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Life cycle assessment applying planetary and regional boundaries to the process level: a model case study

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Life Cycle Assessment applying Planetary and Regional Boundaries to the Process Level: A model Case

Study

Life cycle assessment applying planetary and regional boundaries to the process level: a model case study

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Abstract:

Purpose: The Planetary boundaries framework contains regional boundaries in addition to global boundaries. Geographically resolved methods to assess regional environmental impacts are therefore needed. Existing Planetary boundaries-based life cycle assessment (PB-LCA) methods have limited geographical resolution or are not applicable to full product systems, due to high spatial requirements on inventory data. Here, we enable PB-LCA of full product systems across a comprehensive set of regional and global PB impact categories.

Methods: We propose comparing environmental impacts of individual processes within a product system to assigned shares of regional or global safe operating space (SOS). This is followed by aggregation of process-level results so that accumulated exceedance of assigned SOS is derived across

the entire life cycle. We then present a procedure for aggregating geographically resolved characterization factors (CFs) and SOS to country, continent and global levels, ensuring compatibility with typical life cycle inventory results. We then apply the new techniques to a model laundry case study. It involves 61 selected processes, two geographically resolved PB-LCA methods, related to impacts from freshwater use and nitrogen emissions, and a largely spatially generic PB-LCA method that

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Results and discussion: The calculation of accumulated exceedance of assigned SOS may help inform * corresponding author: Email: anders.bjoern@concordia.ca

decisions about where in a life cycle to focus impact reduction efforts most urgently. The number of Affiliations:

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science. Best practice approaches or a consensus for assigning regional SOS to processes are needed.

Conclusions and outlook: Our study provides a step towards greater operability of geographically

resolved PB-LCA methods by enabling application to a full product system within an assessment that

covers a comprehensive set of impact categories. The case study application shows potential advantages

of the process-level approach and points to the need for quantifying uncertainties in such assessments.

Future studies should seek to explore the potential role of PB-LCA in decision-support compared to

conventional LCA.

Keywords

PB-LCA; planetary boundaries; safe operating space; spatialization; CF aggregation; Biogeochemical flows; Freshwater use.

1. Introduction

The Planetary boundaries (PBs) concept is based on the idea that there are limits to the Earth’s capacity to assimilate environmental impacts whilst maintaining the Holocene-like state in which human civilizations have developed (Rockström et al., 2009a; Steffen et al., 2015). In its most recent version (Steffen et al., 2015), the PBs framework contains nine Earth-system processes (somewhat similar to impact categories in LCA), for which there are currently seven quantified PBs and three sets of regional boundaries (see Figure 1). For each Earth-system process, a “safe operating space” (SOS) can be defined as the distance between a boundary (regional or global) and a reference value, usually representing pre-industrial conditions. Boundaries and reference values are quantified using a variety of techniques from Earth-system science (Steffen et al., 2015). A Planetary boundaries-based life cycle assessment (PB-LCA) links planetary and regional SOS to life cycle inventories (LCIs) via dedicated characterisation factors (CFs) (Fang et al., 2015; Ryberg et al., 2016). In such an assessment, a product system is commonly considered environmentally sustainable if its environmental impact does not exceed its assigned share of the SOS for any PB impact category. Several sharing principles have been applied in the PB-LCA literature to assign shares of SOS and they all require knowledge about the other production or consumption activities that affect the PB impact categories (Bjørn et al., 2020a). In the illustrative example of Figure 1, the product system is judged to be environmentally unsustainable. This is because it exceeds the assigned safe operating space for five of the nine PB impact categories (or Earth-system processes), with respect to a hypothetical sharing principle.

Figure 1: Illustrative example of the common PB-LCA approach according to the nine impact categories (or Earth-system processes) of Steffen et al. (2015). Several impact indicators may exist for each impact category (not shown). The environmental impacts and assigned safe operating space are illustrative and uncertainties are not covered. The letters in parenthesis after each impact category indicate whether Steffen et al. (2015) identify a planetary (P) boundary and/or a regional set of boundaries (R). *There is no boundary defined for Novel entities in Steffen et al. (2015).

The recent comprehensive PB-based life-cycle impact assessment method of Ryberg et al. (2018a) covers seven impact categories (Climate change, Stratospheric ozone depletion, Atmospheric aerosol loading, Ocean acidification, Biogeochemical flows, Freshwater use and Land-system change), including the three with regional boundaries (see Figure 1). The method translates annual elementary flows from

a product system to changes in the value of the PB “control variables” (Steffen et al., 2015) adopted as impact indicators. In a subsequent case study, Ryberg et al. (2018b) applied their method with several sharing principles for assigning SOS to a product. These principles reflect concerns such as equality between individuals or the product’s contribution to the economy. While the impact assessment method of Ryberg et al. (2018a) is comprehensive and relatively easy to apply to LCI results, a key limitation is its handling of regional boundaries. First, Ryberg et al. (2018a) represent the regional boundaries for Freshwater use and Land-system change using spatial archetypes rather than geographical regions. The archetypes are based on aridity for Freshwater use and biomes for Land-system change. A single SOS is identified per archetype, though each may span several continents. Hence, exceedance of SOS in an individual geographical region within an archetype (such as an individual watershed within the semi-arid archetype for Freshwater use) might be overlooked if the aggregate impact for the regions covered by the archetype remains below the single SOS. Second, Ryberg et al. (2018a) do not cover any regional boundaries for Biogeochemical flows (related to phosphorous and nitrogen cycles (Rockström et al., 2009b; Steffen et al., 2015)), even though the quantity of nutrients that the Earth system can sustain greatly depends on their regional distribution (Bjørn et al., 2020c; Kahiluoto et al., 2015; Willett et al., 2019). The limitations related to regional boundaries of the Ryberg et al. (2018a) method are problematic, considering the role of so-called keystone regions in maintaining a stable Earth system (Gleeson et al., 2020) and the growing understanding of how regional state shifts in ecosystems may propagate to the global scale (Bjørn et al., 2019; Gleeson et al., 2020; Lenton et al., 2008; Rocha et al., 2018).

