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Review

Towards comprehensive assessment of mineral resource availability? Complementary roles of life cycle, life cycle sustainability and criticality assessments

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ABSTRACT

Regarding mineral resources, there is ambiguity around concepts such as scarcity, rarity, criticality and depletion and associated assessment methods. This paper investigates three method groups: life cycle impact assessment (LCIA), criticality assessment and life cycle sustainability impact assessment methods. The aim is to clarify how these method groups and concepts relate and their potential roles in a comprehensive mineral resource availability assessment. The study finds that their modeling approaches and practical implementations are sometimes misaligned with what they aim to assess. This results in similarities between methods from different method groups. Some LCIA-methods include elements which belong to criticality assessment, which could explain some of the ambiguity. A reason for misalignment is a lack of distinction between mineral resource stocks, funds and flows. The lack thereof also results in invalid impact pathway cause-effect chains and imprecise terminology allowing for misunderstandings in the "resource debate". Distinguishing between mineral resource stocks, funds and flows resolves misalignments within methods and between method groups and, in turn, ambiguity around concepts such as scarcity, rarity, criticality and depletion. It follows that long-term scopes need to include assessments of depletion of ecospheric stocks. Methods focusing on factors which represent or can influence magnitude and location of technospheric flows are suitable for short term scopes. Different types of technospheric funds, such as resources in active use, end of life products and landfills, can be relevant in short, medium and long-term scopes. Altogether, assessments of stocks, funds and flows are complementary parts of a comprehensive mineral resource availability assessment.

1. Introduction

The question whether humanity is threatened by mineral resource scarcity and if so, when and why, remain open questions despite decade-long discussions among environmental and economic scholars (Ayres, 1999; Henckens et al., 2016; Meadows et al., 1972; Tilton, 1996). Hence, it is perhaps no surprise that there are widely differing views on how to assess mineral resource scarcity as an environmental impact in life cycle assessment (LCA), a methodology used to systematically account for environmental impacts of a product or service over its life cycle (ISO, 2006b).

Natural Resources is one of three Areas of Protection (AoP) in LCA, along with Ecosystem Quality and Human Health. Over the years, there has been much discussion on how to define the AoP Natural Resources (AoP-NR) and how to assess impacts on it (JRC, 2010; Sonderegger et al., 2017; Vadenbo et al., 2014). Natural resources can be described as "sandwiched in between" the ecosphere (i.e. the environment, where they are extracted) and the technosphere[1] (i.e. intentionally man-made systems, where they are used) (Dewulf et al., 2015). Because of this feature, impacts related to them are difficult to categorize as strictly environmental or economic (Steen, 2006). Because of this there are even widely differing views on whether mineral resource scarcity should be

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[1] In this paper, we include in the term *technosphere* not only physical man-made systems but also e.g. social, economic and political ones.

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assessed in LCA at all (Drielsma et al., 2015; Sonderegger et al., 2017).

There is however consensus on an anthropocentric perspective on the AoP-NR. In other words, the focus is on natural resource availability for humans[2] (Berger et al., 2020; de Haes et al., 1999; de Haes et al., 2002; Jolliet et al., 2004; Sonderegger et al., 2017). Still, there are different perspectives on what, more precisely, about resource availability for humans that should be protected, referred to as safeguard subjects (Dewulf et al., 2015): natural resources as such, the ecosphere's provisioning capacity of natural resources or the functionality of natural resources (Sonderegger et al., 2017; Stewart and Weidema, 2005; Weidema et al., 2005).

In accordance with the mentioned safeguard subjects, methods for mineral resource impact assessment in LCA (LCIA) have been based on the perspectives that either geological rarity or extraction costs (energetic or monetary) are the most relevant constraints to resource availability for humans (Steen, 2006). But it has been pointed out that also competition and geopolitics can constitute relevant constraints (Finnveden, 2005; Mancini et al., 2013). As yet, this is typically not considered in LCA, but more so in criticality assessment methodology: "the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame" (Schrijvers et al., 2020). Therefore, it has been suggested that these methodologies could complement each other to assess different constraints to resource availability for humans (Dewulf et al., 2015; Mancini et al., 2013; Mancini et al., 2015; Sonnemann et al., 2015).

In accordance with the suggested complementary roles of LCA and CA, a rethinking of the AoP-NR has been suggested (Dewulf et al., 2015). In addition to the safeguard subjects of LCA, natural resources could be safeguarded for their roles as building blocks in supply chains of products and services, or, ultimately, human welfare (Dewulf et al., 2015). Related to such novel safeguard subjects, new methods have been developed which combine elements of LCA and CA. Some of these methods are referred to as "supply risk methods" (Sonderegger et al., 2020). As yet, there is no agreement about whether such methods can be considered parts of LCA, or if they rather belong to life cycle sustainability assessment (LCSA) (Sonderegger et al., 2020). Nevertheless, in this paper we find it necessary to distinguish them from LCIA methods and CA methods, and hence, refer to them as impact assessment methods in life cycle sustainability assessment (Valdivia et al., 2013) (LCSIA).

Recently, the Life Cycle Initiative, hosted by the UN Environment Programme, established an expert task force on mineral resources (LCI-UNEP). They suggested to define the safeguard subject for mineral resources as: "the potential to make use of the value that mineral resources can hold for humans in the technosphere" (Berger et al., 2020). Seemingly, this definition is broad enough to incorporate the perspectives on safeguard subjects on which LCIA methods are based as well as the novel safeguard subjects which could be addressed by CA and LCSIA methods.

However, the suggested consideration of criticality in LCA methodology is controversial (Berger et al., 2020; Klinglmair et al., 2014; Sonderegger et al., 2020) and entails terminological ambiguity. Terms such as "criticality", "scarcity" and "depletion" are frequently used seemingly interchangeably in the scientific literature (see e.g. formulations by (Gemechu et al., 2016; Ioannidou et al., 2019; Klinglmair et al., 2014; Pell et al., 2018; Schneider et al., 2014) as presented in the Supplementary Information (SI)). Some authors claim that CA is more holistic (Ioannidou et al., 2019), meaningful and relevant (Gemechu et al., 2015) than LCIA. Reportedly, practitioners mistakenly use methods assessing depletion impacts although they are interested in assessing supply disruption impacts (Berger et al., 2020).

