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Absolute environmental sustainability assessment of a Danish utility company relative to the Planetary Boundaries

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Abstract: Increasing environmental pressure from production and consumption of products and services is starting to affect Earth System stability. Thus, the Planetary Boundaries framework introduced a set of absolute boundaries for keeping the Earth System stable and delimiting a safe operating space for humanity. The sum of environmental pressures associated with human activities should not exceed the safe operating space. This include utility companies whose activities relate to supply of water and treatment of waste- and stormwater. This study conducted an absolute environmental sustainability assessment (AESA) of a Danish utility company to evaluate if it could be considered absolutely sustainable relative to an assigned share of the safe operating space. The AESA evaluated the company's impacts relative to an assigned share of the Planetary Boundaries and relative to specific local boundaries for nitrogen and phosphorous emissions. Results showed that the assigned share of the safe operating space was exceeded for 10 of 18 impact categories, e.g. climate related boundaries were exceeded by up to a factor 7.8 while local nitrogen and phosphorus boundaries were exceeded by ca. a factor 16. The AESA can indicate to which degree the company exceeds its assigned share of the safe operating space for certain impact categories and the processes and life-cycle stages to focus on to become absolutely sustainable. This information is crucial for deriving specific impact reduction targets as part of environmental strategies for companies to become sustainable in an absolute sense.

1 Introduction

The environmental pressure stemming from the production and consumption of products and services for humans has been increasing steadily since the industrial revolution (Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015). The pressure on the environment is now starting to affect the stability of the Earth System state which, in contrast to other periods in Earth's lifetime has been unusually stable over the last 12,000 years (termed the Holocene state) (Rockström et al., 2009; Steffen et al., 2018). This stability has coincided with the increased prosperity of humans and civilizations (Rockström et al., 2009), thus destabilization of the Earth System should be avoided. In relation to this, the Planetary Boundaries (PB) framework (Rockström et al., 2009; Steffen, Richardson, et al., 2015) introduced a set of absolute boundaries (i.e. the Planetary Boundaries) for Earth System processes. The well-functioning of the Earth System processes was considered essential for maintaining the Earth System in a Holocene-like state. The PBs, hereby delimit a safe operating space for humanity and the sum of environmental pressures associated with all human activities should not exceed the safe operating space. This includes activities related to supply of water and treatment of waste- and stormwater which are commonly managed by utility companies.

The potential environmental impact associated with the functions provided by utility companies, such as supplying water or managing storm- and wastewater, is commonly assessed using environmental life-cycle assessment (LCA). LCA is a standardized (ISO, 2006a, 2006b) decision support tool, which can be used to quantify the potential environmental impacts of a product or service throughout its entire life cycle, i.e. from material extraction to end-of-life. Previous LCAs of utility companies have focused on quantifying the potential environmental impacts of different technologies with the aim of identifying the technology with the lowest environmental impact per function provided. For instance, identifying the best technologies for supplying water (e.g. Ghimire, Johnston, Ingwersen, & Sojka, 2017; Godskesen, Hauschild, Rygaard, Zambrano, & Albrechtsen, 2013; Uche, Martínez-Gracia, Círez, & Carmona, 2015), managing stormwater (e.g. Andrew & Vesely, 2008; Brudler et al., 2019; Brudler, Arnbjerg-Nielsen, Hauschild, & Rygaard, 2016; O'Sullivan, Wicke, Hengen, Sieverding, & Stone, 2015), and treating municipal wastewater (e.g. Gallego, Hospido, Moreira, & Feijoo, 2008; Opher & Friedler, 2016; Polruang, Sirivithayapakorn, & Prateep Na Talang, 2018; Remy et al., 2016; Risch, Gutierrez, Roux, Boutin, & Corominas, 2015). This has allowed for selecting the technologies with the best environmental performance and has been important for reducing the environmental impact per function provided by the utilities. However, given that population and consumption are increasing at a faster rate than technological improvements, there is a need for introducing assessments that can indicate if current technologies are actually good enough and not just better than the alternatives (Hauschild, 2015).

This has led to the development of Absolute Environmental Sustainability Assessments (AESAs), where, environmental impacts, quantified using LCA, are related to absolute environmental boundaries, such as the PBs. AESA is an emerging field of environmental sustainability assessments (Bjørn et al., 2020) and only a few practical case studies exist (e.g. Algunaibet et al., 2019; Brejnrod, Kalbar, Petersen, & Birkved, 2017; Chandrakumar, McLaren, Jayamaha, & Ramilan, 2019; Ryberg, Owsianiak, Clavreul, et al., 2018; Wolff, Gondran, & Brodhag, 2017). Nevertheless, results of AESAs offer important added value about the sustainability of the assessed activities relative to absolute environmental boundaries. AESAs support assessing if an activity can be considered environmentally sustainable in an absolute sense; and if this is not the case, support setting absolute improvement targets for the activity to become sustainable in absolute terms. For instance, an LCA-based AESA was performed for laundry washing, using a model laundry detergent, in the European Union (EU) relative to an assigned share of the safe operating space, using the Earth System processes of the PB framework as impact categories (Ryberg, Owsianiak, Clavreul, et al., 2018). The results of the AESA were used to identify if laundry washing in the EU could be considered sustainable in absolute terms. It was found that laundry washing in the EU exceeded its assigned share of the safe operating space for a number of impact categories. Hereby, the method allowed for quantifying the impact reductions needed for laundry washing to be sustainable in an absolute sense. Moreover, assessments of different improvement scenarios allowed for evaluating if these were sufficient for making laundry washing sustainable or if more ambitious improvements were needed.

The overall objective of this study was to conduct a full AESA on the Danish utility company VandCenter Syd (VCSyd) to evaluate whether VCSyd could be considered absolutely sustainable relative to the PBs. If this was not the case, this study sought to (i) identify the impact categories, and processes and life-cycle stages to focus on for VCSyd to become absolutely sustainable and (ii) estimate the level of reductions needed for VCSyd to be absolutely sustainable.

2 Methods

To fulfill the objective of this study, the following methods were used. First the environmental impacts of VCSyd was quantified using life-cycle assessment (LCA) methods. Second, the overall environmental boundaries (e.g. the PBs) to be used in the assessment were defined and a share of the safe operating space (SoSOS) that is available for human activities was assigned to VCSyd. Finally, the quantified environmental impacts were related to the assigned SoSOS to evaluate if the environmental impacts from the functions provided by VCSyd could be considered absolutely sustainable. An activity's environmental impacts divided by the assigned SoSOS indicates the environmental sustainability ratio (ESR). The activity can be considered absolutely sustainable if the ESR is equal to or less than one for the evaluated impact categories (Fang, Heijungs, Duan, & De Snoo, 2015).

