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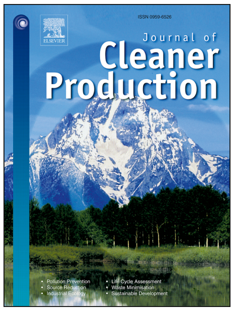

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Challenges in implementing a Planetary Boundaries based Life-Cycle Impact Assessment Methodology

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Abstract

Impacts on the environment from human activities are now threatening to exceed thresholds for central Earth System processes, potentially moving the Earth System out of the Holocene state. To avoid such consequences, the concept of Planetary Boundaries was defined in 2009, and updated in 2015, for a number of processes which are essential for maintaining the Earth System in its present state. Life-Cycle Assessment was identified as a suitable tool for linking human activities to the Planetary Boundaries. However, to facilitate proper use of Life-Cycle Assessment for non-global environmental management based on the Planetary Boundaries, there is a need for linking non-global activities to impacts on a planetary level. In this study, challenges related to development and operationalization of a Planetary Boundary based Life-Cycle Impact Assessment method are identified and the feasibility of resolving the challenges and developing such methodology is discussed. The challenges are related to technical issues, i.e., modelling and including the Earth System processes and their control variables as impact categories in Life-Cycle Impact Assessment and to theoretical considerations with respect to the interpretation and use of Life-Cycle Assessment results in accordance with the Planetary Boundary framework. The identified challenges require additional research before a Planetary Boundaries based Life-Cycle Impact Assessment method can be developed. Research on modelling the impacts on Earth System processes and on allocation of and entitlement to the 'safe operating space' appear to be most urgent for operationalizing a Planetary Boundaries based Life-Cycle Impact Assessment method. The results of a Planetary Boundaries based Life-Cycle Impact Assessment would be highly relevant and could provide novel insights on the environmental performance and sustainability of products and systems.

Keywords

Life-Cycle Assessment, Sustainability, Absolute Sustainability

1. Introduction

It is increasingly argued that the scale of human activities, and their subsequent environmental impacts, now threaten to exceed thresholds for central Earth System processes which could, in turn, potentially destabilize ecological systems (Lenton et al., 2008; Scheffer et al., 2001; Steffen et al., 2007). With the Planetary Boundaries (PB) framework, a number of processes are identified which are both essential for maintaining the Earth System (ES) in its present Holocene-like state and heavily impacted by human activities. For most of these processes, a "Planetary Boundary" is defined, i.e. a level above which there is substantial and increasing risk that perturbation of the process could lead to a change of ES state.

The PB-framework has diffused into policy-making (Galaz et al., 2012) and is also attracting strong interest from industry and industrial organizations (Bjørn et al., 2016; Sim et al., 2016; Stockholm Resilience Centre, 2015). The PB approach is attractive as it provides a framework for managing environmental resources at the global level. However, few of the environmental impacts caused by human activities are actually introduced at the global level, and most operate through local effects. Thus, it is the sum of many local effects (land-use change, release of reactive N and P, etc.) that accumulate to create concerns at the global level and existing metrics developed to assess local environmental impact of anthropogenic systems, such as products and processes, cannot directly upscale to consideration of global impacts of these activities. Given the growing interest, not least from industry, in the PB-framework for assessing human impacts at the level of the ES, we see a need for developing new or adapting existing methodologies designed to assess environmental impact at the local level to provide results that can be linked to the PB-framework.

Life-Cycle Assessment (LCA) is a standardized method for quantifying the environmental impacts of products and technologies (EC-JRC, 2010; ISO, 2006a, 2006b). LCA inventories all environmental interventions, i.e. resource uses and emissions of substances to the environment of a product or a service (hereafter only referred to as product) throughout the product's entire life-cycle. The inventoried environmental interventions are hereafter in the Life-Cycle Impact Assessment (LCIA) classified and characterized into potential environmental impacts (EC-JRC, 2010). The primary strengths of LCA as an assessment tool lie in the inclusion of the full life-cycle, preventing overlooking potentially significant processes, and the coverage of all relevant environmental impacts ranging from the local to global scale (Hauschild, 2005).

The use of LCA for assessing ‘absolute sustainability’ e.g. by using the Planetary Boundaries as environmental sustainability reference, has already been called for by Bjørn et al. (2015) as a way to move beyond assessing an anthropogenic system’s improvements in eco-efficiency and to assess its impacts in relation to the actual state of the environment. In this connection, the PB-framework has been proposed to be included in LCA as part of the normalization and weighting steps of the impact assessment. Bjørn and Hauschild (2015) developed normalization references partly based on the PBs which were matched with existing impact categories in LCA. Tuomisto and colleagues (2012) attempted to weight the severity of existing LCA impact categories based on the distance between the PBs and their current control variable value. Both attempts have limitations owing to their lack of spatial differentiation for the non-global Earth System processes (such as freshwater use) and both adapt the Earth System processes to impact categories that are already used in LCA, thereby creating questionable links between conventional LCIA impact categories and the PBs.

