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Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework

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ABSTRACT

To enable quantifying environmental performance of products and technologies in relation to Planetary Boundaries, there is a need for life-cycle impact assessment (LCIA) methods which allow for expressing indicators of environmental impact in metrics corresponding to those of the control variables in the Planetary Boundaries framework. In this study, we present such a methodology, referred to as PB-LCIA. Characterization factors for direct use in the LCIA phase of a life cycle assessment, or other life-cycle based assessment, were developed for a total of 85 elementary flows recognized as dominant contributors to transgressing specific Planetary Boundaries. Exception was made for "biosphere integrity" and "introduction of novel entities" where a Planetary Boundary is yet to be defined for the latter and characterization models are considered immature for the former. The PB-LCIA can be used to quantify the share of the "safe operating space" that human activities occupy, as was illustrated by calculating indicator scores for about 10,600 products, technologies and services exemplifying several sectors, including materials, energy, transport, and processing. The PB-LCIA can be used by companies interested in gauging their activities against the Planetary Boundaries to support decisions that help to reduce the risk of human activities moving the Earth System out of the Holocene state.

1. Introduction

It has become evident that depletion of Earth's natural resources and services, through human activities, can lead to undesirable conditions on Earth (Daily and Ehrlich, 1992; Vitousek, 1997). In an attempt to reduce the risk of human activities inadvertently leading to a change in Earth System state towards conditions less conducive to humanity, the Planetary Boundaries (PB) framework (Rockström et al., 2009a; Steffen et al., 2015) identified nine key Earth System processes and defined quantitative 'Planetary boundaries' which delimit a "safe operating space" for humanity to act within. The metric of the PB and the state of the Earth System process is expressed by a control variable defined as either an environmental state or flow rate (e.g. stratospheric ozone concentration measured in Dobson units and anthropogenic nitrogen fixation in Tg N per year). Although none of the PBs, in principle, should be transgressed in order to minimize the risk of human activities pushing the Earth System out of its Holocene-like state, anthropogenic pressures have already led to exceedance or near exceedance of several PBs (Steffen et al., 2015). The PB-framework has been adopted by different societal actors such as governmental organizations and industries who have an interest in expressing sustainability in relation to the PBs (Galaz et al., 2012; Stockholm Resilience Centre, 2012; Sim et al., 2016; Bjørn et al., 2016; Clift et al., 2017). Despite this interest, however, consistent and operational methods for quantifying human activities (including the creation of products and technologies) in relation to the PBs are lacking.

1.1. Planetary Boundaries and life-cycle assessment

Life-cycle assessment (LCA) is a decision support tool (ISO 2006a,b; EC-JRC, 2010) for quantifying impacts of human activities on environment, resources, and humans. LCA involves construction of a life-cycle inventory (LCI) comprising all elementary flows (i.e. emissions and resource uses) arising throughout the life-cycle of the assessed activity. The elementary flows in the LCI are, in the life-cycle impact assessment (LCIA) phase, characterized into potential impacts by multiplication with characterization factors (CFs). LCA has been identified as a useful tool for quantifying human activities relative to the safe operating space because LCA is based on the holistic principles of assessing the full life-cycle and including all relevant environmental

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impacts (Bjørn et al., 2015; Ryberg et al., 2016).

Approaches for including the PB-framework in LCA have already been put forward. This was initially seen through development of weighting factors for existing impact categories based on the distance between the PBs and their control variable value (Tuomisto et al., 2012) and as development of normalization references, based on carrying capacities and matched with existing impact categories in LCA (Bjørn and Hauschild, 2015; Sandin et al., 2015). The conversion of the metrics in the PB-framework to existing impact categories in LCA is not straightforward as there is general misalignment within the impact pathways (cause-effect chain mechanisms leading from pollutant emission or resource use to impacts) between the position of conventional LCA indicators and control variables of the PB-framework (Ryberg et al., 2016; Laurent and Owsianiak, 2017). In addition, there is a fundamental difference between conventional LCA indicators and control variables of the PB-framework with regard to the area of protection (resources, ecosystems and human health in LCA, versus Holocene state of the Earth System in the PB-framework) (Ryberg et al., 2016). These important differences pose a challenge with respect to the communication of results to decision makers who may not be familiar with conventional LCA indicators. Communication to decision makers in industries and governments could potentially be eased by expressing impacts in metrics of the PBs which are already known to decision makers. Doka (2015, 2016) presented an LCIA method where impacts of activities were related to a global annual per capita PB allowance, generally expressed in the metrics of the PBs. However, the method's indicators are pre-allocated into an annual equal per capita personal budget which limits the method's applicability to assessments regarding the share of a personal budget occupied by an activity. Thus, the method is suited for consumer-citizen guidance in terms of developing a sustainable lifestyle but is not suited for assessments focusing on how production oriented activities impact the PBs.