2.1 System scope and life-cycle inventory

The inventory on the resource uses and emissions associated with VCSyd were quantified based on an LCA conducted in accordance with the requirements of the ISO standard and the guidelines of the International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2010; ISO, 2006a, 2006b).

The functional unit (FU) for the study, i.e. what to assess, was defined as "annual supply of 8.36 million m^3 water and management and treatment of 29.3 million m^3 storm- and wastewater". This is the service annually provided by VCSyd to its customers. All subsequent assessments are performed relative to the FU. The decision context for this study was defined as 'accounting of environmental impacts' (i.e. situation C1 according to the EC-JRC 2010). Accordingly, the life-cycle inventory (LCI) which expresses the resource uses and emissions resulting from fulfilling the FU was modelled using an attributional modelling approach to best represent the actual physical flows occurring from fulfilling the FU. System-expansion and crediting for 'avoided emissions' is recommended for situation C1 to deal with multifunctional processes that are part of the assessed life-cycle, but not directly related to the FU (EC-JRC, 2010). However, this approach is not suited for AESAs because system expansion and 'avoided emissions' make the assessment dependent on the impact of the avoided emissions and, thus, makes it a relative assessment instead of an absolute assessment. Therefore, multifunctional processes and the additional delivered functions are dealt with by expanding the system to model and include the additional functions as well as the associated environmental impacts. Similarly, the assigned SoSOS is also expanded to reflect the additional delivered function. Thus, the assigned SoSOS is aligned with the system boundaries of the LCI. For instance, a wastewater treatment plant (WWTP) will be assigned a share of the safe operating space based on its main function, i.e. treatment of wastewater. However, if the WWTP also generated electricity and heat for the energy grid, then an additional SoSOS will be assigned based on this additional function. In this way, processes and systems that provide multiple functions will be credited through the assignment of a proportionally larger SoSOS.

A sensitivity and uncertainty analysis of the LCI was conducted to identify the input parameters to which the result is most sensitivity and to quantify the uncertainty of the results (see Supporting Information (SI) 1 Section S2 for details). Figure 1 depicts the system boundaries for the study. Overall, the foreground LCI includes processes related to water supply, waste- and stormwater treatment, groundwater protection (as afforestation), and administration and others. SI 1 Section S1 provides a general overview of the modelling of these different processes for the foreground system. A full overview of all unit processes used for modelling the foreground system is given in SI 2. The background system comprises processes related to electricity and heat production and production of materials used by the foreground system. Data for the foreground system was primarily based on information obtained from VCSyd and from other peer-reviewed literature. The background system was primarily modelled based on data from ecoinvent v3.3 using the 'cut-off' based attributional inventory model (Weidema et al., 2013), but coupled with primary data from VCSyd and other literature where relevant (see SI 1 Section S1).

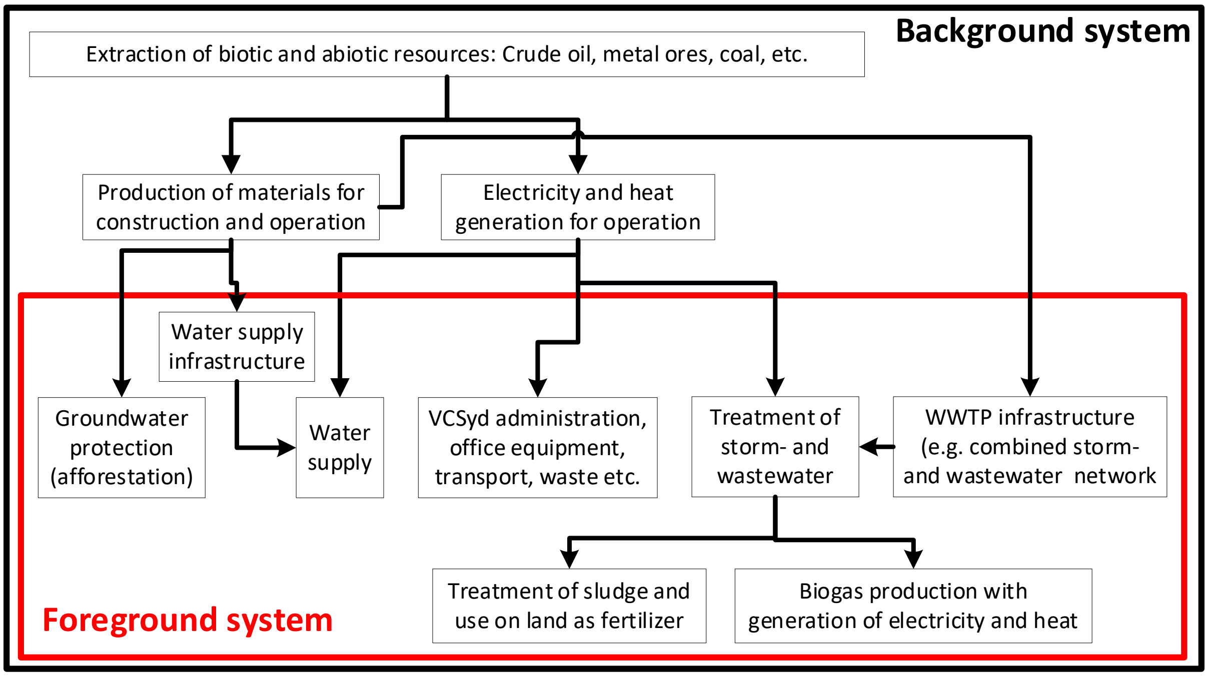

Figure 1 Overall system boundaries for the modelling of the life-cycle inventory including foreground and background system. Only top-level and aggregated processes are shown. A full overview of all unit processes used for modelling the foreground system is given in Supporting Information 2

