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A Planetary Boundary for Mineral, Metal, and Fossil Resource Extraction Rates: How Much Primary Materials Can a Circular Economy Extract?

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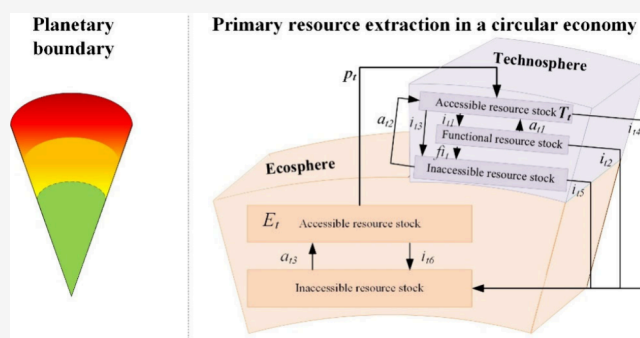
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ABSTRACT: Resource consumption is expected to further increase in the next decades. A circular economy could decrease the environmental impact of this resource consumption by minimizing the primary raw materials consumption and minimizing emissions that render materials inaccessible for further use. However, such a circular economy will still have primary raw material inflows, due to population growth, stock expansion, energy transition, and inevitable dissipation. The potential magnitude of such primary raw material inflows in a circular economy remains unclear. To address this uncertainty, the planetary boundary framework, which defines absolute limits on resource and emission flows, could be utilized. Although this framework incorporates aspects of biomass, water, and land use, mineral, metal, and fossil resources are not included. This study provides a principle for a planetary boundary for these three resources, based on the net accessibility rate and an allocated share of the accessible resource stock in the ecosphere. Inter- and intragenerational equality are crucial for determining this allocated share and for quantifying a sustainable rate of resource extraction in (an economy transitioning toward) a circular economy. Next steps to operationalize this principle provide further guidance to determine the safe operating space for mineral, metal, and fossil resource extraction.

KEYWORDS: Natural resource management, material footprint, abiotic resources, circular economy, planetary boundaries, sustainability targets, material flows, critical raw materials



1. INTRODUCTION

In 2019, per capita primary resource consumption equaled 12 tonnes per year.¹ By 2060, this number is expected to increase to 16.7 tonnes per capita per year.² This resource consumption entails numerous environmental impacts due to natural resource extraction and emissions, including waste and losses. For example, half of global greenhouse gas (GHG) emissions and over 90% of biodiversity loss and water stress can be attributed to resource extraction and processing.³

The planetary boundary (PB) framework provides absolute limits for some of these flows to keep the environmental impact within its safe operating space (SoS).⁴ To maintain the stability and resilience of the Earth system, seven emission-related PBs (climate change, overloading with novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, modification of biogeochemical flows and change in biosphere integrity), and three resource-related PBs (freshwater change, biosphere integrity change and land-system change), have been defined. While the resource-related PBs encompass land, water and biomass, other material resources have been excluded so far.

The (over)exploitation of metals, minerals and fossil resources does not impact the Earth system's stability and resilience in the same way as phenomena like climate change. Metals, minerals and fossil resources are not renewable but also not degradable on a human time scale and unlike fossil fuels, metals and minerals are only relatively depletable.⁵ According to the current PB framework in a *sensu stricto* interpretation (see Table of terminologies in the [Supporting Information](#)), these resources are limited only by their lifecycle processes' influence on other PBs.

In 2023, an extended PB framework included the concept of "safe and just" Earth system boundaries,^{6,7} emphasizing the Earth system's ability to support human life and other living organisms. Also in 2023, an update of the PBs was published,

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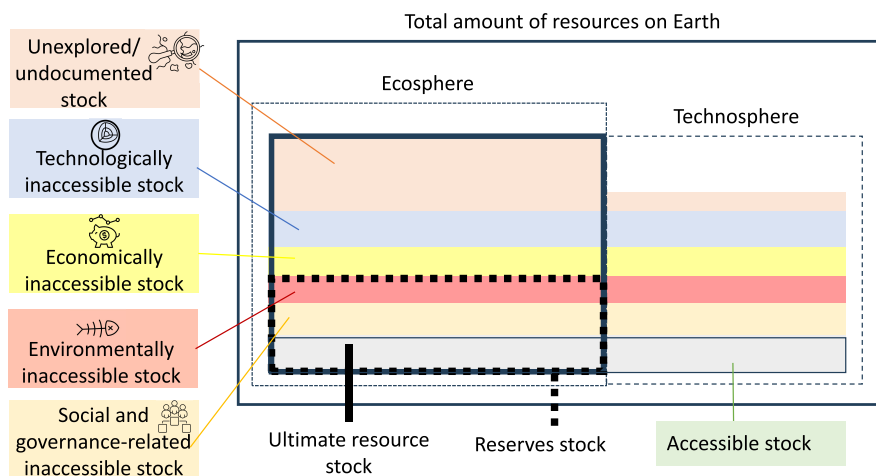