Geographically resolved PB-LCA methods may address these limitations. Such methods contain a set of spatial units (such as watersheds or grid cells) with an equivalent set of safe operating space (SOS), for each impact indicator. For each of these spatial units there is a specific CF or, in cases where elementary

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flows impact more than one spatial unit (for example, due to substance fate processes), there is a specific set of CFs. The recent geographically resolved PB-LCA methods for the impact categories Freshwater use (Bjørn et al., 2020b) and the nitrogen part of Biogeochemical flows (Bjørn et al., 2020c) provide CFs and SOS for thousands of spatial units. Due to their relatively high geographical resolution, these new methods challenge the predominant approach in PB-LCA of comparing (for a given impact category) a product system's aggregated environmental impact to an assigned share of a single global SOS, as illustrated in Figure 1. Instead, the new methods enable a "process-level approach", in which the environmental impacts of individual processes in a product system are compared to their assigned share of the SOS for the regions they impact. So far, the geographically resolved methods (Bjørn et al., 2020c, 2020b) have only been applied to processes whose locations are known with great precision. However, it is rarely possible to obtain this level of spatial resolution across an entire product life cycle. Also, the process-level approach has not yet been applied within a PB-LCA method that covers all PB impact categories (regional and global). In addition, full product system application requires a way of aggregating the process-level results across the life cycle for each impact category to help inform decisions about where in a life cycle to focus impact reduction efforts most urgently.

Here, we make two novel methodological contributions and apply them to a model case study. First, we extend the process-level PB-LCA approach for application to the full life cycle and across a comprehensive set of regional and global PB impact categories (Section 2.1). Second, we enable the use of geographically resolved PB-LCA methods within the extended process-level approach, by presenting a new procedure for aggregating CFs and SOS to match the different levels of spatial resolution encountered in a full LCI (Section 2.2). We then construct a process-level PB-LCA case study (Section 2.3) applying these two methodological contributions with three existing PB-LCA methods (Bjørn et al., 2020c, 2020b; Ryberg et al., 2018b). We present case study results (Section 3) and focus on three

aspects in the ensuing discussion: 1) the additional insights gained from full life cycle application of two geographically resolved PB-LCA methods (for Freshwater use and the nitrogen part of Biogeochemical flows) compared to application only to those processes whose locations are known with great precision (Section 4.1); 2) the influence on results of applying the geographically resolved methods for those two PB impact categories vs. applying differently resolved methods (spatially generic or based on archetypes) (Section 4.2); 3) the insights gained from covering a comprehensive set of PB impact categories, beyond the two noted above (Section 4.3).

2. Methods

The meaning of all variables and their subscripts used in the equations of this section are given in Table 1

Table 1: Meaning of variables and their subscripts.

Variables	Meaning
A	Area of a spatial unit or aggregated region.
AE.aSOS	Accumulated exceedance of assigned (share of) safe operating space.
aSOS	Assigned (share of) safe operating space.
CF	Characterization factor.
EI	Environmental impact.
F	Annual quantity of an elementary flow taking place within a spatial unit.
Occ.aSOS	Occupation of assigned (share of) safe operating space.
M	Mass of an elementary flow for one unit of a process' reference flow.
Q	Quantity of reference flow of process x required for the functional unit of a product system.
SOS	Safe operating space.
SPF	Spatial proportionality factor (used as a weighting factor when calculating the CF of an aggregated region by averaging over CFs of individual spatial units within).
Subscripts	
n	Intersection between a spatial unit and an aggregated region.
e	Elementary flow, specified according to an environmental compartment.
i	Spatial unit in which an elementary flow occurs.
l	Aggregated region in which an elementary flow occurs.
j	Impacted spatial unit.
J	Impacted aggregated region.
k	Impact indicator.
s	Sharing principle.
x	Process.

2.1. Extended process-level PB-LCA

Below, we present the two assessment steps as illustrated in Figure 2.

Figure 2: Graphical representation of the two steps involved in the extended process-level approach for a given impact indicator, involving four processes (numbered #1 to #4).

2.1.1. Step 1: Calculation of the occupation of assigned safe operating space

The first assessment step calculates an occupation of assigned SOS (occ.aSOS) for each process (x) and impact indicator (k), across a comprehensive set of regional and global PB impact categories. Occ.aSOS is defined as the process' environmental impact (EI – columns in top of Figure 2) divided by the SOS assigned to the process (aSOS – dotted lines in top of Figure 2):

$$\text{occ. aSOS}_{x,j,k,s} = \frac{\text{EI}_{x,j,k}}{\text{aSOS}_{x,j,k,s}} = \frac{\sum_e \text{CF}_{e,i,j,k} \times M_{x,e}}{\text{aSOS}_{x,j,k,s}} \quad (\text{Eq. 1})$$

For global impact categories, the calculation of occ.aSOS refers to a single global SOS for all life-cycle processes. For regional impact categories, occ.aSOS refers to the SOS of the specific spatial unit (j)

impacted by each process. In many cases, the impacted spatial unit is the same as the spatial unit in which a process is located (i). However, a process may impact several spatial units (for example, due to substance fate processes), in which case occ.aSOS ideally should be calculated for each of them. In all cases, occ.aSOS may be calculated according to different sharing principles for assigning SOS (s), see Section 2.3.4 for a case study application.

The environmental impact (EI) of Eq. 1 is calculated following standard LCA practice by summing the product of CF (developed specifically for PB-LCA) and elementary flow mass (M) over all elementary flows (e). Note that M should correspond to one unit of reference flow of the process (e.g. 1 kg of crude steel), as it has not yet been scaled to the functional unit of an assessment (this is part of the second step, presented below). Yet, occ.aSOS is likely to be independent of the considered quantity of reference flow. This is because the numerator of Eq. 1 (the process' environmental impact) is always proportional to this quantity and the denominator (the assigned SOS to the process) is likely to also be proportional to this quantity (see Section 2.3.4 for an example).