2.2 Selection of environmental boundaries and safe operating space

In this study, the PBs were used as absolute environmental boundaries, except for the PB "introduction of novel entities" because a PB is yet to be defined. The PBs delimit a safe operating space for humanity. However, for some of the PBs a part of the safe operating space is already occupied by nature. Hence, the safe operating space for humanity should be defined as the PB minus the share that is needed by nature. For instance, the PB for Climate change as Atmospheric CO_2 concentration is defined as 350 ppm CO_2, the natural background level is defined as 278 ppm CO_2. Thus, the remaining 'safe operating space available for humanity' is 72 ppm CO_2 (see Table 1). SI 2 Table S10 provides additional information on the Planetary Boundary level, the natural background level and the safe operating space available for human activities. In this study, we have used the 'safe operating space available for humanity' as boundary rather than the 'remaining safe operating space' (i.e. the PB minus the current control variable value). This means that all activities (existing or future) can be evaluated in terms of their occupation of a share of the safe operating space for humanity. Indeed, if all activities acted within their assigned share of the safe operating, then the sum of activities would also act within the total safe operating space for humanity. Likewise, for the PBs where the boundary is currently exceeded (e.g. climate change), it is possible to reduce and maintain pressures associated with anthropogenic activities within the total safe operating space for humanity if all activities reduce their pressures to within their assigned share (assuming that previous boundary transgression has not already generated abrupt or irreversible changes to the Earth System) (Ryberg, Owsianiak, Clavreul, et al., 2018). We decided against use of the 'remaining safe operating space' as it is only suited for assessing if the introduction of a new technology (on top of the existing human activities) will lead to exceedance of the safe operating space for humanity. Hence, the 'remaining safe operating space' approach cannot be used for assessing if a technology is absolutely sustainable. At worst, this approach can discourage a transition towards an environmentally sustainable society. This is because all new (and potentially more sustainable) technologies with even a minimal net-positive CO_2 emission across its life-cycle will be considered unsustainable climate wise as these are added on top of the already unsustainable pressure on the climate, which has been caused by other existing unsustainable technologies (Ryberg, Owsianiak, Clavreul, et al., 2018).

In addition, case and location specific impact categories were included in this study for emissions of nitrogen (N) and phosphorous (P). This was done because the PBs for N and P are characterized by single global scale boundaries in metrics with little relevance for utility companies (see Section 4.2.3 for further discussion). Due to the large amount of N and P emitted from WWTPs, it was considered important to try to quantify and evaluate the importance of these emissions relative to relevant local boundaries. Thus, as a first attempt, the local boundaries related to emissions of N and P were quantified based on the critical load concept. Boundaries were found to be emission of 523 tonne nitrogen per year and 42 tonne phosphorus per year (see SI 1 Section S6 for details).

Table 1 Overview of the impact categories included in the assessment and their spatial scale ranging from global to local and the safe operating space available for human activities. See SI 2 Table S10 for additional information about the Planetary Boundary level, the natural background level and the safe operating space available for human activities. References for the characterizations model are: [1] PB-LCIA (Ryberg, Owsianiak, Richardson, & Hauschild, 2018)**; [2]** (Doka, 2016; Wolff et al., 2017)**; [3] see SI 1 Section S5.**

Impact category	**Unit**	**Spatial scale of characterization model**	**Basis for characterization model**	**Safe operating space available for human activities**
Climate change - Energy imbalance	Wm^{-2}	Global	[1]	1
Climate change as Atmospheric CO_2 concentration	ppm CO_2	Global	[1]	72
Ocean acidification	$\Omega_{aragonite}$ [mole]	Global	[1]	0.688
Stratospheric ozone depletion	Dobson units	Global	[1]	15
Biosphere integrity - BII as maximum species loss	% species lost	Global	[2]	10%
Land-system change – Global forest	% of potential forest	Global	[1]	25%
Land-system change – Boreal forest	% of potential forest	Regional	[1]	15%
Land-system change – Tropic forest	% of potential forest	Regional	[1]	15%
Land-system change – Temperate forest	% of potential forest	Regional	[1]	50%
Freshwater use - Global	km^3 consumptive water per year	Global	[1]	4000
Freshwater use – Semidry basins	Fraction of maximum annual water withdrawal [dimensionless]	Regional	[1]	1
Freshwater use – Dry basins	Fraction of maximum annual water withdrawal [dimensionless]	Regional	[1]	1
Freshwater use – Humid basins	Fraction of maximum annual water withdrawal [dimensionless]	Regional	[1]	1
Atmospheric aerosol loading	Aerosol optical depth [AOD; dimensionless]	Global	[1]	0.11
Biogeochemical flows - P	Tg P to soil per year	Global	[1]	6.2
Biogeochemical flows - N	Tg N fixated per year	Global	[1]	62
Local phosphorous boundary	Emission of Fraction of local safe operating space [dimensionless]	Local	[3]	1
Local nitrogen boundary	Fraction of critical load [dimensionless]	Local	[3]	1

2.3 Quantification of environmental impact in metrics of the boundaries

Environmental impacts associated with the FU provided by VCSyd were quantified for the impact categories listed in Table 1. For the majority of impact categories, the environmental impact potential was quantified using the Planetary Boundaries based Life-cycle impact assessment (PB-LCIA) methodology (Ryberg, Owsianiak, Richardson, et al., 2018). The PB-LCIA methodology is based on environmental steady state models. This allows for expressing how resource uses and emissions associated with annual activities of VCSyd translate into potential environmental pressures in the metrics of the PBs' control variables, i.e. as annual pressures or environmental states in a long-term (steady state) perspective (Ryberg, Owsianiak, Richardson, et al., 2018).

The PB-LCIA includes all Earth System processes in the PB-framework except for Changes in biosphere integrity and Introduction of novel entities. Thus, impacts related to Changes in biosphere integrity where included based on the method presented in Wolff et al. (2017) and based on the work by Doka (2016). Based on the PB for Change in biosphere integrity defined as maintaining a biodiversity intactness index of 90% (Steffen, Richardson, et al., 2015), Doka (2016) converted this to a relative reversible species loss from various emissions and set the boundary as 10% loss of total species. The total number of species in the method by Doka (2016) was based on the ReCiPe LCIA-methodology (=1.95 million known species; Goedkoop et al., 2013) where the damage indicator for the area of protection 'natural environment' is expressed as species·year. Thus, the boundary is defined as maximum loss of 195,000 species. For consistency, the potential number of species lost in this case study was estimated by using the damage model for the indicators 'natural environment' in the ReCiPe 2016 LCIA-methodology (Huijbregts et al., 2016).