Such claims and ambiguous uses of central concepts suggest that the differences between these methodologies are poorly understood, even among method developers. Recently, several review papers have clarified similarities and differences within methodologies addressing the AoP-NR. The LCI-UNEP review LCIA and LCSIA methods (Berger et al., 2020; Sonderegger et al., 2020). They categorize methods into seven principal questions and provide recommendations on which method(s) to use depending on which question is considered relevant. Another outcome of the LCI-UNEP is a review focusing exclusively on LCSIA methods analyzing, among other things, their impact mechanisms in terms of cause-effect chains (Cimprich et al., 2019). The Sustainable Management of Primary Raw Materials (SUPRIM) project has "taken a step back" to discuss the foundations of LCIA methods in order to reach a common understanding among the LCA community and the mining industry of potential problems with resource use and to develop corresponding methods (Schulze et al., 2020a, b). The International Round Table on Materials Criticality (IRTC) have addressed the reported need for harmonization within the criticality field (Dewulf et al., 2016; Graedel and Reck, 2016) by reviewing methodological differences among CA and LCSIA methods (Schrijvers et al., 2020).

A prominent methodological difference pointed out in recent reviews is the distinction between "inside-out" and "outside-in" impacts (Berger et al., 2020; Cimprich et al., 2019). Inside-out refers to impacts from product systems on the ecosphere, and ultimately future generations, as in LCIA. Outside-in refers to impacts mainly originating from within the technosphere on the system under study (e.g. product systems and producers), as in CA and LCSIA methods (Berger et al., 2020; Cimprich et al., 2019).

Further, it has been established that there is prevalent misalignment between what methods aim to assess (hereafter called *intended scopes*) and what they, de facto, assess as a result of their methodological constructs[3] (hereafter called *actual scopes*). This has been studied for LCIA methods by Drielsma et al. (2015); Schulze et al. (2020b) and for CA and LCSIA methods by Schrijvers et al., (2020). However, despite the observed potential for complementary use (Dewulf et al., 2015; Mancini et al., 2013; Mancini et al., 2015; Sonnemann et al., 2015) neither of these reviews has however analyzed LCIA, CA and LCSIA methods collectively. Thus, there is still limited understanding as to why there is misalignment between intended and actual scopes and how the methodologies may complement each other. In addition, the observed ambiguity concerning central concepts addressed by LCIA, CA and LCSIA, e.g. depletion and criticality (Gemechu et al., 2016; Ioannidou et al., 2019; Klinglmair et al., 2014; Pell et al., 2018; Schneider et al., 2014), calls for clarifications regarding their relations to the fundamental concepts of rarity and scarcity.

Accordingly, this paper aims at, first, identifying and clarifying the relations between these methodologies and concepts and, second, demonstrate the importance of additional methodological considerations to enable a more comprehensive assessment of the AoP-NR. The paper is thought to be primarily relevant to method developers but elucidatory also for any practitioners and decision-makers interested in sustainability of mineral resource use.

2. Method

To achieve this aim, a literature review was first carried out. The review of LCIA and CA primarily builds on synthesis of previous reviews of such methods but also on other relevant publications, including original publications of specific methods (see SI Table 1 for an overview

[2] In discussing availability for humans, we use the term *rarity* to refer to limited availability of resources regardless whether there is a demand or not (Ljunggren Söderman et al., 2013). We use the term *scarcity* to refer to limited and demanded resources. Further, *availability* denotes physical presence of a resource whereas *accessibility* denotes direct possibility to make use of a resource (Schulze et al., 2020a).

[3] We use the term methodological construct to refer to what is called "modelling concept" and "practical implementation" in the SUPRIM project (Schulze et al., 2020a).

Table 1
Analytical framework consisting of three dimensions: temporal perspective, cause-effect chain and safeguard subject.

Temporal perspective	Short (0–20 years), medium (20–100 years), long (>100 years)				
Cause-effect chain for extraction of mineral resources	Cause: extraction or use of mineral resources	Fate: physical changes to conditions in the ecosphere	Exposure: change in available quantity, quality or functionality of a resource and potential competition among users	Effect: adverse effects on directly affected users that adapt or are unable to adapt	Damage: severity of observed effects
Safeguard subject	Safeguard resource: stocks, funds, flows				

of synthesized review studies and specific methods discussed in this paper). LCSIA methods have so far only been reviewed by the LCI-UNEP (Berger et al., 2020; Cimprich et al., 2019; Sonderegger et al., 2020) whose authors have also contributed to the development of such methods. Therefore, a new review of LCSIA methods was carried out (see SI for method).

Based on an initial reading of all reviews, and with consideration to research gaps pointed out or left by the most recent ones, three dimensions were chosen to constitute the framework used to analyze the methodologies (see Section 2.1 Analytical Framework and Table 1): temporal perspective, cause-effect chain and safeguard subject. Thereafter, a detailed reading established the intended and actual scopes of the methodologies in each dimension. Reasons for misalignment between intended and actual scopes both within and between methodologies were analyzed and suggestions on how to align them were conceived.

The analysis was largely inspired by Drielsma et al. (2015) who analyzed intended and actual safeguard subjects of LCIA methods. In contrast to previous reviews (Drielsma et al., 2015; Schrijvers et al., 2020; Schulze et al., 2020b) we are not primarily concerned with (mis) alignment between intended and actual scopes of individual methods. Rather, we are interested in (mis)alignment between intended and actual scopes of the methodologies. At times, this requires analysis of individual methods as well.

Since both LCIA and CA methods have been extensively reviewed, we consider such reviews the best possible data source for establishing the intended and actual scopes of these methodologies. We comprehensively establish intended scopes in all three dimensions of the analytical framework. Actual scopes are established comprehensively in the temporal dimension (Section 3.1-3.3) and discussed in the cause-effect chain and safeguard subject dimensions using specific methods as illustrative examples (Section 3.5). In general, the synthesis of previous reviews serves to establish what can be considered predominant scopes of methodologies (see SI Table 3–6 for linkages between full quotations from the review studies and our claims), whereas statements about specific methods are used as examples of such predominant or, conversely, outlier scopes of each methodology.