Figure 1. Different types of (in)accessible stocks (the separate categories of inaccessible stock are a simplified visualization; in reality, a stock can be inaccessible because of multiple reasons).

mentioning besides Earth system's stability, also its life-support systems conducive to human welfare.⁸ Both of these PB concepts add human welfare (i.e., "its ability to support humans") to the equation, extending the original PB framework beyond purely biophysical resilience and stability. This extension can be considered as a *sensu lato* interpretation. To ensure such human welfare, essential services like shelter and mobility require a functioning technosphere, which depend on natural resources beyond carbon, water and nutrients.^{9–11} Velez-Henao and Pauliuk (2023) estimated a minimum demand of 6 tonnes·capita⁻¹·year⁻¹ of primary resources to maintain basic human wellbeing, a figure that also includes metals, minerals and fossil resources (at least in the current society).¹² These material resources can become inaccessible for an undefined period, for example through dissipation as emissions. If resource extraction exceeds a certain safe operating level, the accessible supply might be insufficient to meet future demand, threatening human welfare. According to the *sensu lato* interpretation of the PB framework, this would entail transgressing a PB SoS. As natural abiotic resources such as minerals, metals and fossil resources have not been included in the existing PB framework, this study focuses on addressing this gap.

2. EXISTING STRATEGIES TO COMPILER A SAFE OPERATING SPACE FOR RESOURCE EXTRACTION

Although a PB for abiotic resource extraction has not yet been included, multiple efforts have pursued four general strategies.

The first strategy estimates existing natural resource reserves as a SoS and relates it to annual extraction. For instance, based on the 1999 zinc reserve base of 430 Mtonnes, a constant yearly primary zinc extraction rate limit of 8.6 Mtonnes·year⁻¹ for the next 50 years was calculated. Recalculating this limit every few years was recommended, keeping the 50-years depletion horizon that allows for resource substitution or the development of alternatives.¹³

The second strategy determines a SoS based on a safe historical primary resource extraction rate. Following this strategy, a target of 6–8 tonnes·capita⁻¹·year⁻¹ by 2050 for the Sustainable Development Goal on equitable resource use was proposed.^{14,15} This target was based on two primary resource extraction estimations for 2050, where the primary resource extraction was frozen at the 2000 level either per year (50

Gtonnes·year⁻¹ resulting in 6 tonnes·capita⁻¹·year⁻¹) or per capita per year (8 tonnes·capita⁻¹·year⁻¹). Bringezu (2015) used this same strategy to define a target range for total material consumption in 2050, ranging between the 2000 level and half of this value.¹⁶ Why the material resource consumption of 2000 is considered sustainable, remains unclear.

The third strategy defines its SoS based on other PBs. For example, a SoS for Germany's crude oil extraction was set based on the global SoS for climate change using a two-step process. First, Germany's share of the climate change SoS was calculated by considering its population size relative to the world's population size (equal per capita principle). Then, the share of GHG emissions from Germany's crude oil extraction was compared to the total GHG emissions of the country. This share determined how much of Germany's SoS should be allocated to crude oil extraction (grandfathering principle). As a result, a SoS of 57 to 405 Mtonnes of crude oil can still be extracted by Germany.¹⁷ Desing, Braun and Hischier¹⁸ proposed a similar approach for multiple metals, finding primary raw material budgets (kg resource use per year) 40 times smaller than 2016 production volumes, using the grandfathering principle. Raw material budgets for zinc, copper and aluminum, were set at 0.21, 0.43, and 1.06 Mtonnes·year⁻¹, respectively.