A way to overcome these two limitations is to include the Earth System processes and PBs as part of the LCIA. Firstly, this would allow for spatially differentiated assessment of Earth System processes that are not fully global, such as freshwater use, where local to regional conditions may be significant. Secondly, the diffusion of the PB-framework into policy and industry makes it a very strong concept and means that it is recognized by people outside of the LCA-community. Indeed, taking advantage of the already known PB-framework could ease communication of recommendations to industry and policy. Moreover, by presenting LCA results in the same metrics as the Planetary Boundaries, questionable links between current impact categories in LCA and the control variables in the PB-framework are avoided. For example, the LCIA impact category land-use change was by Sandin et al. 2015 related to the Planetary Boundary biosphere integrity. Indeed, this allowed for relating the PB to the LCA results, however, because land-use change is only one of many contributors to the overall effects on biosphere integrity, this excludes potential contributions from other pressures, such as climate change, freshwater depletion and pollution, thus, potentially creating a bias against products or technologies with a higher land use.

Having a Planetary boundary-based LCIA-methodology (hereafter referred to as PB-LCIA-methodology) with impact categories where the indicators correspond to the Earth System processes' control variables would combine the decision-support strengths of the PB-framework with the technology assessment strengths of LCA. A PB-LCIA-methodology could help in the operationalization of sustainability assessments as each PB can be assumed to delimit a specific 'safe operating space' (SOS) that can be occupied by humanity without risking destabilization of a Holocene-like state of the ES. In essence, the human enterprise can be considered as being sustainable, on a planetary level, if none of the PBs are exceeded. While there are potential benefits in combining the strengths of LCA with the strengths of the PB-framework to support decision-making, a number of methodological differences exist between the PB-framework and the LCIA-framework. These differences need to be addressed before the PB-framework can be used as the basis for a LCIA-methodology. During our work with LCA and the PBs, we identified six key challenges for including the PB-framework in LCIA (see Table 1). The challenges are related to technical issues in modelling and including the Earth System processes and their control variables as impact categories in LCIA and challenges with respect to the interpretation and use of LCA results in accordance with the PB-framework. This study provides an overview of the challenges, discusses the feasibility of developing a PB-LCIA-methodology, and proposes ways to proceed in including the PB-framework in LCIA.

Table 1. Key challenges to including Planetary Boundaries in Life-Cycle impact assessment

- Introduction of a new area of protection: the Holocene state of the Earth System
- Calculation of characterization factors for the Earth System processes' control variables for use in Life-Cycle Impact Assessment
- Identifying and dealing with Earth System processes where the impacts overlap
- Facilitating spatial differentiation of control variables at sub-global level
- Applying the precautionary principle instead of best-estimates for defining the safe operating space
- Inclusion of environmental constraints in Life-Cycle assessment and how to allocate the 'safe operating space' in an operational way for sustainability assessments

2. Key challenges

2.1. Introduction of a new area of protection: the Holocene state of the Earth System

LCIA-methodologies are constructed to protect specific areas of protection (AoP). The traditional AoP used in LCA is defined by three intrinsic values i.e. human health, biotic natural environment and abiotic natural environment (Jolliet et al., 2004). An overarching goal in LCA (and thus LCIA) is to assess all potential impacts that are recognized to contribute to damage of the defined AoPs.

The PB-framework's AoP differs from the AoP in traditional LCA. The AoP for the PB-framework is to keep the ES in a Holocene-like state as this is considered to be a functional value for protecting humanity (Rockström et al., 2009a). This rationale is based on the definition of Earth as a system where humans are an embedded part of the system. Given that everything that we associate with modern humanity (development of agriculture, written language, etc.) has developed while the ES was in the Holocene state, the PB-Framework argues that this is the only ES state where we know for certain that modern human societies can flourish (Rockström et al., 2009a, 2009b; Steffen et al., 2015). The PB-framework argues, therefore, that humanity should take a precautionary approach and avoid impacting the ES to a degree that could potentially push the system into a different state. The objective of an LCA using a PB-LCIA methodology will, thus, be to assess the magnitude of the environmental impacts that contribute to destabilization of the Holocene-like state and, thereby, assess to what extent the analyzed product contributes to exceedance of the PBs. The challenge of using a new AoP is, therefore, theoretical in terms of how to use and interpret LCA results with this new AoP. This single AoP is narrower than the three AoPs traditionally applied in LCA and will, therefore, result in the omission of some of the impact categories that are normally included in LCA to cover the three traditional AoPs. The narrow AoP in the PB-framework may lead to results where potential environmental problems not related to the PB are overlooked. Hence, it is important to be aware of how the new AoP will affect the questions that can be answered using the PB-LCIA-methodology, and this should thus be taken into account when defining the goal of the assessment.

2.2. Calculation of characterization factors for the Earth System processes' control variables for use in Life-Cycle Impact Assessment