2.1. Analytical framework

The temporal dimension refers to the time frame of methods, or more precisely, the time between the decision-making situation (i.e. use of a method) and the potential impact. It should be noted that there are semantic differences with respect to the terms “short”, “medium” and “long term” within these literatures. For clarity, a temporal scale adapted from Drielsma et al. (2015) is used throughout the article (short=0–20 years; medium=20–100 years and long>100 years) but methods’ specific formulations are also referred to when necessary.

Cause-effect chain dimension refers to the extent and nature of the modelled impact pathway, i.e. the sequence of cause-effect mechanisms describing a potential impact. Cause-effect chains constitute the theoretical foundation of LCIA, which is the stage in LCA “aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system throughout the life cycle of a product” (ISO, 2006a). This is done by multiplying the inventory of elementary flows associated with a product system with characterization factors (CFs). Elementary flows are inventory flows that cross the system boundary between ecosphere and technosphere, e.g. emissions and resources. Characterization factors (CFs) represent the relative importance of elementary flows for a particular environmental impact category and are derived by modeling cause-effect chains through steps such as fate, exposure, effect and damage. (Hauschild et al., 2018)

In general, the modeling complexity increases along the cause-effect chain. Therefore, a distinction is made between two types of environmental impact category indicators: midpoint and endpoint (Bare et al., 2000; Hauschild et al., 2018). Midpoint indicators reflect impacts early in the cause-effect chain, where modeling complexity and thus uncertainty, but also environmental relevance is generally lower. In contrast, endpoint indicators reflect impacts “close to or at the very endpoint of the chain – the Area of Protection” (Hauschild et al., 2018) where uncertainty but also environmental relevance is higher (Bare et al., 2000; Hauschild et al., 2018).

Despite the fundamental role of cause-effect chains in LCIA, LCIA methods for mineral resource assessment have, to our knowledge, not been analyzed at such a detailed level as cause-effect chain steps. In addition, analysis of cause-effect chains have been argued important for aligning actual and intended scopes of CA methods (Schrijvers et al., 2020). So far, cause-effect chains related to criticality have only been conceptually discussed in works related to the development of LCSIA methods (Cimprich et al., 2019). Further, a comprehensive analysis of all these methodologies enables clarification concerning the relations between concepts they address e.g. depletion and criticality, to fundamental concepts of rarity and scarcity. Table 1 illustrates a cause-effect chain for mineral resources which is used for this purpose and for the comparison with CA and LCSIA methods. This cause-effect chain for mineral resources is adapted from a cause-effect chain for natural resources in general (Hauschild et al., 2018). It deserves to be mentioned that the cause-effect chain steps of LCIA were initially used to describe emission-related environmental impacts. Therefore, they may not be ideal for describing resource-related impacts. Developing new terminology for cause-effect chain steps of resource-related impacts was however outside the scope of this research.

The Safeguard subject dimension refers to what, within the AoP-NR, is to be protected (or safeguarded). It has already been established by Dewulf et al. (2015) that LCIA predominantly addresses the safeguard subjects: natural resources as such, and, the ecosphere’s provisioning capacity, and that CA and LCSIA methods could potentially address the novel safeguard subjects, “supply chain” and “human welfare”. It is also clear that LCIA methods safeguard resource availability for future generations while CA and LCSIA methods safeguard resource availability for the system under study[4] (Berger et al., 2020; Drielsma et al., 2015). Therefore, we rather focus on whether the resources which are safeguarded are stocks, funds or flows. The categorization of stocks, funds and flows has been valuable in the analysis of other kinds of natural resources (Sonderegger et al., 2017) but not sufficiently utilized for mineral resources.

- Stock resources are considered to exist as a finite amount in the ecosphere and can be considered non-renewable since renewal rates are insignificant with respect to the time scales of human extraction rates (Klinglmair et al., 2014).

[4] It deserves to be mentioned that “future generations” or “system under study” are thereby the “users” described in the cause-effect chain dimension.

- Fund resources can be regenerated, and hence, either be depleted or expanded depending on the rates of renewal and extraction (Klinglmair et al., 2014; Sonderegger et al., 2017).
- Flow resources are non-depletable but may be limited at a certain time or at a certain place because of e.g. competition (de Haes et al., 2002; Klinglmair et al., 2014), uneven geographical distribution or because it might not be possible to move them from their original location for use in another location (Swart et al., 2015).

In LCA, mineral resource availability is characterized as a stock problem, i.e. “a depletion or a dissipation problem” (Sonderegger et al., 2017). We demonstrate in this paper that this may be a limiting characterization in pursuit of a comprehensive assessment of mineral resource availability. We suggest that mineral resources can, just as e.g. water resources, pose flow, fund and stock problems. To illustrate, flow problems can concern rivers and mineral exports from a specific nation. Fund problems can concern lakes (such as the Aral Sea) and mineral resources in e.g. landfills or products reaching their end of life. Stock problems can concern fossil groundwater and mineral resources in the Earth’s crust. A noteworthy difference is whether renewal can occur naturally, directly powered by incoming solar energy as for water resources, or if renewal also depends on technospheric processes, which are ultimately powered by incoming solar energy, as for mineral resources (Ayres, 1999; Korhonen et al., 2018). Hence, we establish whether methodologies address stock, fund or flow problems as their safeguard subject and hereafter call these safeguard resources.

3. Review of methodologies

3.1. Life cycle impact assessment

3.1.1. Aims

LCIA methods for resource use aim to reflect impacts caused by products systems on the AoP-NR (Sonderegger et al., 2017). However, there has been much discussion on what safeguard subject LCIA should address and on methodology to assess it (Dewulf et al., 2015; JRC, 2010; Sonderegger et al., 2017; Steen, 2006).

3.1.2. Methodological constructs

The lack of agreement concerning assessment of mineral resource availability (Sonderegger et al., 2017) is due to several potentially relevant questions: some which are mainly ecospherically oriented, and others which are mainly technospherically oriented (Berger et al., 2020; Steen, 2006). Accordingly, there are also different types of methodological constructs. The most supported are depletion and future efforts types. Another type are thermodynamic methods. These however have lower support in the literature because they do not reflect scarcity of individual resources but instead exergy (JRC, 2011; Klinglmair et al., 2014; Sonderegger et al., 2020; Sonderegger et al., 2017; Steen, 2006).