2.1.2. Step 2: Calculation of accumulated exceedance of assigned safe operating space

The second assessment step calculates the accumulated exceedance of assigned SOS (AE.aSOS) within a product life-cycle, for a given (global or regional) impact indicator (k) and sharing principle (s), as illustrated in Figure 2:

$$AE.aSOS_{k,s} = \frac{\sum_x \sum_j \left(\begin{array}{l} (EI_{x,j,k} - aSOS_{x,j,k,s}) \times Q_x, \text{ for } EI_{x,j,k} > aSOS_{x,j,k,s} \\ 0, \text{ for } EI_{x,j,k} < aSOS_{x,j,k,s} \end{array} \right)}{\sum_x \sum_j (EI_{x,j,k} \times Q_x)} \quad (\text{Eq. 2})$$

The numerator of Eq. 2 sums the part of environmental impacts that exceed assigned SOS (red parts of column in top of Figure 2) across all life-cycle processes (x) and impacted spatial units (j , in the case of regional impacts). By contrast, environmental impacts that do not exceed assigned SOS (e.g., for Process

#2 in Figure 2) are left out of the aggregation. These summed environmental impact parts are scaled to the functional unit of a product system by multiplication with the quantity of required reference flow (Q) of each process (x). The denominator in Eq. 2 calculates the life-cycle impact and serves to normalize the accumulated exceedance to a scale of 0% to 100% of life-cycle impact (note that an AE.aSOS of 100% is unlikely, as it would mean zero assigned SOS to all processes). This creates a common scale for all impact indicators (k).

The scaling by Q in Eq. 2 provides additional insights on which of the, potentially large number, of life-cycle processes with $\text{occ.aSOS} > 1$ (identified in Step 1) are driving the part of the life-cycle impact judged to be environmentally unsustainable. In the illustrative example of Figure 2, Process #3 has the highest occ.aSOS , but not the highest contribution to AE.aSOS, since its reference flow (Q) is only required in a modest amount by the functional unit compared to those of Process #1 and #4. The processes that have a high contribution to AE.aSOS can be considered “PB hotspots” and their identification may help inform decisions about where in a life cycle to focus impact reduction efforts most urgently.

2.2. Spatial aggregation of geographically resolved CFs and SOS

This section presents an approach to aggregate the CFs and SOS of geographically resolved methods for application within the process-level approach presented above.

2.2.1. Presentation of aggregation approach

We propose an aggregation of CFs and SOS at the spatial unit resolution to three spatial resolutions commonly encountered in LCIs (Mutel et al., 2019; Patouillard et al., 2018): 1) country, 2) continent and 3) global. The CF aggregation approach is inspired by the approach and nomenclature of Bulle et al. (2019) and Figure 3 provides an illustration:

Figure 3: Illustration for the CF and SOS aggregation approach in Eq. 3 and 4, which is relevant when the location of an elementary flow within an aggregated region (such as a country) is uncertain. F_e is total annual quantity of an elementary flow within a spatial unit.

$$CF_{e,i,j,k} = \sum_j (CF_{e,i,j,k} \times \frac{A_{j \cap J}}{A_j}) \times SPF_{e,i} \quad (\text{Eq. 3})$$

$$SPF_{e,i} = \frac{F_{e,i} \times \frac{A_{i \cap I}}{A_i}}{\sum_i F_{e,i} \times \frac{A_{i \cap I}}{A_i}} = \frac{F_{e,i} \times \frac{A_{i \cap I}}{A_i}}{F_{e,I}} \quad (\text{Eq. 4})$$

Eq. 3 and 4 can be used to transform a set of spatial unit CFs to a single CF for an aggregated region (e.g. a country) in which an elementary flow is known to occur. In cases where an elementary flow impacts several spatial units (e.g., due to atmospheric transport and deposition) Eq. 3 and 4 can be used to calculate a set of aggregated CFs, accounting for all impacted aggregated regions (J). The inner

summation of Eq. 3 adds CFs for all impacted spatial units (j – e.g., the nine spatial units in the example of Figure 3) that fall within the impacted aggregated region of interest (J). The area fraction within the inner summation downscales each of these CFs when the impacted spatial unit partially falls outside the aggregated region (the intersection (n) of j and J is smaller than j), which is the case for all spatial units in the example of Figure 3, except #5.

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The outer summation of Eq. 3 calculates an average of the CFs of all spatial units (i) that fall within the aggregated region in which the elementary flow occurs (I), weighted by the spatial proportionality factor Affiliations:

(SPF defined in Eq. 4). The weighting by SPF reflects the assumption that an elementary flow of unknown exact location is most likely to occur in the spatial unit (i) with the highest annual quantity of

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the CFs for spatial unit #5 and #7, respectively. The area fraction in Eq. 4 serves to downscale these

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(again, this is the case for eight of the nine spatial unit in the example of Figure 3). The weighting by SPF

in CF aggregation is common in regionalized LCIA methods and is recommended by the UNEP-SETAC Life

cycle initiative working group on the harmonization of LCIA regionalization (Mutel et al., 2019). The

main difference between those recommendations and the CF aggregation approach proposed here is

that conventional LCA aggregates impacts globally, whereas PB-LCA is concerned with specific impacted

aggregated regions (such as countries).

Next, an SOS for all impacted aggregated regions (J) is calculated by summing the SOS of all the

impacted spatial units (j) falling within each J (again, downscaling where needed):

$$SOS_{J,k} = \sum_j (SOS_{j,k} \times \frac{A_{j \cap J}}{A_j}) \quad (\text{Eq. 5})$$

Aggregated CFs and SOS can be used to calculate occ.aSOS and AE.aSOS according to Eq. 1 and 2, with i replaced by I and j replaced by J .