Most of the control variables for the Earth System processes included in the PB-framework (yellow boxes in Figure 1) differ from the conventional impact indicators used in LCA e.g. the ILCD recommended impact categories for LCA (EC-JRC, 2011), even when the impact categories cover the same type of environmental problem. Figure 1 illustrates the network of impact pathways underlying the PB-framework with the environmental mechanisms linking the environmental exchanges to the impacts that may contribute to exceedance of the PBs and destabilization of the ES. Following LCIA principles, the impact pathways in Figure 1 are divided into “inventory” expressing the environmental interventions, “midpoint” indicators, “endpoint” indicators and “damage” indicators. Midpoint indicators are defined at an intermediary step in the impact pathway; endpoint indicators are defined at the end near the AoP in order to represent the whole impact pathway; damage indicators are defined to reveal changes to the AoP. While the modelling uncertainty increases with the length of the impact pathway covered, the uncertainty in interpretation decreases as the impact indicator becomes more concrete and immediately understandable (Hauschild, 2005). For a PB-LCIA-methodology, the impact indicators should be expressed in the same metric as the control variables of the Earth System processes. Earth System processes not previously included in LCIA will have to be modelled based on non-LCA based models which have to be adjusted to comply with the framework of LCA. This entails that the proportional change in environmental impact per change in quantity of environmental interventions is expressed by a characterization factor (Hauschild and Huijbregts, 2015). Existing LCIA impact characterization models that have the same impact indicators as the Earth System processes’ control variables can be applied in a PB-LCIA. However, the control variables in the PB-framework either express the state of the environment or an otherwise measurable quantity, such as the amount of nitrogen fixed. This differs from some LCIA-models, where the indicator scores express the time integrated cumulative impacts from an emission. For example, the global warming potential over 100 years (GWP100) is often used as an indicator for climate change in LCA. The GWP100 expresses the cumulative radiative forcing integrated over 100 years from a pulse emission and is, therefore, not expressing an actual measurable state in the environment. Hence, the GWP100 is not suitable for relating to an environmental limit. Instead, to comply with the PB-framework, it is suggested that impact models for a PB-LCIA are based on steady state models where the input to these models is continuous emission fluxes, thereby allowing for expressing impacts in metrics that are measurable in the environment and which correspond to the control variables in the PB-framework.

The control variables for the ‘Biogeochemical flows’ category exemplified by the nitrogen (N) and phosphorus (P) cycles are expressed at the level of environmental interventions and do not include the subsequent fate, exposure and effects of the emitted substance in the environment. Here, the control variables are related to the fixation of N and the application of P as fertilizer. Thus, the variables represent proxies of the real environmental problem i.e. actual release of reactive N and P to the environment. The choice of these proxies as control variables is pragmatic as global data on the actual release of reactive N and P is lacking while data on N fixation and P application are available. In addition, these control variables easily translate to policy and management interventions (Steffen et al., 2015). Given, however, that the control variables for the regional P cycle and the N cycle do not address the actual environmental problem, i.e. the direct release of reactive N and P to the environment, it may be expected that the PB control variables for biogeochemical flows will be further developed in the future.

Because LCIA normally takes its starting point in environmental interventions, i.e., releases to the environment, and because the control variables in the PB-framework are expressed as application of P and fixation of N, it is necessary to estimate what the releases of P and N to the environment that are reported in life-cycle inventories correspond to in terms of P applied and N fixed. This is necessary to get a comprehensive overview of P and N driven impacts because, although data on the use of fertilizer may be available for agricultural systems, similar information is lacking for other systems. For instance, emissions of NO_x from combustion processes would not be included in the PB-LCIA since it is not a direct use of fertilizer. Nevertheless, N emissions resulting from combustion are highly relevant to include since fixation of N_2 via combustion processes accounts for ca. 14% of total anthropogenic conversion of N_2 to reactive N (Ciais et al., 2013) and since it for most non-agricultural product systems will be the dominating contribution to the problems caused by nutrient releases. A way forward is to translate emissions of N and P compounds to the environment, back to an equivalent amount of hypothetically fixed N and applied P as fertilizer. As an example, 1 kg of NO_2 emitted from combustion processes would correspond to 0.3 kg of N fixed.

