 4: 765–781

Dearing JA, Wang R, Zhang K, Dyke JG, Haberl H, Hossain MS et al (2014). Safe and just operating spaces for regional social-ecological systems. Global Environ Change 28:227–238

De Vries W, Kros J, Kroeze C, Seitzinger SP (2013) Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Current Opinion in Environmental Sustainability 5:392–402

EC (2011) Common implementation strategy for the water framework directive (2000/60/EC) guidance document. Technical guidance for deriving environmental quality standards. Off J Eur Comm.

EEA (1998) Tropospheric Ozone in EU - The consolidated report. Topic report no. 8/1998. European Environmetal Agency, Copenhagen http://www.eea.europa.eu/publications/TOP08-98 accessed 14.11.2014

EEA (1999) Environmental indicators: Typology and overview. Technical report No 25. European Environment Agency, Copenhagen

Frischknecht R, Steiner R, Jungbluth N (2008) Methode der ökologischen Knappheit—Ökofaktoren 2006, ö.b.u. und Bundesamt für Umwelt, Bern

Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M, Pastor A (2013) Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Current Opinion in Environmental Sustainability 5:551-558

Goodland R (1995) The concept of environmental sustainability. Ann Rev Ecol Syst 26:1–24

Haines-Young R, Potschin M, Chesire D (2006) Defining and identifying Environmental Limits for Sustainable Development. A Scoping Study. Final Full Technical Report to Defra, 103 pp + appendix 77 pp, Project Code NR0102

Hauschild MZ, Wenzel H (1998) Environmental assessment of products. Vol. 2 - Scientific background, Chapman & Hall, United Kingdom, Kluwer Academic Publishers, Hingham, MA. USA. ISBN 0412 80810 2

Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, De Schryver A, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess 18:683–697.HELCOM (2013a) Approaches and methods for eutrophication target setting in the Baltic Sea region. Baltic Sea Environment Proceedings No. 133. Helsinki Commission

Henderson AD, Hauschild MZ, Van De Meent D, Huijbregts MAJ, Larsen HF, Margni M et al (2011). USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: Sensitivity to key chemical properties. Int J Life Cycle Assess 16:701–709

Hettelingh JP, Posch M, Slootweg J, Reinds GJ, Spranger T, Tarrason L (2007) Critical Loads and Dynamic Modelling to Assess European Areas at Risk of Acidification and Eutrophication. Water Air Soil Pollut 7:379–384

IPCC (2013) Intergovernmental Panel on Climate Change. Climate Change. IPCC WGI AR5. Summary for Policymakers

ISO (2006) ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization http://www.iso.org/iso/catalogue_detail?csnumber=38498 . Accessed 14.11.2014

Katragkou E, Zanis P, Tsikerdekis A, Kapsomenakis J, Melas D et al (2015) Evaluation of near surface ozone over Europe from the MACC reanalysis. Geosci Model Dev Discuss 8:1077–1115

Laurent A, Olsen SI, Hauschild MZ (2011a) Normalization in EDIP97 and EDIP2003: updated European inventory for 2004 and guidance towards a consistent use in practice. Int J Life Cycle Assess 16:401–409

Laurent A, Lautier A, Rosenbaum RK, Olsen SI, Hauschild MZ (2011b) Normalization references for Europe and North America for application with USEtox™ characterization factors. Int J Life Cycle Assess 16:728–738

Laurent A, Hauschild MZ, Golsteijn L, Simas M, Fontes J, Wood R (2013) PROSUITE Deliverable 5.2: Normalisation factors for environmental, economic and socio-economic indicators

Mace GM, Reyers B, Alkemade R, Biggs R, Chapin FS, Cornell SE, et al. (2014). Approaches to defining a planetary boundary for biodiversity. Global Environ Change 28:289–297

MEA (2005) Millennium Ecosystem Assessment. Ecosystems and Human Well-being. Synthesis. World Resources Institute. Island Press, Washington, DC