The fourth strategy envisions a sustainable production and consumption system based on scenario analysis within existing PBs, defining the corresponding natural resource extraction rate as the SoS. A scenario analysis to remain within the climate change SoS, resulted in a 8 tonnes·capita⁻¹·year⁻¹ natural resource extraction rate.^{19,20} Specific SoSs for copper and aluminum were calculated similarly, resulting in a SoS of 56.8 Mtonnes·year⁻¹ for copper (biodiversity as limiting boundary) and 43.6 Mtonnes·year⁻¹ for aluminum (CO₂ emissions as limiting boundary).²¹ The "Factor 10 Club" also used this strategy, advocating for a 10-fold reduction of natural resources per capita by OECD countries to avoid systematic degradation of the biosphere.²²

Of these four strategies, only the first directly develops a PB for natural resource extraction itself, extending beyond the impact of resource use on other existing PBs. This strategy focuses on depletion, a traditional focus within life cycle assessment.²³ However, this approach has been criticized since

known economic reserves have actually grown over time due to, e.g., exploration and technological development, indicating no increase in scarcity.²⁴ If unlimited exploration and development, in addition to unlimited energy,²⁵ were considered, the ultimate limit on primary raw materials availability would be the total amount of natural resources available in the ecosphere.” This ultimate reserve is for most natural resources sufficiently large to cover material needs for a long time.²⁶ Globally, natural resources cannot be depleted, unless they are lost into space or subject to radioactive transformations. They can, however, become inaccessible for future use due to the dilution by air, water and soil emissions.²⁷ Thus, resources need to be both available and accessible.²⁸ As the current strategies for defining a PB on natural abiotic resource extraction fail to take this accessibility in account, a new strategy is proposed.

3. ACCESSIBILITY

Accessibility is defined as “the ability to make use of a resource”.²⁸ It applies both to the ecosphere’s resource stock and the technosphere’s resource stock (exploited through recycling or urban mining as discussed in the secondary resource framework of Maung, Lwin and Hashimoto (2019)²⁹). Factors limiting resource accessibility include technological, economic, environmental, and social and governance-related constraints (Figure 1). Technological inaccessibility is caused by the technical infeasibility of extraction or unexplored reserves in ecosphere or undocumented stocks in technosphere. Economic inaccessibility can be caused by unfeasible extraction due to high costs and depends on fluctuating commodity prices, affecting returns on investment (related to the work of Hotelling³⁰). Technological and economic accessible resources in the ecosphere, termed the reserve base, typically define maximum extraction limits due to resource scarcity.²⁷ These accessibility types are also included in classical resource availability schemes, such as the McKelvey diagram.³¹ Environmental constraints, such as the potential marine ecosystem damage to deep sea mining or crude oil’s climate change impacts further restrict accessibility.³² The remaining climate change SoS does not allow for the GHG emissions from all extracted crude oil reserves on a global scale, rendering this natural resource environmentally inaccessible.³³ As a last factor, social and governance-related inaccessibility can be caused by social and political factors, such as social unrest influencing silver extraction rates in Central and South America.³⁴

Figure 2 visualizes the accessible and inaccessible resource stocks and flows, distinguishing between the technosphere and the ecosphere. For the technosphere’s system boundaries, the framework of Dewulf, Hellweg, Pfister, Godoy León, Sonderegger, de Matos, Blengini and Mathieux (2021)³⁵ was followed. Natural resources flow from the accessible stock in the ecosphere to the technosphere to become consumer products or capital investments (p_t). In the technosphere, consumer products and capital investments are produced from the accessible resource stock and enter the functional resource stock (i_{t1}). At their end-of-life, these products leave the functional stock for the accessible (e.g., repairable products; (a_{t1})) or inaccessible resource stock (e.g., landfilled products; (f_{t1})) in the technosphere or leave the technosphere as emissions (e.g., burning fossil fuels; (i_{t2})). Following the framework of Dewulf, Hellweg, Pfister, Godoy León Godoy, Sonderegger, de Matos, Blengini and Mathieux,³⁵ five

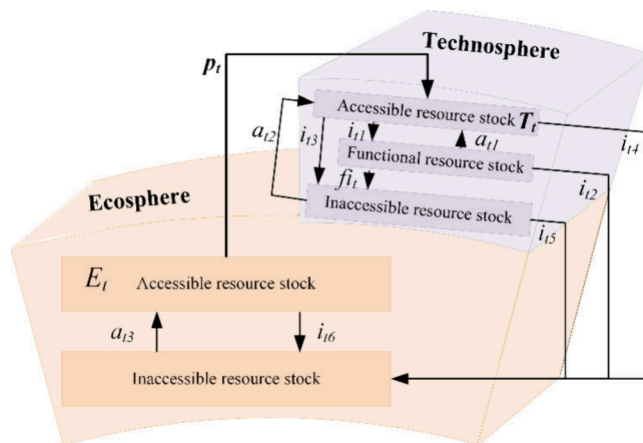


Figure 2. Schematic overview of the accessibility of natural resource flows and stock (with p_t being the primary natural resource extraction rate in the technosphere in year t , $a_t - i_t$ being the amount of natural resources becoming accessible minus the amount of natural resources becoming inaccessible (a_t and i_t represent a net sum and can therefore be negative), E_t being the accessible resource stock in the ecosphere, and T_t being the accessible resource stock in the technosphere).