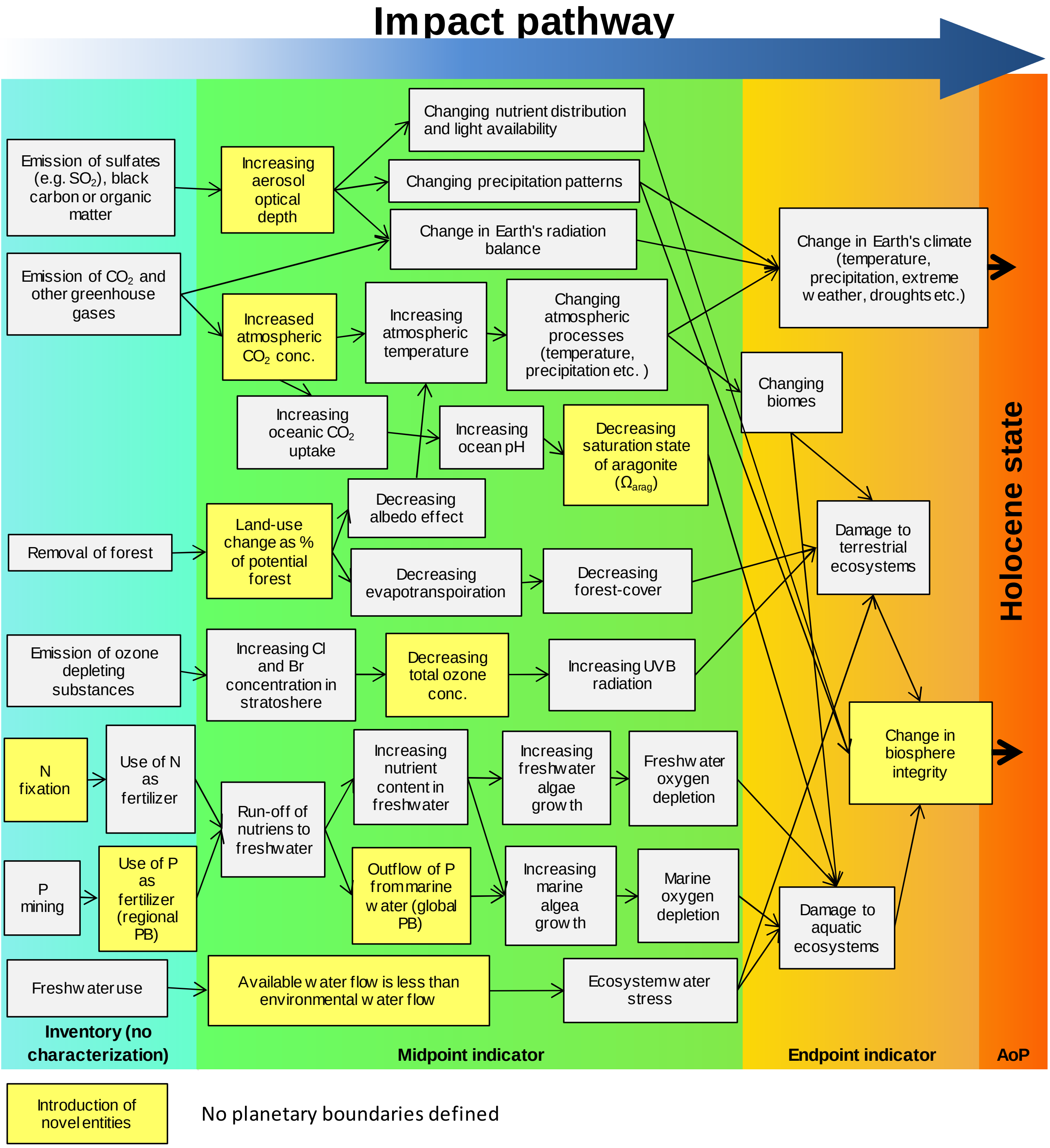
Characterization factors for the PBs ‘Change in biosphere integrity’ and ‘Introduction of novel entities’ can, at present, not be developed. ‘Change in biosphere integrity’ is, together with ‘Climate change’, characterized as a core boundary, i.e. PBs that, on their own, are capable of changing the state of the ES (Steffen et al., 2015). Moreover, biosphere and climate change provide the overarching ES framework through which the other Earth System processes operate (Mace et al., 2014; Steffen et al., 2015). This is also evident from Figure 1 where all other Earth System processes are shown to, either directly or indirectly, affect biosphere integrity.

Focus until now in biodiversity research and conservation has been on species and extinctions. However, Steffen et al. (2015) point out that it is the function of the biosphere in terms of transporting and transforming elements and molecules in the ES that makes the Earth different from all other known planets. Metrics for assessing the function of the biosphere and human impacts on this functioning still need to be developed. Hence, 'Change in biosphere integrity' is currently characterized by two interim control variables, i.e., 'Functional diversity' expressing the current ability of the ecosystem to maintain important ecosystem functions and characterized by the biodiversity intactness index (BII) and 'Genetic diversity' expressing the long-term resilience of the ecosystem which, in lack of better indicators, uses the global species extinction rate as an interim control variable (Steffen et al., 2015). In terms of including 'Change in biosphere integrity' in LCIA, the problem is that cause-effect chains describing how human perturbations affect the control variables for biosphere integrity are largely unknown. However, research on how different impacts affect biosphere integrity is ongoing (see for instance Brown et al., 2014; Mace et al., 2014; McMahon et al., 2011; Newbold et al., 2016; Pauls et al., 2013; Purvis and Hector, 2000), and it is expected that the understanding of the cause-effect chains will be improved in the near future. A better understanding of the cause-effect relationship between biosphere and all contributing impacts is required to satisfactorily include 'Change in biosphere integrity' in an LCA because if only a part of the contributing impacts are included, e.g. climate change and land-use, this may introduce a bias towards products or technologies focusing on reducing the included impacts and potentially neglecting impacts that are not yet included.

'Introduction of novel entities' covers the anthropogenic introduction of new substances (i.e., chemicals, plastic, etc.), increases in the mobilization of elements (i.e., increased release of heavy metals), or physical processes (i.e., electromagnetic and radioactive radiation). In some respects, the PBs overlap one another in that 'Climate change', for example, reflects changes in radiative forcing which are primarily the result of an anthropogenically mediated mobilization of reactive carbon in the ES and 'Stratospheric ozone depletion' results from the emission of new chemicals generated through human innovation. However, control variables have yet to be defined for the 'Introduction of novel entities', although we note that exploratory work trying to establish one or more PBs and control variables expressing the problems of emitting substances to the environment is ongoing (e.g. Diamond et al., 2015; Macleod et al., 2014; Persson et al., 2013; Posthuma et al., 2014; Sala and Goralczyk, 2013). While models for characterizing the fate and effect of chemicals released to the environment are already available in LCIA (e.g. Hauschild et al., 2008 and Rosenbaum et al., 2008), the central question that needs to be answered is to what degree

211 the introduction of novel entities can lead to impacts at the global level that potentially threaten to destabilize the

212 Earth System.



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214 **Figure 1. Overview of the Earth System processes in the PB-framework. The control variables used in the PB-framework for**

215 **expressing the Earth System processes are marked with yellow. The different environmental drivers, states and impacts are**

linked with arrows and are divided into inventory, midpoint, endpoint and damage indicators based on their location in the impact pathway.