A direct alignment between the flows in the PB-LCIA and ecoinvent is currently lacking, thus, elementary flows in the PB-LCIA were adapted to fit the LCI flows in ecoinvent (Weidema et al., 2013). A full list of the characterization factors (CFs) included in the PB-LCIA method and fitted to match the elementary flows in ecoinvent for this study is given in SI 2. Moreover, CFs related to emissions of N and P from the WWTPs were lacking in the original PB-LCIA, but were added to the method based on material flow analyses (MFAs) of the flow of P (Suh & Yee, 2011) and N (Antikainen et al., 2005). This was used to estimate the equivalent mass of P applied as fertilizer to erodible agricultural soils per mass of P emitted to water from a WWTP and the equivalent industrially and intentionally fixated mass of N per mass of N emitted to water from a WWTP (see SI 1 Section S5 for details).

2.4 Assigning a share of the safe operating space

Humans have the moral right to occupying the safe operating space for humanity as every human being has a fundamental right to an environment adequate for living a decent life (WCED, 1987). Thus, in accordance with Lippert-Rasmussen (2015), a sharing of a scarce resource, such as the safe operating space for humanity, should start with a sharing among individual human beings. In contrast, products and services that have a functional value to humans do not have a moral right to occupying the safe operating space for humanity. Instead, these have a right to occupy the safe operating space through their value and importance to humans and they should be assigned a share of the safe operating space based on this. The sharing of the safe operating space among human beings and subsequently among activities (such as products and services) can be based on various sharing principles. The selection of a sharing principle for assigning a SoSOS to the studied system has been found to have a large influence on the final result of an AESA (Ryberg, Owsianiak, Clavreul, et al., 2018).

In this study, the SoSOS was assigned to VCSyd based on the functions that VCSyd provides to its final consumers. This was done using a two-step approach as presented in Hjalsted et al. (2020). First the safe operating space available for human activities (Table 1) was assigned among all human individuals using an equal per capita approach i.e., where all human beings are assigned an equally large SoSOS. With a Danish and World population of 5,764,980 and 7,529,719,390 persons, respectively (World Bank, 2017), a total share of 0.08% was assigned to Denmark. At the Danish national scale, the assigned SoSOS was further scaled to the level of the main functions provided by VCSyd, i.e. water supply, wastewater treatment, and heat and electricity generation. This scaling was based on Danish citizens' consumption of the functions provided by VCSyd relative to their consumption of functions provided by other activities. The rationale for this sharing principle is that personal consumption can be considered as an indicator of human needs, i.e. the functions we spend the most on are also the ones we need the most (see Section 4.2.4 for further discussion of this rationale). Data on personal consumption was based on household final consumption expenditure data. Household final consumption expenditure data provide information on the total spending by household units (i.e. consumers) on goods or services that are used for the direct satisfaction of individual needs or wants (Eurostat, 1995). Household final consumption expenditure is part of the annual national accounts for Denmark (Statistics Denmark, 2019) and provide a robust and comprehensive overview of the consumption patterns of Danish citizens. In total, 0.07% of Danish citizens' spending could be assigned to VCSyd. Thus, the SoSOS assigned to VCSyd was estimated by multiplying the share of the global safe operating space assigned to Denmark (i.e. 0.08%) with the share of the Danish share assigned to VCSyd (i.e. 0.07%) giving a total assigned SoSOS of 5.42×10^{-7} (calculation details are provided in SI 1 Section S7.1). VCSyd also provide wastewater sludge, which is used as fertilizer on agricultural fields. This function was not included as part of assigning a SoSOS to VCSyd because of a lack of data and method for quantifying how big a share of the SoSOS assigned to food and other crop consumption that should be assigned to fertilizer use. Indeed, how to quantify and assign a SoSOS to intermediary products that are part of the upstream supply chain for producing the products and services for final consumption should be further investigated. We acknowledge that this omission will lead to an underestimation of the SoSOS assigned to VCSyd. However, we consider this underestimation to be negligible because fertilizer production constitute a very small part of the functions provided by VCSyd. The sharing of the safe operating space within the local N and P boundaries specific to the catchment area near VCSyd were assigned similar to the selected sharing principle presented above. Because the boundary is already defined at the scale of the assessed activity, there was no need for an initial downscaling to the level of the country. Instead, the assigned SoSOS was only based on citizens' consumption. In total, the resulting assigned share of the local safe operating space for N and P emissions to VCSyd was 1.6% (specific details are provided in SI 1 Section S7.2).

3 Results

The results of the AESA are shown in Figure 2 and Figure 3. Figure 2 shows the ESR for the different impact categories included in the AESA (see SI 2 Table S11 for the absolute values). Overall, results show that VCSyd exceed its assigned SoSOS for 10 out of 18 impact categories. Thus, a more specific analysis of the exceeded impact categories is given in the following. To support such analysis, Figure 3 shows the contribution of different processes and stages in the life-cycle to the impact categories included in the AESA.

For the climate and carbon related impact categories (i.e. Energy imbalance, CO_2 concentration, and Ocean acidification), VCSyd exceeds the assigned SoSOS by up to a factor 7.8 (Figure 2). This is primarily due to electricity use during wastewater treatment and water supply, direct emissions of greenhouse gases (GHGs) from sewers and WWTPs, and materials used for construction activities, such as annual maintenance and construction of sewage network. For Freshwater use, as withdrawal at basin level, the assigned SoSOS is exceeded by a factor 2.2 for both dry and humid freshwater basins. For dry basins, the exceedance mainly comes from water use in upstream processes outside Denmark for production of materials used as part of the construction of buildings and infrastructure used by VCSyd. For humid basins, the exceedance is due to withdrawal of freshwater for water supply for VCSyd's customers. The largest exceedance of the assigned SoSOS is observed for the biogeochemical flows for P and N which exceed the assigned SoSOS by a factor 246 and 339, respectively. The local boundaries for P and N are also exceeded, but only by a factor 16.6 and 16.1, respectively. The exceedance of the SoSOS for the P and N boundaries is due to the emissions of N and P from the WWTP, losses due to overflow of WWTP and sewers, and runoff of wastewater sludge used on fields. The impact category Changes in biosphere integrity is exceeded by a factor 1.5 which is mainly due to withdrawal of freshwater for water supply and due to emissions of methane from the sewer network.