Milà i Canals L, Romanyà J, Cowell SJ (2007) Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in life cycle assessment (LCA). J Clean Prod 15:1426–1440

Montzka SA, Fraser PJ (1999) Controlled substances and other source gases. Chapter 2 in scientific assessment of ozone depletion: 1998, Global Ozone Research and Monitoring Project— report no. 44, World Meteorological Organization, Geneva, Switzerland

Noss RF, Dobson AP, Baldwin R et al (2012) Bolder Thinking for Conservation. Conserv Biol 26:1-4

Odum EP (1971) Fundamentals of ecology, 3rd ed. Philadelphia, PA, USA: W. B. Saunders

Posch M, Seppälä J, Hettelingh JP, Johansson M, Margni M, Jolliet O (2008) The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int J Life Cycle Assess 13:477–486

Posthuma L, Suter II GW, Traas TP (2002) Eds. Species Sensitivity Distributions in Ecotoxicology. CRC Press LLC, Florida

Rockström J, Steffen W, Noone K et al (2009) Planetary Boundaries: Exploring the Safe Operating Space for Humanity. Ecol Soc 14(2):32

Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Köhler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13:532–546

Saad R, Koellner T, Margni M (2013) Land use impacts on freshwater regulation, erosion regulation, and water purification: a spatial approach for a global scale level. Int J Life Cycle Assess 18:1253–1264

Sala S, Farioli F, Zamagni A (2013) Life cycle sustainability assessment in the context of sustainability science progress (part 2). Int J Life Cycle Assess 18:1686–1697

Sala S, Benini L, Mancini L, Pant R (2015) Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalisation factors. Int J Life Cycle Assess. Submitted.

Sayre NF (2008) The genesis, history, and limits of carrying capacity. Ann Assoc Am Geogr 98:120-134

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591-596

Seppälä J, Hämäläinen RP (2001) On the meaning of the distance-to-target weighting method and normalisation in life cycle impact assessment. Int J Life Cycle Assess 10:393-398

Shine KP, Fuglestvedt JS, Hailemariam K, Stuber N (2005) Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. Climatic Change 68:281-302

Smakhtin V, Revenga C, Döll P (2004) A Pilot Global Assessment of Environmental Water Requirements and Scarcity. Water Int 29:307–317

Steffen W et al (2004) Global Change and the Earth System. A Planet Under Pressure. The IGBP series. Springer

Steffen W, Richardson K, Rockstrom J, Cornell SE, Fetzer I, Bennett EM et al (2015). Planetary boundaries: Guiding human development on a changing planet. Science 347: 736

Struijs J, Beusen A, van Jaarsveld H, Huijbregts MAJ (2009) Aquatic eutrophication. Chapter 6. In: GoedkoopM, Heijungs R, Huijbregts MAJ, De Schryver A, Struijs J, Van Zelm R (eds) ReCiPe 2008 A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and the endpoint level. Report I: characterisation, first edition, 6 January 2009 http://www.lcia-recipe.net – accessed 14.11.2014

Struijs J, Beusen A, de Zwart D, Huijbregts M (2011) Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment. Int J Life Cycle Assess 16:59–64

Tuomisto HL, Hodge ID, Riordan P (2012). Exploring a safe operating approach to weighting in life cycle impact assessment – a case study of organic, conventional and integrated farming systems. J Clean Prod 37:147-153

Umweltbundesamt (2004) Manual on methodologies and criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends. Mapping Manual 2004. Federal Environmental Agency. Berlin

UNDESA (2012) World Population Prospects: The 2012 Revision. Total Population - Both Sexes, United Nations Department of Economic and Social Affairs http://esa.un.org/wpp/Excel-Data/population.htm accessed 14.11.2014

Van Vuuren DP, Edmonds J, Kainuma M et al (2011) The representative concentration pathways: an overview. Climate Change 109:5–31

Van Zelm R, Huijbregts MAJ, Den Hollander HA, Van Jaarsveld HA, Sauter FJ, Struijs J, VanWijnen HJ, Van de Meent D (2008) European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmos Environ 42:441–453