The depletion type is used as a midpoint indicator by several LCIA methods (JRC, 2011; Klinglmair et al., 2014). It is based on the ratio between use and some measure of availability, for instance reserves, reserve base, crustal content or crustal concentrations. The aim of depletion methods is to reflect that current resource use reduces resource availability (i.e. increases rarity) which, assuming that future generations will demand resources, causes scarcity (Alvarenga et al., 2016; Klinglmair et al., 2014; Steen, 2006; Swart et al., 2015). A crucial feature of depletion methods is the chosen measure of availability. It is claimed that it should ideally represent the stock which is “ultimately extractable” (Van Oers et al., 2002; van Oers and Guinée, 2016) but this is notoriously problematic to estimate (Drielsma et al., 2015; Sonderegger et al., 2017). Using a geological factor such as crustal content involves considerable uncertainty since the share that will become available to humans is highly dependent on future extraction technologies (Drielsma et al., 2015; Sonderegger et al., 2017). Using an economically contingent factor on the other hand, such as reserves, is also limiting because it only reflects resources that are economically extractable (Drielsma et al., 2015; Sonderegger et al., 2017). Ratios of use and availability using such factors can increase or decrease over time depending on the rates of exploration and extraction and thereby do not reflect increased rarity of ecospheric stocks (Drielsma et al., 2015; Sonderegger et al., 2017). Lastly, the measure of availability could include technospheric as well as ecospheric stocks, as in the Anthropogenic Stock Extended Abiotic Depletion Potential (AADP) (Schneider et al., 2011), since it is argued that resource availability for humans does not necessarily decrease because of extraction, but rather, dissipation.

Another feature of depletion methods is whether to include extraction rates or not (Sonderegger et al., 2020). The inclusion of extraction rates can be considered as a factor reflecting the current importance (JRC, 2011; Klinglmair et al., 2014) or “social value of a resource” (Guinée and Heijungs, 1995). Hence, inclusion of extraction rates could lead to underestimation of the importance of resources which are not currently used to large extent, but which may be in higher demand in the future (Sonderegger et al., 2020). Arvidsson et al. (2020) argue that extraction rates are the elementary flows of an LCA of the current global economy, which makes them inappropriate to include in derivation of CFs for impact assessment.

The future efforts type is based on the notion that *“in the long run the effort to extract resources will increase”* (Sonderegger et al., 2017) as a result of decreasing ore grades. This is based on the, sometimes questioned (Ericsson et al., 2019), assumption that high grade ores are used first (Berger et al., 2020). Future efforts methods are typically considered endpoint indicators because they model impacts beyond reduced availability of ecospheric stocks (JRC, 2011; Klinglmair et al., 2014; Swart et al., 2015). Notably, this requires modeling of cause-effect mechanisms related to the technospheric process of future extraction (Klinglmair et al., 2014) as opposed to cause-effect mechanisms in the ecosphere as is customary in LCIA. This has been criticised by Finnveden (2005) since modeling of the technosphere belongs to the life cycle inventory as opposed to impact assessment.

3.1.3. Temporal scope

Few LCIA methods explicitly state which temporal scopes they are intended for. Nevertheless, it is clear that LCIA methods predominantly intend to reflect long term impacts considering the ambition to represent the “ultimately extractable reserve” (Van Oers et al., 2002), the long term mechanism of future efforts methods (Sonderegger et al., 2017) and that rarity of ecospheric stocks is relevant in the long term (Drielsma et al., 2015; Schulze et al., 2020b; Sonderegger et al., 2017; Steen, 2006).

However, the methodological constructs of LCIA methods often result in actual temporal scopes that are misaligned with the intended long term scope. Drielsma et al. (2015) analyzed the temporal validity of CFs of ten widely used LCIA methods and concluded that only Abiotic depletion potential (ADP) based on crustal concentrations (Guinée and Heijungs, 1995; Van Oers et al., 2002) is aligned with its intended temporal scope. Other LCIA methods (e.g. (Finnveden and Ostlund, 1997; Goedkoop and Spriensma, 2001; Goedkoop et al., 2009; Hauschild and Wenzel, 1998; Schneider et al., 2011; Van Oers et al., 2002)) have increasingly preferred the use of factors such as prices, reserves and currently processed ore grades (i.e. technospheric) over geological (i.e. ecospheric) factors (Drielsma et al., 2015). This limits their actual temporal scopes to the short and medium term (Drielsma et al., 2015). Considering that extraction rates are dynamic, Arvidsson et al. (2020) argue that the actual scope of also the ADP based on crustal concentrations is misaligned with its intended long term scope, even when they are based on time series data over several years as in van Oers et al. (2019).

3.1.4. Cause-effect chain scope

Most LCIA methods, both depletion and future efforts types, intend to model that physical extraction from the ecosphere into the technosphere (*cause*) increases rarity of ecospheric stocks (*fate*) (Drielsma et al., 2015; Schulze et al., 2020b; Sonderegger et al., 2020; Sonderegger et al., 2017; Steen, 2006; Swart et al., 2015). The cause-effect chain scope of depletion methods extends to users' *exposure* to increased rarity of ecospheric stocks, and hence scarcity, assuming there may be a demand. Since the demands of future generations are, to large extent, non-foreseeable (JRC, 2010; Sonderegger et al., 2017; Steen, 2006; Swart et al., 2015) there are typically no assumptions regarding which resources will be demanded. Being midpoint indicators, depletion methods do not intend to model any consequences of scarcity in neither effect nor damage steps (Klinglmair et al., 2014; Swart et al., 2015). Future efforts methods, on the other hand, are generally referred to as damage-oriented (Goedkoop M., 2009; Steen, 1999). They explicitly model consequences of scarcity (Klinglmair et al., 2014; Sonderegger et al., 2020; Steen, 2006; Swart et al., 2015) in terms of *effect* and *damage* (Fig. 1). The *effect* is that users adapt to scarcity of high grade ores through substitution to lower grade ores. The *damage* is the increased production cost resulting from the substitution.