inaccessible stocks were identified in the technosphere: hoarded stocks, tailings, landfills, abandoned stocks and dispersed stocks. Within the technosphere, resources flow from the accessible to the inaccessible resource stock (e.g., production waste; (i_{t3})) or vice versa (e.g., enhanced landfill mining; (a_{t2})) or to the inaccessible resources stock in the ecosphere (e.g., production process emissions or landfill leaks to the environment; (i_{t4} and i_{t5})). In the ecosphere, the inaccessible resource stock can become accessible (a_{t3}), e.g. by exploration. Another example would be the chemical uptake or deposition of emissions; however, for fossil resources, this process will not occur on a human time scale. Conversely, the accessible resource stock can become inaccessible, due to price shocks or environmental constraints (i_{t6}). The net accessibility rate is the sum of inaccessible resource flows becoming accessible (a_t) minus the sum of accessible resource flows becoming inaccessible (i_t).

As technological, economic, environmental and social and governance-related constraints on accessibility depend on specific times and production and consumption systems, the accessibility of the resource stock changes over time.

4. TOWARD A PLANETARY BOUNDARY FOR MINERAL, METAL AND FOSSIL RESOURCE EXTRACTION RATES

To build up the principle, a differentiation is made between three types of (circular) economies: a fully circular economy, a maximal circular economy and, an economy in transition toward a maximal circular economy.

A fully circular economy would be characterized by the primary resource extraction p_t being zero; the resource stock in the ecosphere would be fully preserved for future generations and the resource flows a_{t3} and i_{t6} would become irrelevant. However, there is a level of unavoidable resource dissipation i_{t2} , i_{t4} , i_{t5} . Thermodynamic laws dictate that entropy increase will always occur, resulting in the loss of materials i_t that need to be compensated for by new primary materials (inevitable dissipation). This makes the fully circular economy a utopic concept.

In a maximal circular economy, secondary resource use (a_{t1} and a_{t2}) is maximized and the inaccessibility of accessible and functional resources is minimized (i_{t2} , i_{t3} , and i_{t4}). The primary resource extraction p_t would then compensate for the sum of the unavoidable resource dissipation i_{t2} , i_{t4} , i_{t5} . The PB of such a maximal circular economy is defined by the net accessibility rate ($a_t - i_t$), given the condition that secondary resource use (a_{t1} and a_{t2}) is prioritized over primary resource extraction (p_t).

Currently, we still need to transition toward a maximal circular economy; additional primary resources are needed for three reasons: (1) to compensate for the inevitable dissipation that cannot be compensated for by the net accessibility rate; (2) to transition to a maximal circular economy, for example, through the energy transition;³⁶ (3) to supply for additional material demand (among others, stock expansion) related to population growth or better fulfilling basic human needs.¹⁵ Therefore, an additional primary resource flow from the accessible resource stock in the ecosphere is required. This resource flow, comprising a share (α_t) from the stock E_t , should be small enough to ensure E_t is not depleted before a maximal circular economy is reached.

Evidently, a sustainable production and consumption system entails that no other PB is trespassed in the lifecycle of this resource extraction. The environmental constraint on accessibility of natural resources also includes this. eqs 1-3 provide the proposed principle for a PB for mineral, metal and fossil resource extraction. eq 1 illustrates that the primary resource extraction rate (p_t) should be smaller than the net accessibility rate ($a_t - i_t$) in addition to an allocated share (α_t) from the stock E_t required for the transition. eq 2 gives the condition that secondary resources should be prioritized, hence there can only be primary resource extraction (p_t) if the accessible resource stock in the technosphere (T_t) does not contain any available secondary resources ($T_t = 0$). eq 3 limits the allocated share (α_t) in such a way that the accessible resource stock in the ecosphere E_t is not depleted before the transition to a circular economy has concluded.

$$p_t \leq a_t - i_t + (\alpha_t \times E_t) \tag{1}$$

$$p_t \times T_t = 0 \tag{2}$$

$$\int_{t_{\text{today}}}^{t_{\text{circular-economy}}} \alpha_t \times E_t \, dt \leq E_t \tag{3}$$