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2.2.2. Application to methods for Freshwater use and the nitrogen part of Biogeochemical flows

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Freshwater use and Bjørn et al. (2020b) for the nitrogen part of Biogeochemical flows using geographic * corresponding author: Email: anders.bjoern@concordia.ca

information systems (GIS) software with a Python code. Supplementary Material (SM) 1 presents Affiliations:

¹Methodological details. The method for Freshwater use of Bjørn et al. (2020b) provides SOS and CFs for 11,050 watersheds in monthly time steps. We converted the original environmental impact indicator

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factors are not able to capture seasonal variations, but more practical to apply than monthly, due to the current lack of temporal information in most LCI databases.

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The method for the nitrogen part of Biogeochemical flows of Bjørn et al. (2020c) provides SOS for 3,797 grid cells (each with an area of $\approx 60,000\text{km}^2$ at the Equator) for natural soil, SOS for 6,081 watersheds for freshwater and SOS for 66 large marine ecosystems for coastal water and corresponding CFs for different chemical forms of nitrogen emissions to soil, freshwater, coastal water and air. We aggregated the CFs and SOS for impacts on natural soil and freshwater and left out the variables related to coastal water, as we judged the method's spatial resolution of coastal water to be too crude to quantify impacts on that environmental compartment.

2.3. Case study application of process-level PB-LCA

2.3.1. Goal and scope

We based the cradle-to-grave PB-LCA case study on a model European laundry detergent as described by Ryberg et al. (2018b). We adapted the case study of Ryberg et al. (2018b) for the application of geographically resolved PB-LCA methods (see SM 2 for details). We defined the functional unit as “*doing 196 washes per year of 4.5 kg of normally soiled dry fabric at 40.4°C with a model liquid detergent in the UK*”. The washing frequency, load and temperature is representative of the user behaviour in the average household in UK and Ireland in the year 2014, according to the International Association for Soaps, Detergents and Maintenance Products (AISE, 2015a). The water use and detergent dosage per washing cycle were based on pan-European technical standards for washing machines (AISE, 2015b). We followed attributional modelling principles (as prescribed by Ryberg et al. (2018a) for this type of assessment) and handled multifunctional processes by economic allocation. SM 8 contains a reflection on the methodological choices of the case study.

2.3.2. LCI modelling

We modified the inventory of Ryberg et al. (2018b) as a basis for the LCI modelling executed in SimaPro V8.5.2.0 (PRé, 2019). This involved changing all flow quantities (product flows and elementary flows) to match the household-scale functional unit of this case study and replacing European average processes with UK-specific processes in the detergent manufacture, use and waste treatment stages (e.g., related to electricity grid mix) (see details in SM 2).

Next, we selected a subset of all processes involved in the full inventory (>1,000) for the process-level PB-LCA. This was done to keep a focus on processes in the foreground system and on processes in the background system that have a non-negligible contribution to global impacts, as well as to keep the number of calculations manageable. Hence, we selected the following processes: 1) all foreground

processes related to ingredients, and 2) all processes that contributed more than 1% to any global impact for the impact indicators of Ryberg et al. (2018a). This resulted in the selection of 61 processes, see Figure 4, which accounted for, on average, 88% of the life-cycle impacts for the nine impact indicators of Ryberg et al. (2018a).

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Figure 4: Schematic representation of the product system organized into seven major clusters of processes. The number of processes that were selected for process-level assessment (61 in total) are indicated in the upper left corner of each cluster, followed by, in parentheses, the number of these processes that were spatialized (20 in total).

Next, in order to apply the two geographically resolved methods described in Section 2.2.2, we divided the 61 processes into two groups, one to be spatialized, that is, assigned to a spatial unit or aggregated region (Patouillard et al., 2018), and another group to remain spatially generic. The spatially generic group was composed of the 41 background processes that contributed less than 1% to global impacts for Freshwater use and the nitrogen part of Biogeochemical flows according to the impact indicators of Ryberg et al. (2018a). We judged spatialization to be unnecessary for these processes, due to their low contribution to the two impact categories for which geographically resolved PB-LCA methods exist (Bjørn et al., 2020c, 2020b). The remaining 20 processes to be spatialized (see parentheses of Figure 4) were part of the foreground system and/or contributed more than 1% to global impacts for Freshwater

use and the nitrogen part of Biogeochemical flows. We based their spatialization on representative locations of production (e.g. a specific manufacturing facility), or on geographically resolved production statistics (see Section 4.4.2 for uncertainties related to spatialization). For example, we spatialized the

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process for palm fruit bunch production (used to produce palm oil, later synthesized to a surfactant ingredient) to a specific watershed in Indonesia (on Borneo) that has the highest area of oil palm

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processes, we attributed 13 to a spatial unit (e.g., a specific watershed or grid-cell) and 7 to a country. * corresponding author: Email: anders.bjoern@concordia.ca

Note that amongst the 61 processes selected for process-level assessment, we constructed 12 by Affiliations:

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²Unilever Safety and Environmental Assurance Centre, Unilever R&D, Colworth Science Park, Sharnbrook, MK44 1LQ, UK. as the former is a sub-processes of the latter. Details on the spatialization and merging of processes can be found in SM 3.

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2.3.3. Application of PB-LCA methods

We applied the PB-LCA methods of Bjørn et al. (2020b) (for Freshwater use) and Bjørn et al. (2020c) (for the nitrogen part of Biogeochemical flows), including the aggregated CFs and SOS (see Section 2.2), as

well as Ryberg et al. (2018a) (for a comprehensive set of impact categories) to each of the 61 selected

processes. For each process, we matched its spatialization with a specific spatial unit or aggregated

region. For example, we applied CFs aggregated to the country level to processes spatialized to

countries and global CFs to the 41 spatially generic processes. For the spatially generic impact categories

of Ryberg et al. (2018a) we applied global CFs to all 61 processes, whether spatialized or not. Note that

the global CFs and SOS of Bjørn et al. (2020b) and Bjørn et al. (2020c) for Freshwater use and the

nitrogen part of Biogeochemical flows are not identical to the global CFs and SOS of Ryberg et al.