3.1.5. Safeguard subject scope

Since most LCIA methods intend to reflect that extraction from the ecosphere increases rarity of ecospheric stocks, it is concluded that the *safeguard resources* of LCA are *resource stocks*. As implied by the LCI-UNEP definition of the safeguard subject (Berger et al., 2020) it should be added that ecospheric stocks are not safeguarded in order to stay in the ecosphere but rather for their potential future occurrence as technospheric flows to be used by future generations. However, many LCIA methods do not actually assess impacts on resource stocks, because they have increasingly moved away from the use of ecospheric factors in preference for factors, such as reserves (Drielsma et al., 2015; Sonderegger et al., 2017) (as discussed under *Temporal scope*). Recalling the description of *resource funds* (Section 2.1), it can be seen that factors such as reserves or "anthropogenic stocks" (Schneider et al., 2011) rather represent funds than stocks. To illustrate, extraction from reserves (Drielsma et al., 2015; Sonderegger et al., 2017; Tilton, 2001) or urban and landfill mines (Ayres, 1999) can be counterweighed by renewal through exploration and products reaching their end of life, respectively.

3.2. Criticality assessment

3.2.1. Aims

CA methods aim to identify resources that have high probability of supply disruption and importance to specific users e.g. companies, nations, supra-national regions and technologies which therefore would be vulnerable to supply disruption (Buijs et al., 2012; Dewulf et al., 2016; Schrijvers et al., 2020). Erdmann and Graedel (2011) describe CA as focusing on "less precise concepts" (compared to studies assessing resource availability for specific technologies based on geological measures e.g. Andersson (2000)) such as political stability of mining countries, market imbalances and government interventions to address concerns of short and medium term resource availability. Partly because of this and partly because vulnerability to supply disruption is largely dependent on the user (Schrijvers et al., 2020) criticality is a matter of degree rather than an absolute state (Buijs et al., 2012).

3.2.2. Methodological constructs

CA methods predominantly assess criticality using two axes which are commonly denoted "supply risk" and "vulnerability to supply risk" (Dewulf et al., 2016). Glöser et al. (2015) point out that referring to one axis as "supply risk" is inaccurate since the term "risk" is defined as the product of probability and consequence. Thus, "supply risk" is synonymous to criticality (supply risk = probability of supply disruption * consequence of, or vulnerability to, supply disruption = criticality). Therefore, the terms *supply disruption probability* and *vulnerability* are used henceforth. Each axis normally comprises several factors which are combined into criticality scores (Achzet and Helbig, 2013; Helbig et al., 2016b).

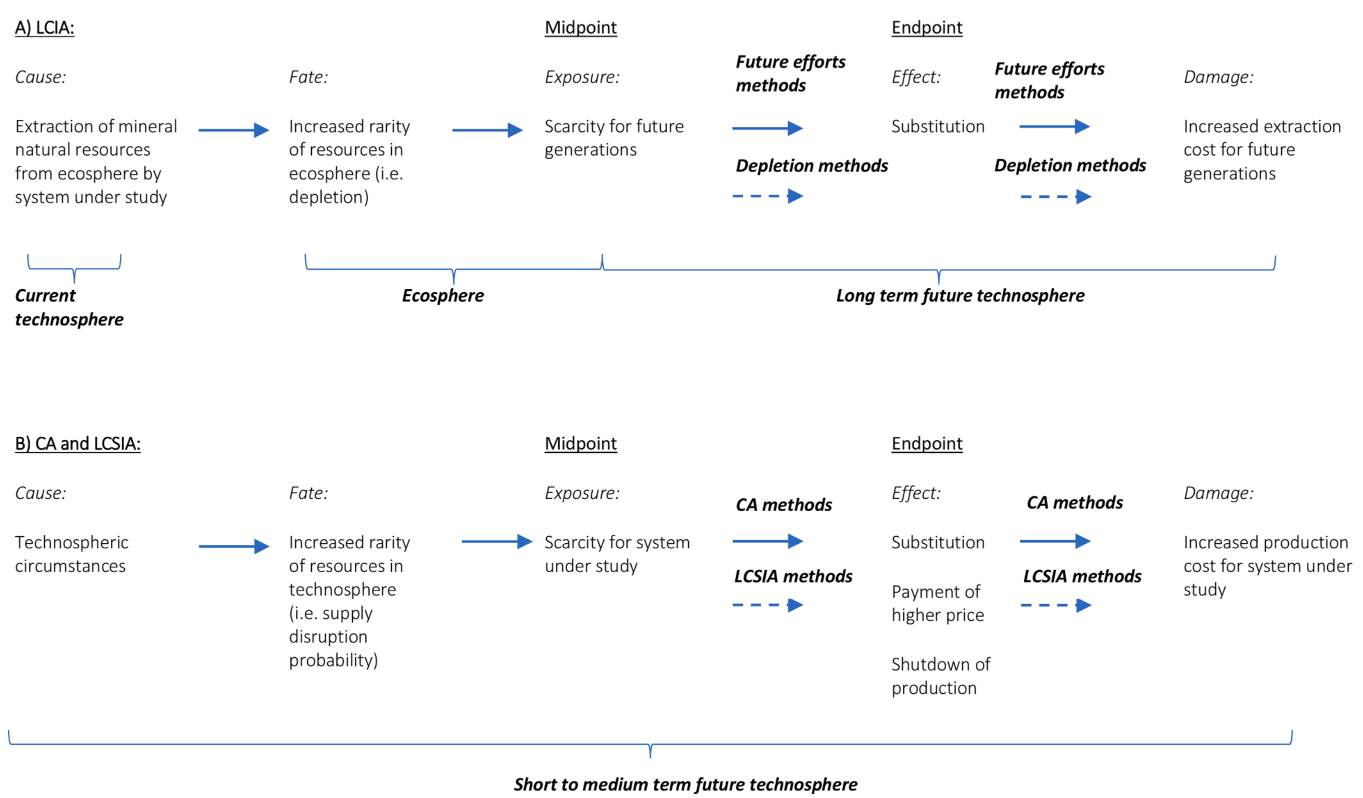

Fig. 1. Predominant intended cause-effect chain scopes of A) LCIA and B) CA and LCSIA methods. Full and dashed arrows denote modelled and implicit cause-effect mechanisms respectively.