2.3. Identifying and dealing with Earth System processes where the impacts overlap

In traditional LCIA-methodologies, impact categories are selected to ensure that they are mutually exclusive and collectively exhaustive. This ensures that the LCIA meets the ISO standard's requirement for coverage of all relevant environmental impacts (ISO, 2006a) while also avoiding having indicators placed at different locations on the impact pathway where the impact coverage overlap. Having more than one impact indicator expressing the same impact may result in "double counting" which can introduce a bias towards studied systems with lower impact scores for the "double counted" impacts compared to studied systems with lower impact scores for other impact categories. The identification of overlapping impact coverage and the interactions between Earth System processes can be identified in the PB-framework (see Figure 1). Here, overlaps with other indicators located earlier in the impact pathway are found for "Change in biosphere integrity", "Ocean acidification" and "Flow of phosphorus from freshwater to oceans". Particularly, 'Change in biosphere integrity' overlaps with all other Earth System processes because all other Earth System processes in the PB-framework operate and interact through the biosphere. Indeed, very few interventions (if any) at the inventory level of an LCA contribute directly to changes in biosphere integrity. Instead, the impacts would occur indirectly through the other Earth System processes. As shown in Figure 1, 'Change in biosphere integrity' can be considered an Endpoint indicator expressing the potential damage at ES level from the combined impacts to the other Earth System processes. Thus, it appears more practical to include 'Change in biosphere integrity' as a separate Endpoint indicator expressing the total effect of the other Earth System processes.

Emissions that successively contribute to more than one impact category are referred to as emissions with serial impacts and it is generally recommended that such emissions are fully included for all impact categories where they may contribute (Guinée, 2015). This is the case for "Ocean acidification" and "Flow of phosphorus from freshwater to the ocean". For example, emissions of CO_2 will initially increase the atmospheric CO_2 concentration and contribute to climate change, however, a share of the emitted CO_2 will be taken up by the oceans where it will lead to decreasing pH and, thereby, contribute to ocean acidification. Hence, both climate change and ocean acidification should be included as midpoint indicators in the LCA because, even though both are a consequence of CO_2 emissions, the impacts they express are different.

2.4. Facilitating spatial differentiation of control variables at sub-global level

Spatial differentiation reflecting local or regional differences in environmental sensitivities is often important when modelling non-global impacts in LCIA (Potting and Hauschild, 2006) and is a focus in current research into characterization modelling for many non-global impact categories in LCIA (see examples in Hauschild and Huijbregts, 2015). The last decade has seen the development of a number of regionalized impact assessment methods for spatially differentiated characterization of impacts such as terrestrial acidification, ecotoxicity of metals and water use (Humbert et al., 2009; Owsianiak et al., 2013; Pfister et al., 2009; Potting and Hauschild, 2006). The PB-framework includes a number of regional (or sub-global) system processes because it was acknowledged that changes in control variable values at the sub-global level can transgress to ES level by affecting the functioning of the core Earth System processes, i.e. ‘Climate change’ and ‘Change in biosphere integrity’ (Steffen et al., 2015). The Earth System process ‘Freshwater use’ was, for example, defined at a river basin level to illustrate that, while the global PB has not been transgressed, the level of excessive water withdrawal in some river basins can potentially lead to collapse of the regional ecosystem and biosphere. ‘Freshwater use’ is highly spatially distributed and the effects from water withdrawal may differ substantially between river basins (Gerten et al., 2013). For these Earth System processes, spatial differentiation in the impact modelling is important as global averages may hide regional exceedances of the SOS. The inclusion of spatially differentiated impacts is technically challenging in that it requires the incorporation of numerous spatially differentiated impact scores into an aggregated set of impact scores, and ideally one single score expressing the level of potential impact. A way forward could be to show results for a set of archetypes. An approach for ‘Freshwater use’ could, for example, be to define archetypes based on the Aridity Index (UNEP, 1997) and assigning river basins into: “arid”, “semi-arid” and “humid” categories. This approach would draw upon previous experience in LCA (see Kounina et al., 2013 for recent review of existing methods) where water has been categorized based on water scarcity and weighted according to the water availability in the region. The results could then be shown for each archetype as well as an aggregated single score where withdrawals are weighted based on the archetype i.e. withdrawal in arid regions is weighted higher than withdrawal in humid regions. This approach could solve the problem where exceedances in arid regions are “hidden” by water abundance in other regions, although it would not solve issues where exceedances in one archetype region is “hidden” by water abundance elsewhere in the same archetype region. The potential need for weighting introduces a value-based assignment of weights which needs to be further studied in order to come up with a scientifically defendable and operational solution.