(2018a) for those two impact categories. This is because the former reflects an aggregation of regional

boundaries and the latter directly reflects the PBs estimated in Steffen et al. (2015) and because of differences in impact indicators (more details in Section 4.2). The method for the nitrogen part of

Biogeochemical flows of Bjørn et al. (2020c) is the only case where an elementary flow impacts more

spatial units or aggregated regions than the spatial unit in which the flow occurs. This is due to

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atmospheric transport and deposition of air emissions. We applied that method to calculate

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(i.e., using CFs where $i = j$ in Eq. 1 or $i = J$ in Eq. 3). In addition, we calculated the global impact of each * corresponding author: Email: anders.bjoern@concordia.ca

process by summing the calculated impacts for each spatial unit (j) or region (J), globally. Affiliations:

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For illustration purposes, we assigned SOS to the 61 selected processes by applying the Gross Value added (GVA) principle, modified to account for emission transport across regions. A region is, in this

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(watersheds or grid-cells) to the global level. For the sake of simplicity, we only assigned regional SOS to

a process for the region in which the process is situated. The GVA principle is one of the most commonly

used in the literature (Bjørn et al., 2020a). GVA can be defined as revenue generated by a process minus

the cost of purchased goods and services and is largely composed of salary to employees and operating

surplus (Eurostat, 2008; Randers, 2012). The principle reflects the perspective that the regional SOS

assigned to a production process should be proportional to its contribution to the regional economy. We

calculated the assigned regional SOS (aSOS) to a process (x) for a given impact indicator (k) as:

$$aSOS_{x,k} = \frac{GVA_x}{GVA_{total}} \times SOS_k \times \frac{EI_{endogenous,k}}{EI_{total,k}} = \frac{P_x \times rGVA_x}{GVA_{total}} \times SOS_k \times \frac{EI_{endogenous,k}}{EI_{endogenous,k} + EI_{exogenous,k}} \quad (\text{Eq. 6})$$

GVA_x is the GVA of process x and GVA_{total} is the total GVA of the region in which x is situated. P is the

basic price (in short, the price at the “factory gate” before taxes and subsidies are considered (Eurostat,

2008)) of a unit of product flow (e.g., 1 kg palm oil) and rGVA is the relative GVA (expressed as GVA per unit of basic price). GVA_{total} was calculated using a highly geographically resolved global dataset of gross domestic product (Kummu et al., 2018). P was obtained from Ecoinvent 3.5 (Wernet et al., 2016) and

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rGVA from the multi-regional input-output database Exiobase 3 (Stadler et al., 2018), based on the classification of Ecoinvent processes to Exiobase product categories of Agez et al. (2020). SOS was

Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael ZWicky³, Ryberg, Morten

presented in Section 2.2.

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¹The last term in Eq. 6 (related to environmental impacts, EI) accounts for emission transport across regions and effectively pre-assigns one part of a region's SOS to all local processes and another part to

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GVA principle, because processes located outside a region do not directly contribute to the economy of

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the total impact on a region that is endogenous, as opposed to exogenous (this is in accordance with the

Status Quo sharing principle (Ryberg et al., 2018b)). We quantified $EI_{endogenous}$ and $EI_{exogenous}$ by

characterizing geographically resolved inventories of total elementary flows (also used as F in the

application of Eq. 4, see SM 1 for data sources). The pre-assigned share of SOS to a region's local

processes ($EI_{endogenous}/(EI_{endogenous}+EI_{exogenous})$ in Eq. 6) is 1 for most impact categories considered here.

This is because global impact categories (per definition) only have a single region and because impacts

for some regional impact categories (like Freshwater use) are limited to the region of the elementary

flow (meaning zero exogenous impacts). However, for the nitrogen part of Biogeochemical flows of

Bjørn et al. (2020c) emissions of nitrogen from outside a region can impact the region through

atmospheric transport and deposition of air emissions and through riverine transport of freshwater and

soil emissions. For that impact category, we found the pre-assigned share of SOS to a region's local

processes often to be less than half and that it decreases with decreasing region size. SM 4 contains details on the aSOS calculations.

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Table 2 shows the occupation of assigned SOS (occ.aSOS, see Eq. 1) by each of the 20 spatialized

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nitrogen part of Biogeochemical flows (Bjørn et al., 2020c). Results are also given for the same two * corresponding author: Email: anders.bjoern@concordia.ca

impact categories in the method of Ryberg et al. (2018a), which are spatially generic (nitrogen) and Affiliations:

based on spatial archetypes (freshwater). Occ.aSOS for all 61 processes and impact indicators are documented in SM 6 and corresponding environmental impacts are documented in SM 5. Note that

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it is situated, only a single occ.aSOS was calculated for each process and impact indicator. For an

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see the case study of Bjørn et al. (2020c). Processes with occ.aSOS above 1 have higher impacts than

their assigned SOS, with respect to the GVA sharing principle, thus indicating potential environmental

unsustainability. Note that such processes do not necessarily have a high contribution to life-cycle

impacts, because occ.aSOS is independent of the functional unit here (see Section 2.1.1).

Table 2: Occupation of assigned SOS (dimensionless) by the 20 spatially resolved processes for Freshwater use and the nitrogen part of Biogeochemical flows. Results for all processes and impact indicators are given in SM 6. Values above 1 illustrate exceedance of assigned SOS and are shown in bold. Processes in italic are spatialized to a country instead of a spatial unit.