The error bars in Figure 2 indicate the 95% confidence interval (see Table S11 for background values) and it only crosses 1 on the y-axis for Atmospheric aerosol depletion and Changes in biosphere integrity. This indicates that conclusions about sustainability or unsustainability are robust in relation to the uncertainty of the LCI except for these two impact categories where it cannot be said with 95% certainty whether VCSyd can be considered absolutely sustainable (or unsustainable). In general, however, Atmospheric ozone depletion is most likely to be absolutely sustainable as the majority of the 95% confidence interval is below the assigned SoSOS while Changes in biosphere integrity appears most likely to exceed the assigned SoSOS and, thus be unsustainable, because the majority of the 95% confidence interval is exceeding the assigned SoSOS.

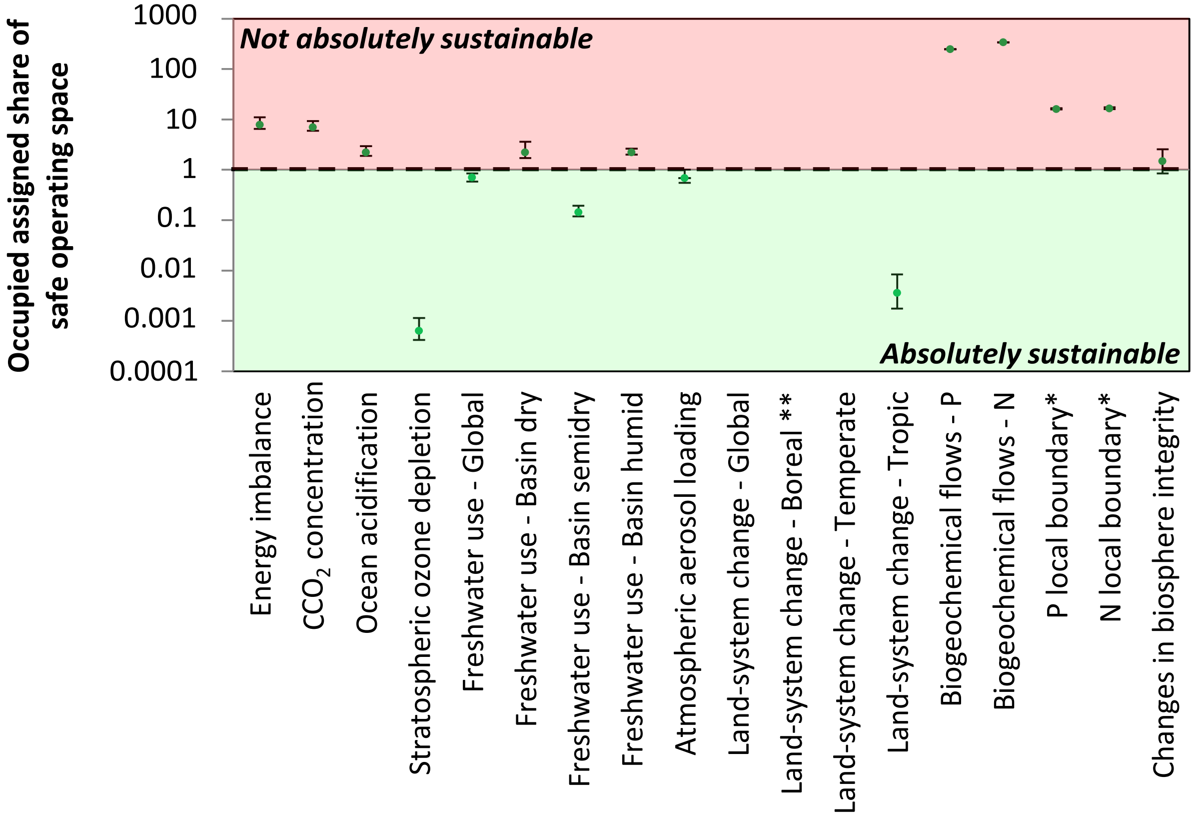

Figure 2 VandCenter Syd's occupation of assigned share of the safe operating space (SoSOS) for all impact categories. Impact scores above 1 indicate exceedance of the assigned SoSOS. Error bars indicate the 95%-confidence interval for the life-cycle inventory. The impact categories, Land-system change – Global and Land-system change – Temperate resulted in negative impact scores which cannot be depicted on a logarithmic scale. * Assignment of safe operating space differs from default assignment approach used for remaining impact categories, please refer to Section 2.4 for details. ** Impact scores for Land-system change – Boreal were zero and are not shown in figure. See SI 2 for underlying data.