Velders GJM, Daniels JS (2013) Uncertainty analysis of projections of ozone-depleting substances: mixing ratios, EESC, ODPs, and GWPs. Atmos Chem Phys Discuss 13:28017–28066

Verheijen F, Jones R, Rickson R, Smith C (2009) Tolerable versus actual soil erosion rates in Europe. Earth-Sci Rev 94:23-38

WBCSD (2000) Eco-efficiency – creating more value with less impact. World Business Council for Sustainable Development

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)

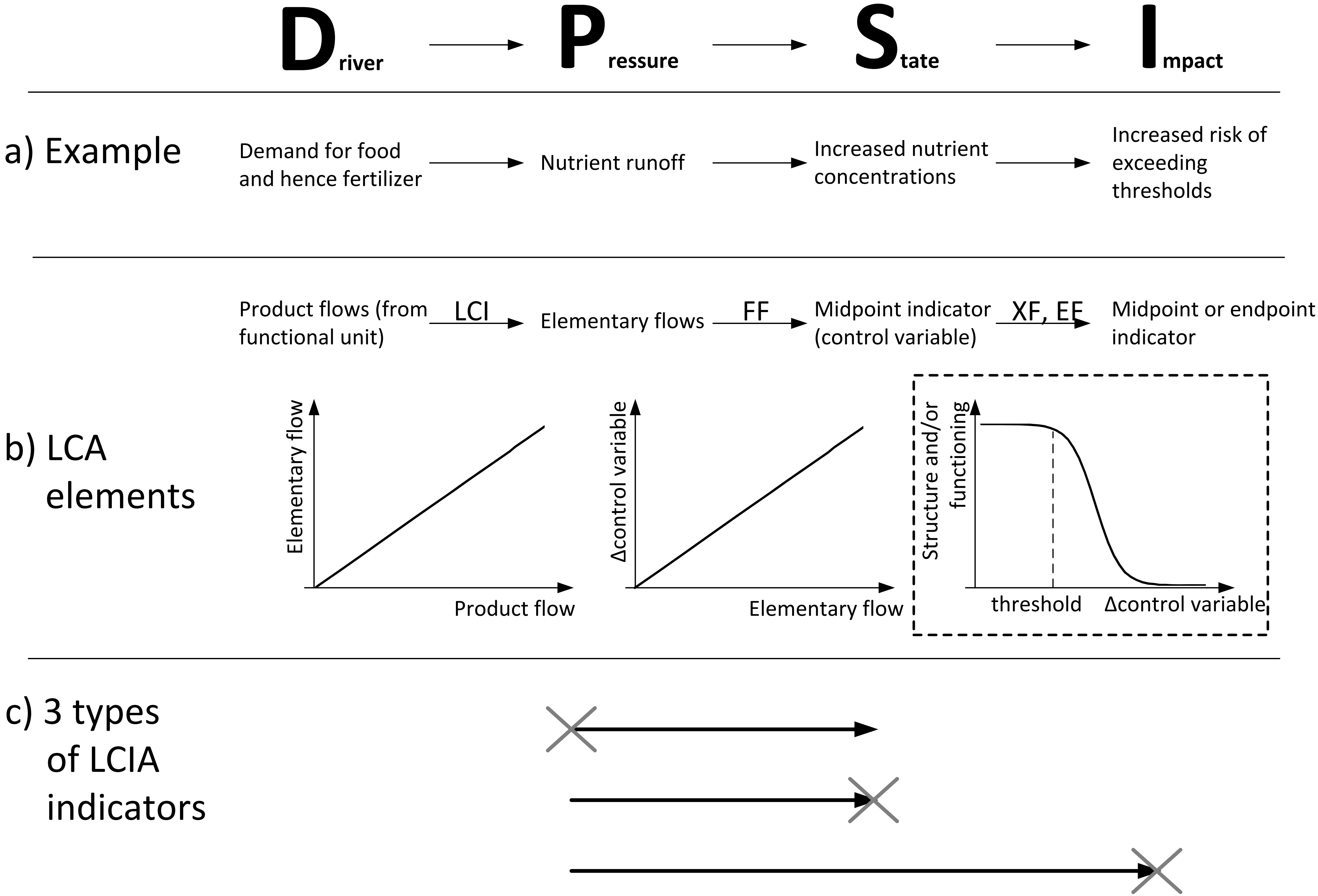
Impact category	**NR_Global** (per person year)	$\frac{NR'_{Global}}{NR_{Global}}$	**NR_Europe** (per person year)	$\frac{NR'_{Europe}}{NR_{Europe}}$	$\frac{NR_{Global}}{NR_{Europe}}$	**CF compatibility**	**Threshold**
Climate change	985kg CO_2-eq	**8.2**	985ton CO_2-eq	**9.4**	1	*GWP100 (CO_2-eq) (Forster et al. 2007)*	Temperature increase of 2°
	522 kg CO_2-eq	**15**	522 kg CO_2-eq	**18**			Radioactive forcing increase of $1W*m^2$
Ozone depletion	0.078kg CFC-11-eq	0.53	0.078kg CFC-11-eq	0.28	1	*ODP (Montzka and Fraser 1999)*	7.5 % decrease in average ozone concentration
Photochemical ozone formation	3.8 kg NMVOC-eq	**15**	2.5 kg NMVOC-eq	**13**	1.6	*Tropospheric ozone concentration Increase (Van Zelm et al. 2008)*	Tropospheric ozone concentration of 3 ppm* hour AOT40
Terrestrial acidification	$2.3*10^3$ mole H+ eq	0.34	$1.4*10^3$ mole H+ eq	0.53	1.7	OT method of Posch et al. (2008)	Deposition of 1170 and 1100 mole H^+ $eq*ha^{-1}*year^{-1}$ globally and for the EU