2.5. Applying the precautionary principle instead of best-estimates for defining the safe operating space

A requirement in LCA is to ensure a fair and unbiased comparison between the studied systems and give a realistic representation of which among the studied systems has the lowest environmental impact. This is sought by aiming for best estimates during characterization of potential impacts, which means that precautionary principles and conservative estimates are avoided in the LCIA phase (Hauschild, 2005). The PB-framework relies on the precautionary principle and the PBs are defined as the lowest value in the uncertainty range to maximize certainty that thresholds are not exceeded (Rockström et al., 2009b), thereby, also giving societies time to react to early warning signs that they may be approaching a threshold (Steffen et al., 2015). Hence, the uncertainty about the location of the threshold for an Earth System process will influence the size of the SOS. Earth System processes with higher uncertainty about the location of the threshold will have a relatively smaller SOS compared to Earth System processes with a low uncertainty about the threshold. This approach is in contrast to the LCA approach and the challenge in using the PB-approach in LCA is that a higher weight is implicitly assigned to the most uncertain PBs, although this may not correctly reflect the severity of the impact or the actual location of the threshold.

The use of best-estimates or a precautionary approach will have a clear effect on the relative size of the SOS available for the studied product or technology. This challenge is, therefore, whether the best-estimate approach or the precautionary principle is most applicable for use in a PB-LCIA methodology. The justification for using the precautionary principle is that this is in line with the PB-framework and the goal of staying in a Holocene-like state. Moreover, this would make LCA results directly comparable to the boundaries in the PB-framework, while PBs defined based on best-estimates cannot be directly related to the boundaries in the PB-framework. A PB-LCIA based on best-estimates could, therefore, only be used for ranking the relative environmental performance of products and technologies and not for assessing the studied system relative to the PBs as defined in the PB-framework. With regards to the characterization models translating the environmental interventions into potential impacts, these should still be based on best-estimates to provide a realistic estimate of the potential impacts associated with the studied system and to avoid bias in the characterization of the environmental impact. Overall this would give an assessment where best-estimate potential impacts are related to the PBs, as defined in the PB-framework.

2.6. Inclusion of environmental constraints in Life-Cycle assessment and how to allocate the 'safe operating space' in an operational way for sustainability assessments

The main objective of LCA is to minimize the total environmental impact. Indeed, LCA is based on utilitarian ethics and the product or technology having the lowest weighted total environmental impact is preferred in a comparison between product and technology. Hence, traditional LCA allows trade-off between impacts, assessed systems with high impact scores for some impact categories may be preferred if these are compensated by sufficiently low impact scores for other impact categories. The PB-framework does not accept trade-offs between PBs because each PB should be respected and exceedance of one PB cannot be compensated by reducing impacts contributing to other Earth System processes (Rockström et al., 2009b). The inclusion of such constraints shifts the assessment from utilitarian ethics towards more traditional teleological ethics which seeks to maximize human wellbeing but without harming humans or lead to consequences with potentially catastrophic events (Macdonald and Beck-Dudley, 1994). The use of environmental constraints in LCA, thus, expands the assessment to seek the minimum total environmental impact without exceeding the SOS for any of the Earth System processes instead of only seeking the minimum total environmental impact.

The constraints introduced in a PB-LCIA-methodology can be used to relate the impact scores of the studied system to the SOSs, delimited by the PBs, to give an indication of the magnitude of each impact category relative to the PBs. Relating the impact scores to the SOS is similar to normalization in traditional LCAs, where impact scores of the studied system are related to the impact of a common reference to indicate the magnitude of each impact category relative to the reference (ISO, 2006a; Ryberg et al., 2014). However, such normalization will not show whether the studied system actually can be considered environmentally sustainable because the impact scores will, for all products in practice be below the PBs. To facilitate assessment of the studied system's environmental sustainability, the SOSs have to be allocated into smaller portions which represent the share of the SOS that the studied anthropogenic system can be considered entitled to occupy. It is important to note that such a PB-LCIA methodology can only be used for determining whether or not the studied system exceeds its allocated SOSs and, thus, whether or not it can be considered sustainable. Unless one system consistently show lower scores in all impact categories, a PB-LCIA method cannot readily be applied for identifying the environmentally speaking best anthropogenic system as this would require either modelling of the full impact pathway for all Earth System processes from environmental intervention to destabilization of the Holocene or weighting of the impacts of each Earth System process relative to its potential for destabilizing the Holocene state.

There have been a number of attempts to allocate the SOS for some of the boundaries in the PB-framework. Krabbe et al. (2015) focused on climate change and staying within the 2˚C guardrail and, therefore, estimated how much different industrial sectors each should reduce their carbon emissions. The allocation of the SOS between industrial sectors was based on the sectors' current emissions and a predicted sectoral emission pathway expressing each industrial sector's ability to reduce its carbon emissions. Sandin et al. (2015) allocated the PBs to set reduction targets for the textile sector on the basis of the share of the SOS the textile sector could be considered entitled to. Here, the SOS was allocated in three ways; first based on a 'grandfathering' approach, i.e. the allocated share of the SOS correspond to the current share of environmental impacts credited to the textile sector; the second and third approach were to allocate half and double of the share estimated using the grandfathering approach (Sandin et al., 2015). Further, studies downscaling the SOS to a national level, primarily based on a per capita approach have been made for Sweden and Switzerland (Dao et al., 2015; Nykvist et al., 2013). In addition to these practical examples, Häyhä et al. (2016) proposed a theoretical framework for translating the PBs to a national or regional scale for use in policy targets; highlighting the need for taking biophysical, socio-economic, and ethical dimensions into account.