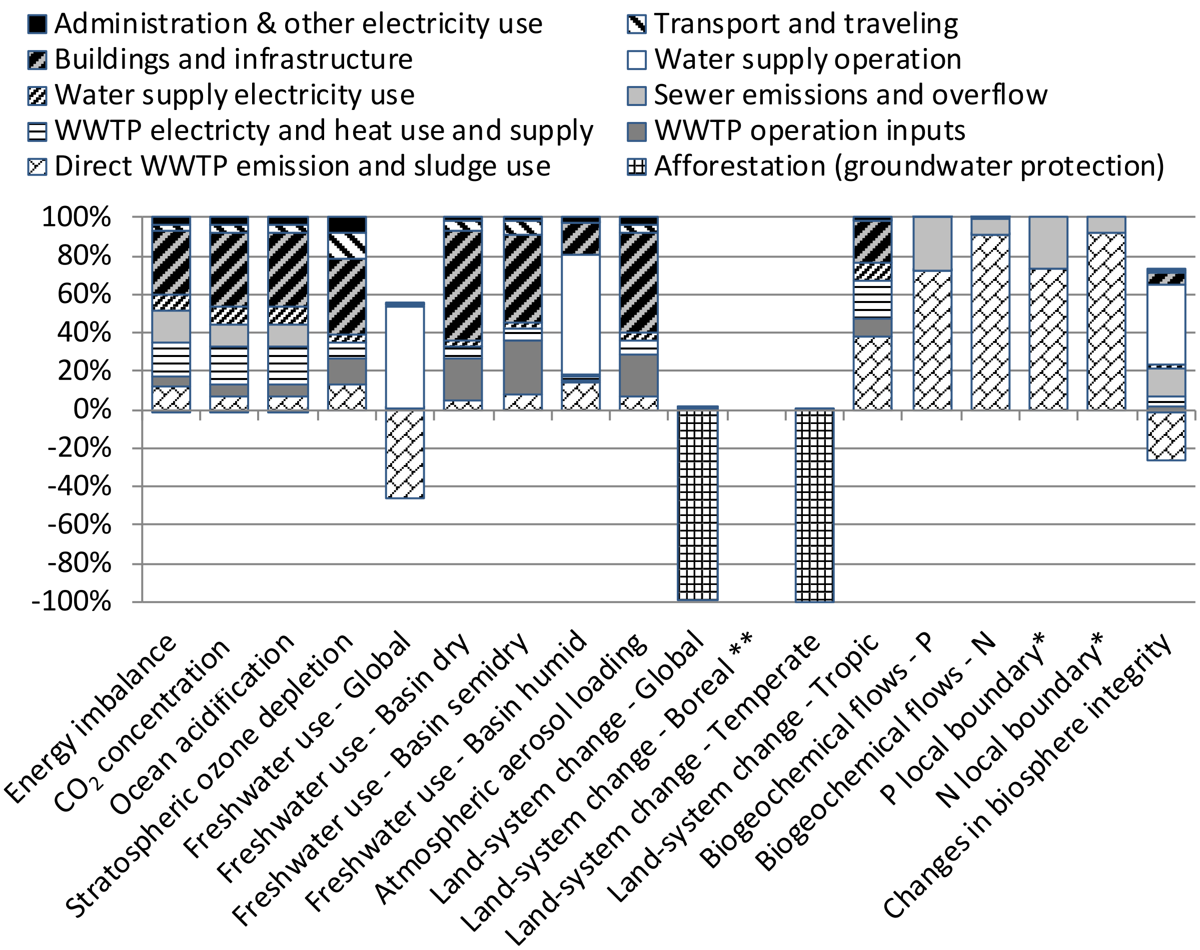

Figure 3 Contribution to total impact score for main activities of VandCenter Syd. * Assignment of safe operating space differs from default assignment approach used for remaining impact categories, please refer to Section 2.4 for details. ** impact scores for Land-system change – Boreal were zero and are not shown in figure. See SI 2 for underlying data.

4 Discussion

4.1 Recommendations for reducing environmental impacts

The results indicate that focus should be on reducing pressure on the impact categories for which the assigned SoSOS is exceeded. Reductions of GHGs contributing to climate change and N and P emissions are, in particular, needed as these are where the largest exceedances of the SoSOS are observed. Here, it should be noted that the functions provided by a utility company, such as VCSyd, i.e. supply of water and treatment of the wastewater are essential for a society to function. Thus, simply stopping the operation of VCSyd and its associated functions is not a viable option for reducing environmental pressures. Indeed, the environmental consequences of doing so would likely be much worse, e.g. due to the direct emissions of wastewater to aquatic environments. Thus, it is recommended that options for reducing the environmental pressures associated with VCSyd should primarily be technologically driven in terms of reducing emissions per function provided.

It was found that about 30% of impacts on Climate change – Energy imbalance stem from emissions from the sewer and from the WWTP and almost 100% of impacts related to N and P impact categories stem from emissions from sewer and WWTP overflow, WWTP effluent, and runoff of wastewater sludge applied on agricultural fields (Figure 3). These emissions are a function of the composition of the wastewater (i.e. the C, N and P content of the wastewater) and to a lesser extent a result of the activities needed for VCSyd to function. Thus, it can be argued that the activities that are responsible for the specific wastewater composition should also be accountable for the emission of substances in the wastewater, and that this should not be accounted for in an AESA of a utility company. In fact, about 80% of both P (Chen & Graedel, 2016) and N (Leach et al., 2012) is used as part of food production (e.g. used for food and feed additives or as chemical fertilizers). Accordingly, the majority of N and P in wastewater stem from humans (Tjandraatmadja, Pollard, Sheedy, & Gozukara, 2010) and are functions of N and P in the foods taken in. This is similar for the C content in the wastewater. Indeed, the resulting composition of the wastewater is mainly a result of food consumption by VCSyd's customers and unless the citizens change their habits and consume less food, it is unlikely that the amount and composition of wastewater will change substantially. However, VCSyd has the largest potential for taking measures to reduce these emissions as they6 occur while being managed by VCSyd,. Hence, it was considered relevant to include the pressures related to these emissions as part of the AESA because the wastewater treatment is the activity that can most effectively affect the magnitude of emissions of C, N, and P in the wastewater to the environment. Thus, although VCSyd cannot directly influence the amount and composition of the wastewater, they have the potential for implementing measures to improving the treatment and to remove environmentally harmful substances.

For GHG emissions from the wastewater in the sewers and WWTPs, VCSyd has already taking measures for reducing direct emissions. For instance, biogas used for generation of electricity and heat is being produced at one of the WWTPs. Hereby, N and C in the wastewater is recovered and used for energy generation instead of being directly emitted to the environment. Indeed, increased production of biogas at the rest of VCSyd's WWTPs, or other uses of the C resource available in the wastewater, should be further investigated and could draw on ongoing research into recovery and use of carbon in wastewater (see e.g. Puyol et al., 2017). Reductions of the GHGs from the sewer system should also be sought. The potential climate problem related to methane emissions from domestic sewage has been known for about 30 years (Guisasola, de Haas, Keller, & Yuan, 2008; Minami & Takata, 1997). However, the relatively substantial contribution to total GHGs emissions from the sewer system is a recent finding (Risch et al., 2015).

For N and P emissions, the majority of emissions stem from the treated wastewater and options for capturing a higher share of N and P in the wastewater should be sought. Research measures for doing so is ongoing Desmidt et al., 2015; Egle, Rechberger, Krampe, & Zessner, 2016; Lin, Guo, Shah, & Stuckey, 2016; Sengupta, Nawaz, & Beaudry, 2015; van der Hoek, Duijff, & Reinstra, 2018). This is not only important for reducing N and P emissions, but also for recovering and reusing the nutrients. In particular, P which is a scarce resource and closing the P cycle should be prioritized (Desmidt et al., 2015; Scholz, Ulrich, Eilittä, & Roy, 2013). However, measures for reducing emissions of GHGs and N and P should not be undertaken without evaluating their effect on the other impact categories. This is important to avoid unintentional burden shifting where measures for reducing one impact category to be within the assigned SoSOS leads to a breach of the assigned SoSOS for other impact categories.

