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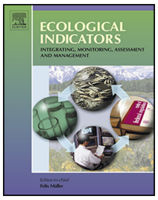

A proposal to measure absolute environmental sustainability in life cycle assessment

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ABSTRACT

Environmental monitoring indicates that progress towards the goal of environmental sustainability in many cases is slow, non-existing or negative. Indicators that use environmental carrying capacity references to evaluate whether anthropogenic systems are, or will potentially be, environmentally sustainable are therefore increasingly important. Such absolute indicators exist, but suffer from shortcomings such as incomplete coverage of environmental issues, varying data quality and varying or insufficient spatial resolution. The purpose of this article is to demonstrate that life cycle assessment (LCA) can potentially reduce or eliminate these shortcomings.

We developed a generic mathematical framework for the use of carrying capacity as environmental sustainability reference in spatially resolved life cycle impact assessment models and applied this framework to the LCA impact category terrestrial acidification. In this application carrying capacity was expressed as acid deposition (eq. mol H^+ ha^{-1} $year^{-1}$) and derived from two complementary pH related thresholds. A geochemical steady-state model was used to calculate a carrying capacity corresponding to these thresholds for 99,515 spatial units worldwide. Carrying capacities were coupled with deposition factors from a global deposition model to calculate characterisation factors (CF), which expresses space integrated occupation of carrying capacity (ha year) per kg emission. Principles for calculating the entitlement to carrying capacity of anthropogenic systems were then outlined, and the logic of considering a studied system environmentally sustainable if its indicator score (carrying capacity occupation) does not exceed its carrying capacity entitlement was demonstrated. The developed CFs and entitlement calculation principles were applied to a case study evaluating emission scenarios for personal residential electricity consumption supplied by production from 45 US coal fired electricity plant.

Median values of derived CFs are 0.16–0.19 ha year kg^{-1} for common acidifying compounds. CFs are generally highest in Northern Europe, Canada and Alaska due to the low carrying capacity of soils in these regions. Differences in indicator scores of the case study emission scenarios are to a larger extent driven by variations in pollution intensities of electricity plants than by spatial variations in CFs. None of the 45 emission scenarios could be considered environmentally sustainable when using the relative contribution to GDP or the grandfathering (proportionality to past emissions) valuation principles to calculating carrying capacity entitlements. It is argued that CFs containing carrying capacity references are complementary to existing CFs in supporting decisions aimed at simultaneously reducing environmental impacts efficiently and maintaining or achieving environmental sustainability.

We have demonstrated that LCA indicators can be modified from being relative to being absolute indicators of environmental sustainability. Further research should focus on quantifying uncertainties related to choices in indicator design and on reducing uncertainties effectively.

1. Introduction

During the last decades the number of sustainability indicators and their use in decision-making has greatly increased (Hak et al., 2012; Singh et al., 2012). Many such indicators rank anthropogenic

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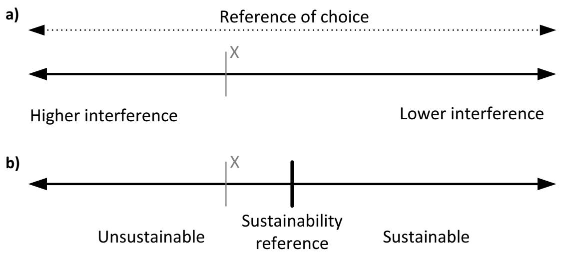

Fig. 1. The concepts of relative (a) and absolute (b) environmental sustainability indicators. The ranking of the hypothetical system *X* depends on the chosen reference(s) (a). System *X* is environmentally unsustainable because its environmental interference is higher than the sustainability reference (b).

systems according to their sustainability score. For instance, Switzerland ranked highest and Somalia lowest in the 2014 Environmental Performance Index of countries (Hsu et al., 2014). Another example is Greenpeace's Guide to Greener Electronics (2012a,b), which ranked 16 large electronics companies. Here we term indicators used for ranking *relative environmental sustainability indicators* (RESI) because indicator scores of studied anthropogenic systems are relative since they are evaluated by comparison to indicator scores of one or more reference systems, chosen specifically to match the nature or function of the studied system. While RESI can reveal how the sustainability performance of system X compare to that of a chosen reference system, it cannot evaluate whether system X can be considered sustainable on an absolute scale (Moldan et al., 2012). This limitation is very problematic considering that the state of the environment is declining by and large (Steffen et al., 2015; WRI, 2005). Therefore the global economy and its subsystems are in fact drifting further away from the goal of 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).