Terrestrial eutrophication	$2.8*10^3$ mole N eq	0.13	$1.8*10^3$ mole N eq	0.30	1.5	OT method of Posch et al. (2008)	Deposition of 1340 and 1390 mole N $eq*ha^{-1}*year^{-1}$ globally and for the EU
Freshwater eutrophication	0.84kg P eq	0.74	0.46kg P eq	**3.22**	1.8	*P concentration increase (Struijs et al. 2009)*	P concentration of 0.3mg/L
Marine eutrophication	29 kg N eq	0.32	31kg N eq	0.55	0.95	*N concentration increase (Struijs et al. 2009)*	N concentration of 1.75 mg/L
Freshwater ecotoxicity	$1.9*10^4$ $[PAF]*m^3*day$	0.036	$1.0*10^4$ $[PAF]*m^3*day$	0.85	1.8	*CTU (Rosenbaum et al. 2008)*	HC5(NOEC)
Land use, soil erosion	1.8 tons eroded soil	**4.9**	1.2 tons	**9.3**	1.6	Saad et al. (2013), land occupation CFs only	Tolerable soil erosion of 0.85 $tons*ha^{-1}*year^{-1-}$)
Land use, biodiversity	$1.5*10^4$ m^2*year	0.42	$9.5*10^3$ m^2*year	0.79	1.6	LCI data, land occupation only	31 % conserved land area

Water depletion	306 m^3	**1.3**	490 m^3	0.52	0.63	LCI data classified as blue water consumption	Conservation of 57 % of river flows for aquatic ecosystems and 30 % for terrestrial

Figure caption

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

Figure 1



Driver
Pressure
State
Impact
a) Example
Demand for food and hence fertilizer
Nutrient runoff
Increased nutrient concentrations
Increased risk of exceeding thresholds
Product flows (from functional unit)
LCI
Elementary flows
FF
Midpoint indicator (control variable)
XF, EF
Midpoint or endpoint indicator
b) LCA elements
Elementary flow
Product flow
Δcontrol variable
Elementary flow
Structure and/or functioning
threshold
Δcontrol variable
c) 3 types of LCIA indicators