The factors included in each axis vary substantially between methods (Achzet and Helbig, 2013; Helbig et al., 2016b; Schrijvers et al., 2020). To reflect supply disruption probability, methods tend to include a variety of factors: geological, technological, economic, social, regulatory and geopolitical (Achzet and Helbig, 2013; Dewulf et al., 2016; Erdmann and Graedel, 2011; Graedel et al., 2012; Graedel and Reck, 2016; Schrijvers et al., 2020). The most common ones are geographical concentration of production or reserves combined with political stability (called “country risk”) and “depletion time” expressed as the ratio between use and some measure of availability e.g. reserves or reserve base (Achzet and Helbig, 2013; Schrijvers et al., 2020). The vulnerability axis is most commonly addressed through factors reflecting “substitutability” and “value of products affected” by supply disruption (Helbig et al., 2016b; Schrijvers et al., 2020).

3.2.3. *Temporal scope*

The intended temporal scopes of CA methods range between “short” (less than 5 years), “medium” (5–15 years) and “long term” (a few decades) (Erdmann and Graedel, 2011; Graedel and Reck, 2016; Schrijvers et al., 2020), which corresponds to *short* and *medium term* in our temporal dimension. The intended temporal scope has implications for which factors are relevant to include (Graedel et al., 2012). Temporally dynamic factors e.g. social, economic and geopolitical are relevant in the short term, but much less so beyond the short term (Graedel et al., 2012). Conversely, geological factors such as crustal concentrations as included by e.g. (BGS, 2012,2011; Duclos et al., 2010) may not be indicative of supply disruption within the intended temporal scopes of CA (Achzet and Helbig, 2013; Graedel and Reck, 2016; Schrijvers et al., 2020). Hence, methods that combine factors of different temporal scope have unclear actual temporal scopes (Buijs et al., 2012; Dewulf et al., 2016; Schrijvers et al., 2020). In addition, the actual temporal scopes of CA methods have been claimed to be limited to the present or short term due to the use of historic or present data for factors that are inherently dynamic (Buijs et al., 2012; Ioannidou et al., 2019).

3.2.4. *Cause-effect chain scope*

Because CA methods have yet to be described in terms of cause-effect chains (Schrijvers et al., 2020) this section proposes such a description. It draws on the described cause-effect chains for LCSIA methods (Cimprich et al., 2019) (further described in 3.3) and CA review studies.

In CA, factors representing causes of supply disruption are predominantly geopolitical, technological, economic, social and regulatory (Achzet and Helbig, 2013; Erdmann and Graedel, 2011; Graedel and Reck, 2016). These will hereafter be referred to collectively as *technospheric circumstances*. Being less measurable and less precise (Buijs et al., 2012; Erdmann and Graedel, 2011), and intended to be prospective, technospheric circumstances (*cause*) are less predictably connected to a *fate* compared to LCIA. For instance, “country risk” does not as predictably increase rarity in the technosphere as extraction from the ecosphere increases rarity in the ecosphere. Thus, technospheric circumstances can be regarded as *potential causes* reflecting increased probability that resources could become increasingly rare in the technosphere (*fate*). Users with a demand are *exposed* to technospheric rarity of resources, causing scarcity.

Further, a resource is more critical the more vulnerable a user is to its potential supply disruption. This is measured through “impact or economic disruption that could result from scarcity” (Graedel and Reck, 2016), i.e. potential consequences of supply disruption. Users can adapt (*effect*) to scarcity through substitution to other resources or payment of a higher price. Alternatively, they can fail to adapt and shut down production (*effect*). Severity of such effects can be quantified in terms of increased production costs (*damage*)[5]. This is often included by CA methods for companies and nations through factors such as “value of products affected” and “value of utilized material” (Helbig et al., 2016b; Schrijvers et al., 2020) but to less extent by CA methods for technologies (Bauer et al., 2010; Buchert et al., 2009; Habib and Wenzel, 2016; Helbig et al., 2016a; Helbig et al., 2018; Moss et al., 2017; Roelich et al., 2014).

In summary, the cause-effect chain scopes of CA methods predominantly range from *potential causes* reflecting increased probability of scarcity to *effects* and often *damage* of scarcity for a user (Fig. 1).

3.2.5. *Safeguard subject scope*

As regards the safeguard resources, the description of *resource flows* (Section 2.1) is strikingly similar to the concerns addressed in CA, namely, potential rarity of resource flows at a certain time and place due to e.g. competition and uneven geographical distribution. Thus, the intended safeguard resources are resource flows in the technosphere.

3.3. *Life cycle sustainability impact assessment*

3.3.1. *Aims*

LCSIA methods include some indicator of supply risk (i.e. criticality) for a product (Cimprich et al., 2019). In contrast to CA, LCSIA methods aim to connect criticality to a functional unit (a quantified description of the performance of a product system used in LCA). This is argued useful as a complement to LCA to inform decision-making with regard to products systems from supply risk, in addition to environmental, perspectives (Cimprich et al., 2017a; Cimprich et al., 2017b; Mancini et al., 2018).

3.3.2. *Methodological constructs*

CFs of LCSIA methods reflect the potential of technospheric circumstances to impact product systems outside-in, through supply “disruption of inventory flow” (Cimprich et al., 2019). Just as LCIA, LCSIA methods intend to provide CFs that can be multiplied with inventory flows of a product system. In contrast to CFs of LCIA which are applied solely to elementary flows, CFs of a few LCSIA methods (Bach et al., 2016; Cimprich et al., 2017a; Schneider et al., 2014) may as well be applied to inventory flows along the entire supply chain. This is intended to reflect that supply disruption can occur anywhere upstream from the producer of the product which is assessed (Cimprich et al., 2019; Sonderegger et al., 2020). Other methods are explicitly (Criticality-based impact assessment method (CIAM) (Tran et al., 2018)), or seemingly, intended to be applied to elementary flows (Global resource indicator (GRI) (Adibi et al., 2017) since it is described as a method used ”in place of a simple depletion potential”). Considering this formulation, the GRI could potentially have been categorized as an LCIA method. However, this demonstrates one problem this article aims to address, namely, that some methods are difficult to categorize because they combine factors relevant for different questions, in this case, intending to be used as a “depletion potential” method while including factors representing “geopolitical availability”.