As evidenced by the examples presented above, allocation of the SOS is highly normative and can be impractical because the allocation key will depend on value-based choices. To further illustrate the number of value-based choices and data required for allocating down to a product level, an example for a dining table sold in the European Union (EU) is provided. First the share of the SOS allocated to consumers in the EU is estimated as the percentage of people living in EU relative to the World, i.e. 7% (Eurostat, 2016a; United Nations, 2015). From this, final consumption expenditure (FCE) data is used as a proxy for EU consumers' preference towards certain products or services as the FCE provides information on the share of income that consumers spend on different product and services. The FCE spent on COICOP category CP051: 'furnishings, household equipment and routine household maintenance' in EU is 5.6 % (Eurostat, 2016b), thereby giving an entitlement of 0.4 % of the SOS for this category in EU. To scale to the table level, a price based allocation is applied, thus, if the dining table costs 600 Euro this is related to the total amount spent on category CP051, i.e. 1.4E+11 Euro in 2012 (Eurostat, 2016b). The price based allocation assumes that the price of the dining table reflects potential supply and demand on such table, thus the share of the SOS allocated to the dining table reflects the demand of the consumers. The final share of the SOS which the dining table should not exceed is estimated to be 5.7E-12. As stated above, this is only an example of how allocation can be performed on a product level. The example includes choices about the allocation of SOS between nations and regions which in this case was based on an equal per capita assumption, and the allocation of the SOS between products was in this case based on the consumption patterns of consumers in EU. However, the allocation could have been performed in a different way which would have yielded a different allocation factor, e.g. by not assuming an equal per capita share and by using a different indicator than FCE for allocating. Transparency about the allocation is, therefore, important as this will significantly influence the size of the SOS allocated to the studied system and, thus, be central when assessing environmental sustainability.

Because requirements for more choices and data increase at small scale, the uncertainty of the result also increases. As a consequence of this, there is a need for investigating for which scale of anthropogenic systems such allocation is meaningful and useful. It is important to find a suitable compromise between the number of value-based choices needed for allocating the SOS and the scale of the assessed system. A way to resolve this could be to propose and test different approaches and methods and on the basis of this seek a consensus on which values and choices to apply for allocating the SOS. However, the vested interests of central actors in such a process will make this consensus seeking a difficult endeavor, as specific choices will inevitably favor some systems and disadvantage others. Further research is, therefore, required on how to allocate the SOS in a practical and meaningful way, in order to allocate the SOS to a product level, which is a requirement for performing a Planetary Boundary based LCA on a product level. Due to the knowledge-gap on product level allocation, it currently appears more practical to allocate the SOS on a larger scale such as national, company, or industrial sector scale, rather than at the product level. The larger scale requires fewer choices with regard to defining the allocation key, thus keeping uncertainty low, while also giving central actors involved in the studied system ample room for making internal decisions and case-specific trade-offs within the country, company or sector in order to stay within the allocated SOS. In addition to allocation from a production perspective, allocation of the SOS may be done on a personal citizen scale taking a consumer perspective. For instance, by defining a personal PB budget that each citizen is free to spend on consumer goods and services, where the lifestyle of the citizen can be considered as sustainable if the spending does not exceed the allocated personal budget. An example of such approach has already been shown for climate change as a means to increase consumer awareness and encourage more sustainable consumption (Carbon Trust Advisory and The Coca-Cola Company, 2012).

3. Discussion

The challenges identified above are summarized for all Earth System processes in Table 2. They can be categorized as being either technical challenges or more theoretical challenges in terms of how fundamental assumptions forming the basis for the PB-framework differ from the assumptions underlying LCA. The technical challenges, e.g. the development of new characterization models based on the control variables in the PB-framework is regarded as a very large task which will require increased research on characterization modelling of the Earth System processes. A current limitation in developing a PB-LCIA-methodology is that ‘Introduction of novel entities’ and ‘Change in biosphere integrity’ cannot be included due to the lack of well-defined control variables and boundaries. Nevertheless, given the large ongoing research on the subject it appears that it may be possible to include these Earth System processes in the near future. It is in any case likely that a PB-LCIA-methodology must be continuously refined according to advancements in Planetary Boundaries research, as already observed in the development of the Earth System processes’ control variables and PBs since presented by Rockström and colleagues (Rockström et al., 2009b).

The more theoretical challenges, like addressing the use of a PB-LCIA-methodology and the interpretation of the results introduced changes that differ from the traditional assumptions upon which LCA is based, and may potentially change the way LCA results can be used and interpreted. The change in fundamental principles, such as the changed AoP and the introduction of the precautionary principle, is in accordance with the PB-framework where they are crucial assumptions and a prerequisite to avoid unacceptable global environmental shifts. As such, a PB-LCIA method will serve the purpose of aligning the management of product and technology portfolios and the general (environmental) management for companies that orient their management towards the PBs. However, these differences may significantly change the result of LCAs and it is important for the development of a PB-LCIA-methodology to address the theoretical differences to avoid misapplication due to a lack of understanding of the underlying assumptions. Furthermore, it is at present, unknown whether the recommendations to decision-makers will be contradictory between traditional LCA and LCA using a PB-LCIA-methodology. It is likely that the results from the two approaches will answer different questions and a recommendation might be to use them in a complementary manner to obtain more insightful results and better recommendations to decision-makers. The challenges related to the allocation of the SOS are important for operationalizing assessments of environmental sustainability. It is important to look further into this issue to be able to assess whether or not a studied system can be considered environmentally sustainable. In relation to this, there is a requirement for further investigating methods for allocating the SOS to a product level. Hence, at this point, until further research has been conducted in this field, it is suggested to restrict the allocation of the SOS to a larger scale, such as a national, company or sector level.