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	Geographically resolved methods			Differently resolved methods	
	Freshwater use	Biogeochemical flows, nitrogen	Biogeochemical flows, nitrogen	Freshwater use	Biogeochemical flows, nitrogen
<p>Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael Zwicky³, Ryberg, Morten³</p> <p>* corresponding author: Email: anders.bjoern@concordia.ca</p> <p>Affiliations:</p> <p>¹ CIRCEP, Mathematical and Industrial Engineering Department, Polytechnique Montreal, C.P. 6079, succ. Centre-Ville, Montreal, QC H3C 3A7, Canada</p> <p>² Unilever Safety and Environmental Assurance Centre, Unilever R&D, Colworth Science Park, Sharnbrook, MK44 1LQ, UK.</p> <p>³ Quantitative Sustainability Assessment group, Department of Technology, Management and Economics, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark.</p>					
<i>Coconut production (M1)</i>	1.2	0.015	0.048	2.2	0.46
<i>Palm fruit bunch production (M2)</i>	0.0070	0.030	0.28	0.14	59
<i>Palm fruit bunch production, on land</i>					
<i>Acetic acid production (I1)</i>	20	0	0	0.29	0
<i>Rapeseed, extensive production (M4)</i>	52	1700	1200	1.00	1300
<i>Rapeseed, intensive production (M5)</i>	45	1500	740	0.86	1100
<i>Anionic surfactant production (I2)</i>	0	0.054	3.1	0	0.45

Citric acid production (I3)	620	7.4	12	19	47
Enzymes production (I4)	0.18	0	0	0.0016	0
Fluorescent whitening agent production (I5)	540	40	660	7.9	210
Lauric acid production (I6)	0.020	0	0	0.037	0
Monomer Z surface, R used, M onen	0	0.028	0.23	0	0.045
Polycarboxylate production (I8)	370	560	8.4	5.5	3.3
Deionised water production (I9)	-44*	0	0	-0.41*	0
Triethanolamine production (I10)	17	140	28	0.24	380
Electricity production, hard coal (U1)	300	39	1400	11	290
Electricity production, biogas (U2)	36	9.5	250	1.4	170
Tap water supply (U3)	2100	0	0	6.1	0
Electricity production, natural gas (U4)	17	3.7	130	0.63	28

*Negative due to negative water consumption.

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Figure 5 shows the accumulated exceedance of assigned SOS (AE.aSOS) of the 61 processes as defined in Eq. 2, according to the process clusters of Figure 4. The results are given for 1) the three impact

indicators covered by the geographically resolved methods for Freshwater use (Bjørn et al., 2020b) and the nitrogen part of Biogeochemical flows (Bjørn et al., 2020c), 2) the two impact indicators of Ryberg et al. (2018a) (“differently resolved”) covering those impact categories, and 3) the remaining indicators of

Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Ryberg et al. (2018a) covering other impact categories, all spatially generic. See SM 7 for a figure (S1)

with all 61 processes and another figure (S2) with processes categorized according to level of * corresponding author: Email: anders.bjoern@concordia.ca

spatialization (spatial unit, country or none). Since AE.aSOS is normalized by the life-cycle impact, for Affiliations:

each impact indicator (see Eq. 2) it can be understood as the share of the total impact of the 61 processes that exceeds assigned SOS to individual processes. Processes that have a high contribution to processes that exceeds assigned SOS to individual processes. Processes that have a high contribution to

AE.aSOS both have a high contribution to the life-cycle impact and a high occ.aSOS (Table 2) and can be considered “PB hotspots”.

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Figure 5: Accumulated exceedance of assigned SOS (normalized by life-cycle impacts) for the 61 selected case study processes organized in five life cycle stages for 12 PB-LCA impact indicators. BF = Biogeochemical flows. GR = geographically resolved. SAR = spatial archetype resolution. SG = spatially generic.

4. Discussion

4.1. Insights from case study application of geographically resolved methods to a full life cycle

The development of the spatially aggregated CFs and SOS (Section 2.2) allowed the occupation of assigned SOS to be calculated for all 61 selected processes for the geographically resolved methods (Bjørn et al., 2020c, 2020b) (column 2-4 of Table 2 and SM 6). Hence, in addition to the 13 processes

that could be spatialized to a watershed or a grid cell, the new approach allowed coverage of a further 7 processes spatialized to a country (in italics in Table 2) as well as coverage of 41 spatially generic processes (see SM 6). This expansion of case study processes from 13 to 61 lead to an 18% and 62%

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increase in the mass of elementary flows covered for freshwater use and the nitrogen part of Biogeochemical flows, respectively. Of the 61 processes, between 16 and 21 processes (depending on

Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael Zwickly, Ryberg, Morten

assigned SOS (Bjørn et al., 2020c, 2020b) (see Table 2 and SM 6). Of these 16-21 processes, 5-7 were * corresponding author: Email: anders.bjoern@concordia.ca

spatialized to a spatial unit, 5-6 to a country and 3-10 were spatially generic (again, depending on which Affiliations:

Indicator is considered). This shows that the application of aggregated CFs and SOS, in addition to CFs, CRAIG, Mathematical and Industrial Engineering Department, Polytechnique Montréal, C.P. 6079,

succ Centre-Ville, Montréal, QC H3C 3A7, Canada and SOS at the spatial unit resolution, can lead to the identification of more processes that exceed their

²Unilever Safety and Environmental Assurance Centre, Unilever R&D, Colworth Science Park, assigned SOS in a product life cycle than an assessment that only considers processes that can be

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The accumulated exceedance of assigned SOS (AE.aSOS) was driven by different processes for the three

geographically resolved impact indicators (see Figure 5). For Freshwater use, a single process, tap water

supply to the use stage, spatialized to the Thames basin in the UK, accounted for more than half of

AE.aSOS (see Figure S1 in SM 7). This was due to a high environmental impact (a water consumption of

8.1m³, compared to a life-cycle total of 12.1m³) and a high occ.aSOS (2100, see Table 2), according to

our application of the GVA principle (the choice of sharing principle in PB-LCA is further discussed in

Section 4.4.4). For the two geographically resolved impact indicators related to the nitrogen part of

Biogeochemical flows, AE.aSOS was driven by a larger number of processes, with 12 processes each

accounting for 5-28% of exceedance for one or both indicators (see Figure S1 in SM 7). For the indicator

related to freshwater impacts of nitrogen emissions, around half of the highly contributing processes

related to *Ingredients and packaging manufacture* and were spatialized to a spatial unit. By comparison,

the highly contributing processes for the nitrogen indicator related to natural soil impacts were all part of the *Use stage* and *Energy and infrastructure* and were spatialized to a country or were spatially generic (see Figure S2 in SM 7). Taken together, the results for the three geographically resolved impact indicators show that the calculation of occ.aSOS can allow for the identification of a handful of PB-hotspots within a full product system. Moreover, the results show that the application of aggregated CFs Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael Zwickly³, Ryberg, Morten cover highly spatially resolved processes.