3.3.3. *Temporal scope*

The intended temporal scope of LCSIA methods assessing supply risk is short term (Berger et al., 2020; Cimprich et al., 2019; Sonderegger et al., 2020). The actual temporal scope of LCSIA methods assessing supply risk is also concluded to be short term based on the temporal validity (Buijs et al., 2012; Graedel et al., 2012) of commonly used factors e.g. country risk (SI Table 7). In addition to the short term scope, some LCSIA methods intend to include indicators of medium and long term scopes (usually based on LCIA methods e.g. ADP and AADP). In ESSENZ (Bach et al., 2016), factors of different temporal validity are kept separate, so that the actual temporal scopes of supply risk are short term as intended. In contrast, Adibi et al. (2017) acknowledges the importance of temporal distinctions and intend to provide CFs with short and medium term scopes (called “long term”), but nonetheless,

[5] Lost revenue due to production being shut down can be seen as increased production cost.

combine factors of disparate temporal validity: geological availability, geopolitical availability and recyclability (medium term CFs include assumptions of 90% recycling rates and excludes one of three factors of geopolitical availability, namely, geopolitical stability). This obscures the actual temporal scopes of the resulting CFs.

3.3.4. Cause-effect chain scope

Just as in CA, there are various factors representing technospheric circumstances which may *cause* technospheric rarity (*fate*) (Cimprich et al., 2019) (SI Table 6). Users with a demand for resources may be *exposed* to technospheric rarity, causing scarcity (i.e. "disruption of inventory flow" (Cimprich et al., 2019)). Other factors represent reduced exposure to technospheric rarity e.g. domestic resource production in countries where users are located (Cimprich et al., 2019).

Further, just like CA, LCSIA methods intend to reflect that a resource has higher supply risk the more vulnerable a user is to its potential supply disruption. Thus, *effect* and *damage* steps intended to be reflected are, in principal, identical to CA (see Section 3.2). In contrast to CA however, only a few LCSIA methods actually include vulnerability factors. These are: "substitutability" by Cimprich et al. (2017a), "value of utilized material" by Pell et al. (2018) and "value of products affected" by Tran et al. (2018) (SI Table 6). In other methods, it is merely implicitly assumed that users are vulnerable to supply disruption (Cimprich et al., 2019; Sonderegger et al., 2020).

The lesser inclusion of vulnerability factors compared to CA is probably linked to the user dependency of vulnerability factors (Mancini et al., 2018; Schrijvers et al., 2020) and LCSIA methods' ambition to derive CFs which are generally applicable. Compared to *exposure*, which at least to some extent can be reflected using factors that are independent of the user (e.g. country risk), *effect* and *damage* (adaptation or failure to adapt to scarcity and the costs thereof) are to greater extent dependent on the user. Thus, *effect* and *damage* are to less extent generally applicable. For this reason, Mancini et al. (2018) excluded the "economic importance" axis from the criticality scores for the European Union (EU), rendering CFs that reflected only supply disruption probability. In contrast, Tran et al. (2018) constructed CFs from the entire criticality scores for the EU (EC, 2010, 2014), i.e. including also resources' economic importance to the EU. It can be discussed to which users, other than the EU, that such CFs are relevant.

In summary, the predominant cause-effect chain scope of LCSIA methods assessing supply risk is similar to that of CA, except for less *effect* and *damage* step modeling (Fig. 1).

3.3.5. Safeguard subject scope

The safeguard resources of LCSIA methods are, like CA methods, resource flows which may be rare in the technosphere at a certain time and place. For LCSIA methods, this is all the more clear considering that the concern is a potential "disruption of inventory flow" (Cimprich et al., 2019).

3.4. Comparison of LCIA, CA and LCSIA

3.4.1. Temporal scopes

LCIA, CA and LCSIA methods do not intend to have similar temporal scopes. LCIA intends to have a long term scope (Drielsma et al., 2015) while CA and LCSIA methods predominantly intend to have a short, and to some extent, medium term scope (Cimprich et al., 2019; Schrijvers et al., 2020). Despite such dissimilar intended temporal scopes, the actual temporal scopes of LCIA, CA and LCSIA methods are largely similar. LCIA methods' increased preference for economic factors over geological ones have shortened their actual temporal scopes to the short and medium term (Drielsma et al., 2015). Conversely, actual temporal scopes of CA are sometimes unclear due to inclusion of long term factors, e.g. crustal concentrations, alongside short term factors (Buijs et al., 2012; Dewulf et al., 2016; Schrijvers et al., 2020). Thereby, although the intended temporal scopes are fundamentally different the actual temporal scopes of LCIA, CA and LCSIA methods are all predominantly short to medium term. The widespread use of "depletion time" factors within both LCIA (Sonderegger et al., 2017), CA (Achzet and Helbig, 2013) and LCSIA methods (Schrijvers et al., 2020) is a clear testament to similarities in actual temporal scopes.

3.4.2. Cause-effect chain scopes

Fig. 1 illustrates that depletion LCIA methods and LCSIA methods predominantly reflect potential scarcity whereas future efforts LCIA methods and CA methods also reflect potential consequences of scarcity.[6] Thereby, they can be seen as midpoint and endpoint indicators for their respective safeguard subject: resource availability for future generations (LCIA) and the system under study (CA and LCSIA). The intended impact pathways of LCIA, CA and LCSIA methods can be described with similar cause-effect chain steps but with a few crucial differences (Fig. 1). The *cause* in LCIA is physical extraction from the ecosphere by the system under study. In CA and LCSIA, technospheric circumstances are *potential causes*. In LCIA, there is a long temporal difference between the *cause* and *effect* (implied by the distinction between current and future technosphere in Fig. 1). In CA and LCSIA, there is much less of a temporal difference between cause-effect chain steps since they are all modelled to possibly occur in the short to medium term future. The *fate* is increased rarity in ecosphere (LCIA) or technosphere (CA and LCSIA). In all methodologies, the *exposure* is scarcity caused by increased rarity and technospheric demand. The intended temporal scope determines the extent to which demand is foreseeable. Users with a largely non-foreseeable demand, such as future generations, may be exposed to increased rarity of resources in the ecosphere resulting in potential scarcity of technospheric flows in the long term future technosphere. Systems under study, on the other hand, have largely foreseeable demand. Thereby, they may be exposed to increased rarity of specifically demanded technospheric flows, resulting in potential scarcity. The *effect* is substitution to lower ore grades (LCIA) or substitution to other resources, payment of higher price or shutdown of production (CA and LCSIA). The *damage* is increased extraction cost of resources for future generations (LCIA) or increased production cost of products for the system under study (CA and LCSIA) due to the effects.