4.1. An illustrative example. An example of this principle is provided for the year 2024 (Figure 3). Here, the current total accessible resource stock in the ecosphere of a specific metal is 1000 Mtonnes (E_{2024}). The accessible resource stock in the technosphere (T_{2024}) is assumed to be zero, as all secondary resources are used by the functional stock. The net addition to the accessible resource stock in both ecosphere and technosphere is 10 Mtonnes ($a_{2024} - i_{2024}$). A maximal circular economy would have a SoS in 2024 equaling this 10 Mtonnes. If the transition to such circular economy would take 100 years, with a linear decrease per year in the natural resource requirement, the allocated share of the accessible resource stock from the ecosphere would be 20 Mtonnes-year⁻¹ in year 2024 ($\alpha_{2024} * E_{2024}$), decreasing to 0 Mtonnes-year⁻¹ in year 2124 ($\alpha_{2124} * E_{2124}$). The natural resource extraction rate p_{2024} would then be 30 Mtonnes-year⁻¹.

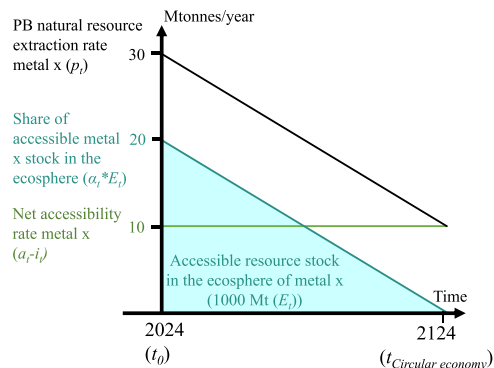


Figure 3. Illustrative example (PB: Planetary Boundary): the blue diagonal line illustrates the linearly decreasing allocation share α_t over time.

5. STEPS TOWARD OPERATIONALIZATION OF THE PRINCIPLE

To quantify the SoS for a specific resource, different steps can be followed (Figure 4). First, the total natural resource amount

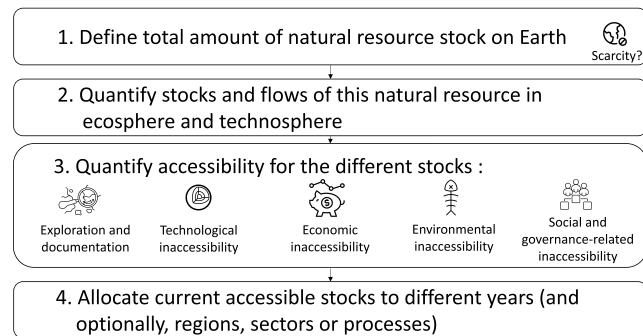


Figure 4. Toward operationalization of the principle.

on Earth is estimated based on known reserves. While scarcity issues may arise for some resources, materials with a large crustal content (e.g., quartz minerals), are less likely to face such limits.²⁶

The second step involves quantifying the different resource stocks using, for example, material flow analysis.³⁷ For the 34 critical raw materials identified by the European Commission,³⁸ specific material flow analyses have been conducted to quantify their stocks and flows in the EU economy.^{39,40}

The third step quantifies the accessibility of stocks in both technosphere and ecosphere. Government geological surveys, like the USGS, can provide crucial information on the technological and economic accessibility of ecosphere stocks.⁴¹ For stocks in the technosphere, Dewulf, Hellweg, Pfister, Godoy León, Sonderegger, de Matos, Blengini and Mathieux³⁵ proposed a framework to identify and quantify irrecoverable states or actions leading to inaccessibility, illustrated by EU cobalt flows. Of the 36 kt extracted cobalt in 2016, 30% augmented the functional resource stock whereas 70% joined the inaccessible resource stock (21% to tailings, 31% to landfill, 12% to downcycling, 1% to dissipation and 4% to hoarding). Inaccessibility is not binary, but exists on a spectrum, as quantified by Dewulf, Beylot, Monfort, Lai, Saldivar, Muller and Mathieux (2024),⁴² using a time-to-accessibility parameter. There is a continuous range of access, given a continuous range of energy, environmental and economic costs involved.

Highly inaccessible resources, such as those dissipated as emissions could have a more significant negative impact on the net accessibility rate compared to temporarily inaccessible resources, like hoarded resources. To determine environmental accessibility, modeling and scenario analysis are needed to understand how much could be used without transgressing at least one other PB. The models from the fourth strategy discussed earlier, can serve as a starting point. Social and governance-related inaccessibility should be determined case-by-case, considering local and geopolitical factors. Additional factors impacting inaccessibility, beside the five here proposed, may require further refinement of the accessibility concept.