Therefore, methods that allow for expressing impacts in the metrics of the PBs and which can be scaled to the scale of the assessed activity, incl. both consumption and production oriented activities, are still required. Having, such method could also aid quantifying and evaluating progress with relation to the 12th sustainable development goal on ensuring sustainable consumption and production patterns (UN, 2015). As a first step towards the creation of such method, Ryberg et al. (2016) identified six key challenges for development and implementation of an LCIA that could fully express impact scores in the metrics of the Planetary Boundaries (referred to as PB-LCIA). The identified challenges were:

1. Introduction of a new area of protection: The Holocene state of the Earth System;
2. Calculation of characterization factors for the Earth System processes' control variables for use in Life-Cycle Impact Assessment
3. Identifying and dealing with Earth System processes where the impacts overlap;
4. Facilitating spatial differentiation of control variables at sub-global level;
5. Applying the precautionary principle instead of best-estimates for defining the safe operating space;
6. Inclusion of environmental constraints in Life-Cycle Assessment and how to assign shares of the 'safe operating space' in an operational way for sustainability assessments (Ryberg et al., 2016).

In this study, we address challenge 2, 3, and 4 i.e. the quantification and expression of impact scores for human activities in metrics consistent with the PB control variables. Challenge 2 is addressed through the development of CFs. Challenges 3 and 4 are part of the CF development and are described for the relevant PBs where overlaps are identified (i.e. "change in biosphere integrity", "ocean acidification", and "flow of phosphorus from freshwater to oceans") or are spatially differentiated (i.e. "freshwater use", "land-system change", and "atmospheric aerosol loading"). A discussion regarding how challenges 3 and 4 are resolved and the resulting implications are provided in Section 4.2.

Challenges related to interpretation of results using a PB-LCIA and assigning shares of the safe operating space (challenge 1, 5, and 6), and the requirements for applying the LCIA methodology are described and discussed in Section 4.1. These are, however, not fully explored in this study where the main focus is on the technical challenges of developing CFs which can be used in LCAs, thus establishing the groundwork for applying a PB-LCIA methodology. To what degree the PB-LCIA yields similar or different conclusions in comparison with conventional LCIA methodology (ILCD 2011; EC-JRC, 2011; Hauschild et al., 2013) is evaluated by calculating impact scores for 10,687 unit processes in the life cycle database ecoinvent which is the most established and comprehensive database of unit processes for LCA. The overall outcome of this study is a PB-LCIA methodology that can be used for assessing impacts of human activities relative to the PBs.

2. Methods

2.1. Current characterization modelling practice

The current LCIA framework is designed to estimate time integrated exposure [γ; mass.time] from a pulse emission of elementary flow [$\Delta\mathbf{m}$; mass] superimposed on a background level (Heijungs, 1995) (Eq. (1)).

$$\boldsymbol{\gamma} = \int_0^T (e^{t\mathbf{A}} \cdot \Delta\mathbf{m})dt \tag{1}$$

where t is time after emission, T is time duration over which exposure is considered, and **A** is a matrix of coefficients expressing a substance's fate in the environment and exposure of humans and ecosystems. T can either be finite (e.g. 100 yrs as used in the GWP100) or infinite ($T \to \infty$) to capture full exposure. The analytical solution to Eq. (1) for $T \to \infty$ and with negative coefficients in **A**, i.e. inputs are removed and not generated in the environment, is given in Eq. (2). This gives the conventional framework for characterization modeling in LCA where γ expresses the time integrated exposure from the emitted elementary flow. γ can be multiplied with an effect factor to express the potential impacts on humans or ecosystems from exposure.

$$\boldsymbol{\gamma} = -\mathbf{A}^{-1} \cdot \Delta\mathbf{m} \tag{2}$$

2.2. Proposed framework for characterization modeling in PB-LCIA

Control variables in the PB-framework are expressed as environmental states or environmental flow rates where emissions and resource uses from human activities should not lead to exceedance of the PBs. Indeed single occurring pulse emissions do not generally lead to exceedance of PBs. On the other hand, long-term exceedance of PBs can be caused by human activities putting continuous pressure on the environment and this, over time, erodes resilience (Goodland, 1995; Scheffer et al., 2001). An LCA intended for relating impact scores to the PBs should include this aspect and, therefore, express impact scores as changes in environmental states or flow rates as a result of continuous pressures (i.e. continuous emission and resource uses).

Because environmental impacts in conventional LCIA are integrated over time and do not relate to a specific point in time, these can only be used for comparative purposes (Heijungs, 1995) and not for expressing changes in environmental states or flow rates. An exception is Global Temperature change Potential from a pulse emission (GTP_P) (Shine et al., 2005; Levasseur et al., 2016) which express change in surface temperature at a point time as a result of a pulse GHG emission. The magnitude of the GTP_P indicator is, however, highly sensitive to the specific time point and the indicator will approach zero after sufficiently long time due to removal of the GHG from the atmosphere. Generally, time-integrated impacts are not suitable for expressing