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processes found to exceed their assigned SOS (occ.aSOS>1), but the geographically resolved method (Bjørn et al., 2020b) identified 16 such processes, whereas the method based on spatial archetypes (Ryberg et al., 2018a) only identified 10. The difference can be explained from the different spatialization approaches for the 20 processes in Table 2. For example, five processes belonging to *Raw materials* and *Ingredients and packaging manufacture* were spatialized to regions in Europe with highly concentrated economic activity, such as the Rhine basin, for the geographically resolved method (Bjørn et al., 2020b). For the other method (Ryberg et al., 2018a), the same five processes were spatialized to the “humid” archetype. This spatial archetype covers ≈70% of the world’s ice-free terrestrial surface, meaning that every unit of value added created within it was allowed a substantially higher freshwater consumption than in the economic hotspot regions in Europe, according to the GVA principle (see Eq. 6). For the indicators related to the nitrogen part of Biogeochemical flows the situation was somewhat

opposite, since a higher number of processes were found to exceed their assigned SOS for the spatially generic method (Ryberg et al., 2018a) (29 processes) than for both of the geographically resolved ones (Bjørn et al., 2020c) (20-21 processes). For example, the two palm fruit bunch production processes (see top of Table 2) only exceeded their assigned SOS for the spatially generic method. This is largely because these processes, for the two geographically resolved methods (Bjørn et al., 2020c), were spatialized to a Børn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael², Zwicky, Ryberg, Morten

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characterized by relatively low economic activity, low CFs and high SOS (allowing each unit of value * corresponding author: Email: anders.bjoern@concordia.ca added a relatively high nitrogen emission, according to the GVA principle). Another reason for the discrepancy is that the impact indicators and quantification of SOS in Bjørn et al. (2020c) (summarized in section 2.1.2) differ from those of the method of Ryberg et al. (2018a). The latter method uses nitrogen fixation as a proxy for the ensuing environmental impact and its corresponding SOS was estimated in a back-calculation from a critical nitrogen concentration in surface run-off, as per Steffen et al. (2015).³Quantitative Sustainability Assessment group, Department of Technology, Management and Economics, Technical University of Denmark, Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark.

The main contributing processes to the accumulated exceedance of assigned SOS (AE.aSOS) for Freshwater use were similar for the method based on spatial archetypes (Ryberg et al., 2018a) and the geographically resolved method (Bjørn et al., 2020b). Yet AE.aSOS was higher in the latter case (88%, see Figure 5), mainly due to a higher contribution from tap water supply to the use stage. This difference is caused by a higher assigned SOS to that process when spatialized to the “humid” spatial archetype than when spatialized to the Thames basin in the UK (also leading to a large difference in occ.aSOS, see Table 2). For the nitrogen part of Biogeochemical flows, the spatially generic method (Ryberg et al., 2018a) yields a higher AE.aSOS than the two geographically resolved methods (Bjørn et al., 2020c, 2020b) (98% vs. 73-76%, see Figure 5). This was mainly caused by a high contribution from palm fruit bunch production for the spatially generic method (see SM 7, Figure S1) compared to a zero contribution for the two indicators of the geographically resolved methods (meaning that environmental impact did not

exceed assigned SOS, as elaborated in the previous paragraph). Hence, the use of geographically resolved methods can point to different PB hotspots than the use of methods that are spatially generic or based on spatial archetypes.

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4.3. Insights from case study application of a comprehensive set of PB-LCA impact categories

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above (“Differently resolved” and “Other impact categories, all spatially generic” in Figure 5) provided * corresponding author: Email: anders.bjoern@concordia.ca

new insights: For some impact categories, like Climate change, a large number of processes (up to 40) Affiliations:

were found to exceed their assigned SOS, whereas for others, such as Stratospheric ozone depletion and CRAC, Mathematical and Industrial Engineering Department, Polytechnique Montréal, C.P. 6079, succ. Centre-Ville, Montréal, QC H3C 3A7, Canada

and system change, this was only the case for a handful of processes (1-6), see SM 6. This reflects the

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CO₂), whereas others are less common (such as forest transformation). Also, the PB hotspots (high

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Agrochemicals only had a high contribution to the phosphorous part of Biogeochemical flows and

Energy and infrastructure processes only accounted for a large part of AE.aSOS for Stratospheric ozone

depletion and Atmospheric aerosol loading (see Figure 5). Also, AE.aSOS was observed to span from 30%

for Stratospheric ozone depletion to close to 100% for Climate change (see Figure 5). This difference is

consistent with the fact that the PB for the former impact category is far from being exceeded by global

emissions, while the PB for the latter has been exceeded (Steffen et al., 2015). The case study

application shows that the process-level approach is applicable to all PB impact categories. The observed

differences in the results between impact categories reaffirms the importance of covering a

comprehensive list of PB impact categories in the pursuit of an environmentally sustainable product life

cycle.