Figure 3 indicates that electricity use accounts for about 30% of total impacts on climate change related impact categories. Thus, electricity use must be reduced and any net consumption of electricity should be generated from low carbon emitting technologies. The construction of buildings and infrastructure was found to account for about 35% of VCSyd's total impacts on climate change. The majority of GHG emissions from the construction of buildings and infrastructure is related to production of concrete, mainly originating in production of cement used for producing concrete. Cement has a large CO_2 footprint because of the high energy requirements for producing cement and due to release of CO_2 during calcination of limestone (Benhelal, Zahedi, Shamsaei, & Bahadori, 2013). Thus, options for reducing GHG emissions related concrete could be investigated. For instance, use of concrete using substitute cementitious material and where the added cements is produced using energy with a lower carbon footprint such as biomass or biogas. Lastly, impacts associated with construction could be reduced by using alternative designs. For instance, stormwater management (SMW) systems based on green infrastructure have been shown to have a lower environmental impact compared to conventional sub-surface SMW systems that are predominantly based on concrete (Brudler et al., 2016).

Impacts on freshwater use and biosphere integrity were also found to exceed the assigned SoSOS (Figure 2). For freshwater use in dry and semi-dry areas, the impact mainly stem from upstream production of construction materials (Figure 3). Thus, similar to reducing GHG emissions related to concrete, it is recommended to investigate the use of less water intensive technologies or sourcing of materials from areas where freshwater is abundant. Moreover, a general reduction in the use of construction materials through improved construction design and/or practice should also be sought. For biosphere integrity, the majority of impacts come from the withdrawal of water for water supply. This cannot be reduced as there is a demand and need for this water. Emissions of mainly methane from the sewers were found to be the second largest contributor to impact on biosphere integrity due to its contribution to climate change. Here, technological means for reducing methane formation in sewers should be investigated. Here, it is important to consider potential tradeoffs or synergies between e.g. biosphere integrity and climate change. For instance, a removal of methane emissions from sewage is both beneficial to the biosphere and the climate. On the other hand, the reduction of methane from sever should not be counteracted by an increased fossil energy use for powering the methane emission reduction. Indeed, it is important to consider the full system and potential tradeoffs among impact categories to avoid sub-optimization or burden shifting. While the results of the AESA indicate that VCSyd cannot be considered absolutely sustainable across all impact categories, the AESA indicates the magnitude of reductions required for VCSyd to become sustainable in an absolute sense. For instance, based on the AESA, VCSyd know that a reduction of about a factor 8 is required to be sustainable climate wise. This is important information for VCSyd, in terms of setting sufficiently ambitious future reduction targets as part of their strategic planning and to avoid burden shifting.

4.2 Recommendations for AESA practitioners

4.2.1 Setting the system boundaries

The result of the assessment show that a number of commonly overlooked processes are actually important contributors to total environmental impacts. It is important to include these as part of the system boundaries to get a complete overview of the environmental impacts associated with the activities performed by VCSyd. The environmental impacts related to construction of buildings and infrastructure are commonly excluded in

LCA of wastewater treatment systems due to the perception that these do not contribute substantially to environmental impacts (Corominas et al., 2013). However, studies which included construction actually found that these processes were relevant to include due to their contribution to some impact categories (Corominas et al., 2013). This study corroborates this as construction related processes were found to account for about one third of the impacts related to climate change and about 50% of impact related to freshwater use via withdrawal from dry and semidry water basins. Similarly, emissions of methane and nitrous oxide (N_2O) from the sewer network were found to contribute 16% of impacts on Climate change – Energy imbalance, which highlight the importance of including this process in an assessment that, among other, assess storm- and wastewater management.

4.2.2 Dealing with multifunctional processes

As done in this study, we recommend that multifunctional processes that are part of the assessed life-cycle, but not covered by the FU are handled by expanding the system boundaries to include the additional functions. This expansion of the AESA's system boundaries should, hereafter, be accounted for in the assigned SoSOS by expanding the scope of the SoSOS to include the additional functions. For instance, VCSyd have three main functions: water supply, wastewater treatment, and electricity and heat generation, which are also reflected in the assigned SoSOS. Thus, a system with several functions will have a similarly large assigned SoSOS because each function must be assigned a SoSOS based on its value to humans. This approach for solving process multi-functionality in LCA-based AESAs is beneficial as it avoids the need for uncertain and often debated assumptions (e.g. system expansion with avoided production or process allocation) that are commonly used in LCA (ISO, 2006b). Avoidance of 'avoided production' methods is beneficial because by introducing avoided production, the AESA becomes relative to the avoided production, thus, switching the assessment from absolute to relative. Process allocation allows for partitioning environmental impacts associated with the multifunctional process among the different functions provided by the process. Allocation of impacts is based on an allocation factor that can be based on either physical or monetary relationships (e.g. economic value, mass, volume, energy content) (ISO, 2006b). Hereby, only impacts allocated to the assessed function are considered in the AESA. However, allocation is also subject to controversy in LCA as the allocation of impacts among functions depends on the value-based choice about which allocation factor to use. This introduces additional uncertainty to the AESA result and can introduce a bias in the AESA (Curran, 2007; Huijbregts, 1998). Thus, avoidance of allocation is beneficial as we avoid introducing uncertainty from the choice of the allocation key. However, currently such approach is likely only possible for the foreground system as approaches for solving multi-functionality is often predefined in existing background LCI databases, such as ecoinvent, using either allocation or system-expansion with avoided production. System expansion of the background system is currently not feasible in AESA because it also requires system expansion of the assigned SoSOS. Methods for aligning the included system processes, through system expansion, and the assigned SoSOS in the background system are currently lacking. Thus, for practical reasons, we currently recommend using process allocation to deal with multifunctional processes in the background system.

4.2.3 Defining environmental boundaries and indicators

The PB framework defines a set of global boundaries for pressures on the Earth System. However, with the update in 2015 (Steffen, Richardson, et al., 2015), the PB framework also includes local to regional scale boundaries (i.e. freshwater use, land-system change, and atmospheric aerosol loading). Thus, indicating the relevance of regional boundaries.

However, the PBs for N and P are still being characterized by global scale boundaries which do not account for the potentially large variability in the response of N and P receiving aquatic ecosystems to N and P loadings

(Carpenter & Bennett, 2011; Carpenter, Stanley, & Vander Zanden, 2011). Moreover, the biogeochemical flow indicators in Steffen et al. (2015b) consider P applied as fertilizer on erodible soil and industrial and intentional biological fixation of N. This highlights a limitation of these current PB indicators for biogeochemical flows. The indicators are relevant for political actions (e.g. monitoring and setting targets) for reducing fixation of N and use of P fertilizers. However, the indicators have little relevance for other industries and sectors, which are also important contributors to emissions of N and P e.g., emissions from WWTPs.