Table 2. Overview of the key challenges per impact category for including the Planetary Boundaries framework in Life-Cycle Impact Assessment

Earth System process	**Challenge 1 –** Introducing of a new area of protection: the Holocene state of the Earth	**Challenge 2 –** Calculation of characterization factors for the Earth System processes' control variables for use in Life-Cycle Impact Assessment	**Challenge 3 –** Identifying and dealing with Earth System processes where the impacts overlap	**Challenge 4 –** Facilitating spatial differentiation of control variables at sub-global level	**Challenge 5 –** Applying the precautionary principle instead of best-estimates for defining the safe operating space	**Challenge 6 -** Inclusion of environmental constraints in Life-Cycle assessment and how to allocate the 'safe operating space' in an operational way for sustainability assessments
Climate change	This challenge relates to general differences between the PB-framework and LCA-framework The PB-framework only considers the natural environment i.e. staying in the Holocene-like state.	Requires modelling from emissions of CO_2 and other GHGs to change in atmospheric CO_2 concentration and change in energy imbalance	The climate change control variable overlaps with ocean acidification and change in biosphere integrity	Global impact occurring independent of where emissions take place	This challenge relates to general differences between the PB-framework and LCA-framework The precautionary principle is maintained for defining the PBs, where the larger certainty on not exceeding planetary thresholds justifies this approach. A best-estimate approach is applied for the characterization modelling to calculate realistic impact scores.	This challenge relates to general differences between the PB-framework and LCA-framework Exceedances of PBs cannot be compensated by reducing the control variable value for other Earth System processes To facilitate sustainability assessments, the SOS have to be allocated to estimate the share of the SOS that the studied system can be considered entitled to occupy
Change in biosphere integrity		Cannot be modelled because the cause-effect chains linking human perturbations to change in biosphere integrity are largely unknown	The Earth System process is a consequence of changes other Earth System processes	A global average is applied although the changes may be at regional/local scale and can cascade to a global level		
Stratospheric ozone depletion		Requires modelling from emissions of ozone depletion substances to change in ozone concentration	Stratospheric ozone depletion overlaps with change in biosphere integrity	Primarily a global impact occurring independent of where emissions take place		
Ocean acidification		Requires modelling from emissions of CO_2 to change in aragonite saturation state	Ocean acidification and climate change are serial impacts both stemming from CO_2 emissions	Atmospheric CO_2 concentration is global and impacts on ocean acidification should be treated as a global impact.		
Biogeochemical flows: (P and N cycles)		Quantities of P and N releases to the environment has to be translated to quantities of P application and fixation of N	The Biogeochemical flows overlapping with change in biosphere integrity because runoff of N and P affect aquatic ecosystems	Although the control variables and PBs for biogeochemical flows express a global average, regional distribution is critical for impacts (Steffen et al., 2015)		
Land-system change		Requires modelling of Land-system change of forest as % of potential forest area	Land-system change is overlapping with change in biosphere integrity	Spatially differentiated between forest types. Aggregation is problematic as a summation of forest area as % of potential forest may hide regional exceedances of the PB due to non-exceedance in other regions		
Freshwater use		Requires modelling of freshwater use as % of mean flow available for withdrawal	Freshwater use is overlapping with change in biosphere integrity	Spatially differentiated at river basin level. Aggregation is problematic as water stressed regions may be hidden by water abundance in others		

Atmospheric aerosol loading	Requires modelling from emissions of aerosols (e.g. black carbon and sulfates) to change in aerosol optical depth	Atmospheric aerosol loading is overlapping with change in biosphere integrity	Aerosol formation is linked to the region of emission and differentiation could be done between geographical areas
Introduction of novel entities	Models for fate and exposure to chemicals are defined. But the ‘Introduction of novel entities’ cannot be included as potential planetary threats are yet to be defined.	Not entirely known at this stage, but the control variable is likely overlapping with change in biosphere integrity	Although changes may be at a regional/local scale, these can cascade to a global level

4. Conclusion

It is clear that the identified challenges in linking the LCA and PB approaches all require additional research before a PB-LCIA-methodology can be developed. Research into the modelling of the new impact categories using the Earth System process control variables, and research on allocation of the SOS appear to be the most urgent for operationalizing a PB-LCIA-methodology and facilitating sustainability assessments. Moreover, research into how a new PB-LCIA-methodology would compare to the results of a conventional LCIA-methodology is required to identify the difference in results about the environmentally best performing product or technology. The development of a PB-LCIA-methodology, which seems to be something desired by companies in order to allow assessments of products and technologies using the PB-indicators, appears relevant and the results of such LCIA-methodology would, hopefully, provide interesting and novel insights on the environmental performance and environmental sustainability of products and technologies.

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Highlights

- Need for tools relating activities at non-global level to impacts on Earth System level
- 6 challenges for developing a Planetary Boundary based LCIA-method were identified
- We discuss the challenges for a Planetary Boundary based LCIA-method
- We find and present further research needed to solve the challenges