4.4. Broader implications of case study findings

4.4.1. Potential advantages of process-level PB-LCA compared to the common PB-LCA

approach

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Process-level assessments, involving a comprehensive set of regional and global PB impact categories, offer novel uses and insights for practitioners and decision-makers. Instead of assessing whether a product system, as a whole, is within or exceeding its assigned SOS, the process-level approach can be

used to identify individual processes exceeding their assigned SOS and subsequently relate this * corresponding author: Email: anders.bjoern@concordia.ca

exceedance to the life-cycle impact. Such an assessment allows decision-makers to identify priorities in Affiliations:

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only three contributed more than 5% to the accumulated exceedance of assigned SOS (AE.aSOS, see SM

7). Identification of such PB hotspots could provide the focus for urgent improvement efforts towards a

product system whose main sources of environmental impact are below their assigned SOS.

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4.4.2. Uncertainties

Process-level assessments capture spatial variations in CFs and SOS for regional impact categories. It

may therefore be less uncertain than the common PB-LCA approach that only covers global CFs and SOS.

Yet, process-level assessments come with a unique set of uncertainties. First, some techniques for

spatializing processes to spatial units (e.g., watersheds or grid cells) involve uncertainty. For example,

several processes of this case study were assigned to spatial units in which they are relatively likely (but

not fully certain) to be situated in, according to geographically resolved production statistics (see Section

2.3.2). Further, when processes are spatialized to a country or a continent (instead of a spatial unit) there is a loss of information on spatial variability in CFs, SOS and parameters used to assign SOS within such aggregated regions. The related uncertainties may be of special concern for large aggregated regions with high geographical heterogeneity, such as the United States or China. Future PB-LCA case studies may use uncertainty propagation (Ryberg et al., 2018b) to understand the robustness of results Bjørn, Anders¹, Sim, Sarah², King, Henry², Patouillard, Laure¹, Margni, Manuele¹, Hauschild, Michael Zwickly³, Ryberg, Morten

collection of spatial process data (Patouillard et al., 2019) in order to reduce uncertainty.
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¹Our approach to calculating accumulated exceedance of assigned SOS (AE aSOS, see Eq. 2) assigns equal weights to all exceedances, regardless of the region in which they occur. Alternative approaches

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understanding of the mechanisms by which exceedance of regional boundaries may lead to destabilization of the Earth system (Bjørn et al., 2019; Brook et al., 2013; Lenton and Williams, 2013).

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4.4.3. Recommendations to software and database developers

Ideally, practitioners should be able to conduct process-level PB-LCA in LCA software, but this is currently not possible. To ensure correct links between spatialized elementary flows and geographically resolved CFs, we encourage inventory database and software developers to follow the recent recommendations of the UNEP-SETAC Life Cycle Initiative working group on the harmonization of LCIA regionalization (Mutel et al., 2019). Specifically for PB-LCA, we furthermore encourage inventory database developers, such as Ecoinvent (Wernet et al., 2016), to: 1) create a database version in which processes occurring in the same production facility are merged. This would save time, negating the need

for manual merging of processes after the calculation of inventory results (see SM 3.2); 2) Ensure that processes labelled as unit processes are, in fact, not system processes (i.e., having “cradle to gate” system boundaries). In carrying out the case study, we discovered several such mislabels (see SM 4), forcing us to make the practical assumption that all upstream processes occurred in the same region.

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SOS and the subsequent calculation of occ.aSOS and AE.aSOS. This would require each link between an * corresponding author: Email: anders.bjoern@concordia.ca

elementary flow and a CF (whether global or covering a spatial unit or an aggregated region) to be Affiliations:

extended with a link to an SOS value and a link to values of the parameters needed to assign that SOS to a process (see Eq. 6, for the case of the GVA principle).

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4.4.4. Future research needs

³Quantitative Sustainability Assessment group, Department of Technology, Management and Process-based PB-LCA is an emerging subset of “absolute environmental sustainability assessment”. As Economics, Technical University of Denmark, Produktionsøret, Building 424, 2800 Kgs. Lyngby, Denmark.

such, the broad recommendations for addressing methodological limitations presented in the review of

Bjørn et al. (2020a) also apply here. For example, SOS estimates should reflect the latest scientific

development and consistency between SOS estimates for different impact categories should be

ensured. Also, the exceedance of one planetary or regional boundary (e.g., for Climate change) may

change the positions of other boundaries (e.g., for Freshwater use) (Lade et al., 2020; Steffen et al.,

2015) and there is a need to quantify these interactions (Bjørn et al., 2019).

In this paper we applied the process-level approach with geographically resolved PB-LCA impact

indicators for Freshwater use and the nitrogen part of Biogeochemical flows. There is a need for also

developing geographically resolved methods for the phosphorous part of Biogeochemical flows and for

Land-system change (see Bjørn et al. (2019) for challenges and opportunities for the latter). Likewise,

new PB-LCA methods should be developed as PB science evolves, for example with respect to Biosphere integrity and Chemical pollution/Introduction of novel entities (see Figure 1).

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In the case study of this paper we applied the GVA principle for assigning SOS for illustration purposes.

However, a principle related to need-fulfilment may be more acceptable amongst a study's stakeholders

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comparing the application of multiple sharing principles (ten were identified in Bjørn et al. (2020a)) to * corresponding author: Email: anders.bjoern@concordia.ca

process-level PB-LCA, to understand the practicality of application and the sensitivity of results to the Affiliations:

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best practice of consensus seeking in SOS assignment with inputs from other scientific communities

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Our study provides a step towards greater operability of geographically resolved PB-LCA methods within

an extended process-level approach that covers a comprehensive set of impact categories. The case

study application shows that a process-level approach may point to more specific priority areas within a

product system than the common PB-LCA approach and that related uncertainties should be quantified

in future applications. As PB-LCA methods continue to evolve and mature, the complementary nature of

these approaches and conventional LCA will warrant further consideration. In particular, the potential

role in decision-support of PB-LCA compared to conventional LCA deserves further attention, for

example with regards to the identification of priority areas within product life cycles.

5. Conclusion and outlook

Post-Print version

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