Indeed, to express the impact of VCSyd in the indicators of the PB-framework, an equivalent value of P applied as fertilizers on erodible soil and industrial and intentional biological fixation of N had to be estimated based on the quantified masses of P and N emissions to the environment. The meaningfulness of such estimate is questionable. First, the environmental issue is not the application of P or fixation of N, but the emission of N and P to the environment. Second, the calculation of equivalent P application and N fixation is problematic because it creates less incentive for improving the N and P removal efficiency of the WWTP. This is because although the direct emissions are reduced when efficiency is increased, the equivalent P application and N fixation will remain unchanged as the same amount of P application and N fixation is still needed e.g., for producing food for human consumption.

Hence, we provided an example on how to assess the impacts of N and P emissions at a relevant scale. We developed two new impact category indicators to express the potential local effects from the direct N and P emissions from VCSyd's WWTPs and from runoff of wastewater sludge applied to agricultural soil (see Section 2.2). These indicators were based on the critical load concept and were developed specifically for a Danish context (SI 1 Section S5) to express the regional safe operating space that is affected by the direct N and P emissions. Results using the new indicators showed that VCSyd exceeded its assigned SoSOS by a factor 16.6 and 16.1 for P and N, respectively. This is in contrast to the exceedance by a factor 246 and 339 for P and N, respectively, using the indicators based on the PB-framework. The difference between impact scores can be attributed to the calculation of the equivalent P application and N fixation where the need for modelling of the flow of N and P from emission to the environment and back to P application and N fixation introduces large uncertainties to the result. Therefore, we recommend revising the current PB indicators for N and P to focus on emissions of N and P to the environment and investigate the development of global spatially differentiated models for N and P to quantify local and regional impacts. Indeed, such development has already been initiated (Li, Wiedmann, & Hadjikakou, 2019).

4.2.4 Assigning the safe operating space

As stated in Section 2.4, the selection of a sharing principle for assigning a SoSOS to the studied system has been found to have a large influence on the final result. This has been quantitatively showed in a number of studies (e.g. Lucas, Wilting, Hof, & van Vuuren, 2020; Ryberg, Owsianiak, Clavreul, et al., 2018; Sandin, Peters, & Svanström, 2015) and has also been studied on a more theoretical level, for instance as part of distributional justice theory in relation to climate change (e.g. Caney, 2017; Grasso, 2012; Häyhä, Lucas, van Vuuren, Cornell, & Hoff, 2016; Ryberg, Owsianiak, Richardson, & Hauschild, 2016; Vanderheiden, 2009). Indeed, we fully agree that this choice is important and as stressed in e.g. Ryberg et al. (2018a) it is important to be transparent about the choice of sharing principle. In this study, we selected a single sharing principle i.e. based on an equal per capita sharing among individuals and further sharing among companies based on their value to individual human beings as expressed by their consumption of the companies' products (see Section 2.4 for the methodological details). The assumption about proportionality between consumption of goods and services and value to the consumer is not fully valid as our current consumption is not constrained by environmental limits. Thus, current consumption patterns do not fully capture our consumption patterns if it was constrained by environmental boundaries. In fact, it is likely that the relative consumption share of "necessity goods" such as food, water, and housing would increase while the share spent on luxury goods (e.g. the newest phones and sports cars) would decrease. However, data on personal consumption in an economy constrained by environmental limits are not available. Hence, we had to rely on the available household final consumption expenditure data as an adequate proxy.

The selection of the sharing principle used in this study was based on a discussion among the study' authors and stakeholders from VCSyd. We evaluated different sharing principles and selected the one used in this study because it aligned with the values of the company. Moreover, it was considered to best reflect a "fair" assignment of the safe operating space and judged not to introduce a potential bias in the results towards VCSyd. However, the choice of a single sharing principle means that the results and findings about absolute sustainability are, in principle, only relevant for users that agree with the applied sharing principle. The results are less relevant to users with other values, which would entail use of a different sharing principle. In such case, the users would have to derive a new assigned SoSOS based on a sharing principle that aligns with their values and use this for re-calculating final results about absolute sustainability.

5 Conclusion

An AESA was conducted to evaluate if the Danish utility company VCSyd could be considered absolutely sustainable relative to an assigned SoSOS. This study showcased a consistent methodological approach for conducting an AESA, i.e. how to define and model the LCI, quantify environmental impacts and assign a SoSOS to the studied system using an equal per capita approach for downscaling to individual human beings and household final consumption expenditure for subsequent upscaling to company scale. It was found that VCSyd cannot be considered fully sustainable in an absolute sense and priority should be given to reduce impacts related to climate change and nutrient emissions to water. Although, VCSyd cannot be considered absolutely sustainable, the AESA allows for identifying the environmental impact categories where reductions are needed and for deriving specific reduction targets for VCSyd to become absolutely sustainable. This information is important for guiding future environmental strategies in order for VCSyd to become absolutely sustainable and can also be applied as guideline for other utility companies to improve their environmental sustainability performance.

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Supporting Information

Supporting Information 1 provide specific details on the life-cycle inventory modelling of the case study as well as additional methods and results for this study.

Supporting Information 2 provides a complete overview of the life cycle inventory for modelling the case study and all unit processes developed as part of this study. Characterization factors used to quantify environmental impacts in metrics of the Planetary Boundaries are provided. Supplementary large tables and data for Figure 2 and 3 are also provided.

Figure Legends

Figure 1 Overall system boundaries for the modelling of the life-cycle inventory including foreground and background system. Only top-level and aggregated processes are shown. A full overview of all unit processes used for modelling the foreground system is located in Supporting Information 2

Figure 2 VandCenter Syd's occupation of assigned share of safe operating space (SoSOS) for all impact categories. Impact scores above 1 indicate exceedance of the assigned SoSOS. Error bars indicate the 95%-confidence interval for the life-cycle inventory. The impact categories, Land-system change – Global and Land-system change – Temperate resulted in negative impact scores which cannot be depicted on a logarithmic scale. * Assignment of safe operating space differs from default assignment approach used for remaining impact categories, please refer to Section 2.4 for details. ** Impact scores for Land-system change – Boreal were zero and are not shown in figure. See SI 2 for underlying data.

Figure 3 Contribution to total impact score for main activities of VandCenter Syd. * Assignment of safe operating space differs from default assignment approach used for remaining impact categories, please refer to Section 2.4 for details. ** impact scores for Land-system change – Boreal were zero and are not shown in figure. See SI 2 for underlying data.