This shortcoming of RESI may be addressed by supplementing RESI by indicators containing reference values of environmental sustainability (Moldan et al., 2012). We term such indicators *absolute environmental sustainability indicators* (AESI) because the proposed environmental sustainability references are absolute, since they are based on characteristics of natural systems independent of the study. While ranking of products or systems is also possible in AESI, the environmental sustainability of a system can additionally be evaluated on an absolute scale, i.e. answering the question "is system X environmentally sustainable or not?" Fig. 1 illustrates the difference and complementarity between RESI and AESI.

The concept of carrying capacity (Sayre, 2008) can be applied in AESI to operationalise and quantify references of environmental sustainability as defined by Goodland (1995). Following Bjørn and Hauschild (2015) we define carrying capacity as "the maximum sustained environmental interference a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert." Here we use "environmental interference" as a generic term for anthropogenic changes to any point in an impact pathway (from emission or resource use to ultimate damage). It follows that total environmental interferences on natural systems, whether caused by resource uses or emissions, can be considered environmentally sustainable if their level is below the affected eco-system's carrying capacity.

"Footprint" indicators, that use carrying capacity as sustainability reference value, can be characterised as AESI. The popular ecological footprint indicator expresses demands on nature in units of "global hectares" and compares this to land availability (termed "biocapacity") to facilitate an evaluation of whether demands are environmentally sustainable (Borucke et al., 2013). This has inspired other footprint indicators such as the well-established water footprint (Hoekstra and Mekonnen, 2012) and first generation chemical footprints (Bjørn et al., 2014; Zijp et al., 2014). Existing footprint indicators, however, have weaknesses such as: (1) the incomplete coverage of all types of environmental interferences that are threatening environmental sustainability, (2) the varying data sources which are generally crude for assessments at the product scale (Huijbregts et al., 2008; Kitzes et al., 2009), (3) the variations in spatial resolution amongst footprints,[1] which can be a source of bias due to the potentially high spatial variability of carrying capacity (Bjørn and Hauschild, 2015), and (4) the inconvenience for users that each indicator is made available by means of a unique software tool. We believe that the life cycle assessment (LCA) methodology has the potential to overcome these weaknesses of current AESI.

LCA aims to cover all relevant environmental interferences over the life cycle (from raw materials to waste management) of products (or other anthropogenic systems). LCA requires a life cycle inventory (LCI), which compiles the physical inputs and outputs (resource uses and emissions) of a product during its life cycle, and is commonly based on product system specific data supplemented by a life cycle inventory database of unit processes (e.g. the average electricity generation of a country). LCA uses characterisation factors (CFs), which express the relationship between the resource uses or emissions of a LCI and measures of associated environmental interference. CFs are obtained from mathematical representations of cause effect-chains that can be spatially resolved and allow the conversion of a LCI into indicator scores for a number of mutually exclusive and collectively exhaustive "impact categories" such as climate change, eutrophication and eco-toxicity.

The characteristics of LCA make it potentially suitable for reducing or eliminating the listed weaknesses of current AESI. However, LCA indicators can be characterised as RESI: Indicator scores are typically used to rank the environmental performance of functionally comparable product systems or scenarios, based on their potential to, via their emissions or resource uses, create a small change in the level of environmental interferences. This small change is typically either calculated as a marginal change in the known existing level of environmental interference or as an approximated linear change in interference within the zone between 0 and a chosen level of interference (see S1 for a conceptual figure of the two approaches) (Hauschild and Huijbregts, 2015). LCA indicators therefore generally do not include carrying capacity as sustainability reference values (Castellani and Sala, 2012). To harness the potentials of LCA in AESI, LCA indicators need to be modified to quantifying occupations of carrying capacity instead of quantifying small changes in levels of environmental interferences. The overall purpose of this article is to provide an initial contribution to this development.

This article aims to (1) develop a generic mathematical expression for calculating spatially resolved occupation of carrying capacity for any emissions based LCA impact category, (2) use this method tentatively on the terrestrial acidification LCA impact category, (3) demonstrate the applicability of the method in a case study, (4) compare the relevance and complementarity of AESI and RESI in decision support.

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[1] The ecological footprint normalises land demands in the unit "global hectares", which means that indicator results are unaffected by spatial differences in yield, while water- and chemical footprints are spatially resolved to varying extents.