This third step links resource use limitations to sustainability. Resources can only be extracted if (1) there is enough of them, (2) if we can sustainably use them, meaning we can access them without passing economic, environmental and social thresholds both on a global and local scale and (3) if we do not make them inaccessible by irreversible steps in the life cycle process (for example using glues, by dilution or by emissions). Statistical entropy analysis can be a tool to assess the accessibility of resources in the functional stocks, i.e. when used in a product (component).⁴³

The quantification of the SoS includes a share α_t of the accessible resource stock in the ecosphere to transition to a maximal circular economy. This stock serves as a resource budget to be used within its SoS and can be allocated to different years in the final step of the framework. In Figure 3, a linearly decreasing allocation over time was assumed. To allocate a yearly share α_t of this resource budget, the following questions should be raised: 'What is the theoretical minimum of inevitable dissipation that needs compensation?'; 'How much primary resources are required for the transition?' and; 'How much resource use is justifiable for population growth and meeting human needs, for current and future generations?'

In a maximal circular economy, the accessible stock in the ecosphere would be constant and the net accessibility range would act as regeneration rate of accessible resources. A steady state with regard to material flows and stocks would be reached, ideally within the SoS of all PBs while fulfilling basic global human needs.^{44,45}

After defining a yearly global resource budget, this could be further allocated to countries, sectors or product cycles.⁴⁶ Such an allocation should enhance intragenerational equality, consider existing stocks and build-up capacity and account for the resource demand for technologies to mitigate current global environmental challenges (for example, renewable energy technologies). Various ethical principles offer multiple allocation strategies, but no universally accepted strategy exists.^{47–49}

Accessibility and inaccessibility are specific to each resource, requiring separate PBs for different metal, mineral and fossil resources. For the allocation of the accessible resource stock of a specific resource, substitution possibilities for an alternative resource could be considered.

The proposed principle applies to fossil, mineral and metal resources; biotic resources were out of scope. Biotic resources are renewable, which means that their regeneration rate can be used to define a sustainable resource budget.⁴⁶ Although fossil, mineral and metal resources are non-renewable, their net accessibility rate can be considered similarly to the regeneration rate for renewable resources.

This study proposes a new principle for a planetary boundary for mineral, metal and fossil resource extraction. The extraction rate remains within planetary boundaries when lower than the (1) net accessibility rate (the sum of accessible resources becoming accessible minus the sum of accessible resources becoming inaccessible), plus (2) an allocated share of the accessible resource stock in the ecosphere. This principle allows further extraction, but only if the extracted accessible resources are replaced by inaccessible resources becoming accessible and secondary resources are prioritized. The additional share of the accessible resource stock to be extracted is based on ethical principles defining how the resource stock should be allocated intra- and intergenerational, as also implemented by the safe and just Earth system targets.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.4c08688>.

Table of terminologies, their definitions or explanations, and appropriate references as used in the manuscript to support the understanding of the manuscript (Table A1) (PDF)

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. **Gweny Thomassen**: Conceptualization, Methodology, Writing - Original Draft, Visualization, Project Administration, Funding Acquisition; **Adithya Eswaran**: Conceptualization, Writing - Review & Editing; **Steven Van Passel**: Resources, Writing - Review & Editing, Supervision, Project Administration, Funding Acquisition; **Jo Dewulf**: Conceptualization, Resources, Writing - Review & Editing, Supervision, Project Administration, Funding Acquisition.

Notes

The authors declare no competing financial interest.

Biography



Gwenny Thomassen is a sustainability engineer, working as a postdoctoral researcher at the Universities of Antwerp and Ghent. She obtained her master degree in bioscience engineering at the KU Leuven and successfully defended her PhD in Business Economics at Hasselt University in cooperation with the Flemish Institute on Technological Research (VITO), focusing on the integration of prospective environmental and techno-economic assessment methods for algae-based biorefineries. She is the junior manager of the Policy Research Center on Circular Economy (CE Center), where she investigated the effects of technological learning on circular technologies. In the CE Center, she is leading the research cluster on scenario analysis and looking into how the material footprint reduction target of 30% by 2030 in the region of Flanders (Belgium) can be translated towards individual processes, products and need (systems).

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ABBREVIATIONS

PB, planetary boundary; SoS, safe operating space; GHG, greenhouse gas

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