3.4.3. Safeguard subject scopes

In LCIA, the intended safeguard resource is predominantly ecospheric stocks, affected inside-out by current extraction. However, the actual safeguard resource is not always ecospheric stocks as intended (Drielsma et al., 2015; Sonderegger et al., 2017) but ecospheric funds, such as reserves. In CA and LCSIA methods, the safeguard resource is technospheric flows affected outside-in by technospheric circumstances. Safeguard resources will be further discussed in the next section.

3.5. Suggestions for comprehensive assessment of mineral resource availability

In this section we elaborate on the distinction between stocks, funds and flows (Fig. 2) and argue that distinguishing between them in assessments of mineral resource availability improves: temporal validity; methodological consistency with regard to cause-effect chains; conceptual and terminological precision.

Fig. 2 visualizes the complementary roles of stocks, funds and flows in a comprehensive view of mineral resource availability. *Ecospheric stocks* are resources presumed to be ultimately accessible to humans. Their magnitudes decrease by primary extraction. *Ecospheric funds* are subsets of ecospheric stocks which are accessible in shorter temporal scopes. They are located in the ecosphere but their magnitudes are

[6] A recently published LCSIA method (Santillán-Saldivar et al., 2020) does however reflect consequences of scarcity by estimating increased costs of resources.

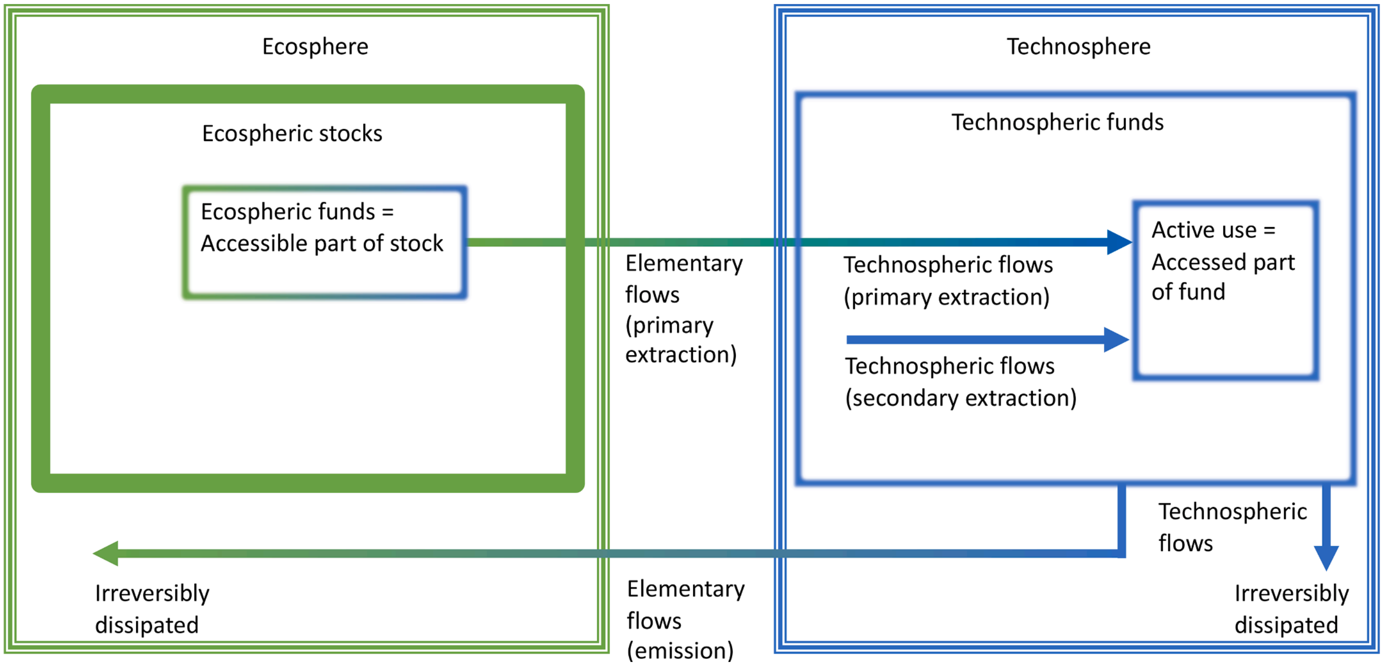

Fig. 2. Relations between: ecospheric stocks; ecospheric and technospheric funds; primary and secondary technospheric flows. Note: Resources in active use are a subset fund of technospheric funds. The other subset fund of technospheric funds are resources in hibernation, i.e. in landfills and end of life products. These are currently not in active use but they are potentially accessible. Legend: green=ecosphere, blue=technosphere. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

influenced (i.e. can be renewed) by technospheric circumstances such as exploration, demand and extraction technology. Further, there are various types of *technospheric funds* which are relevant in different temporal scopes. For instance, resources occupied in long-lasting and recyclable infrastructure are technospheric funds which are relevant for medium to long term scopes. Resources in recyclable end of life products are relevant for short term scopes. Lastly, *technospheric flows* are extracted from ecospheric stocks as well as technospheric funds. Technospheric circumstances such as trade barriers can influence the magnitude and location of technospheric flows and, consequently, the accessibility for users that demand them at certain times and places.

The first benefit of distinguishing between these resource categories for mineral resources concerns temporal validity. Factors that represent magnitude and location of technospheric flows as such (e.g. extraction rates from specific countries) or circumstances that can influence them (e.g. political stability) are clearly relevant for assessing the availability of mineral natural resources in the short term. However, they are hardly relevant in the medium term and definitely not in the long term. Yet, existing LCIA, CA and LCSIA methods have paid little attention to this categorization and combined factors representing stocks, funds and flows despite having widely different intended temporal scopes. Some examples are the inclusion of flow and fund factors in methods that intend to have long or medium term (called "long term") scopes, e.g.: extraction rates in the LCIA method ADP; geopolitical availability in the "long term" CFs of the LCSIA method GRI; anthropogenic "stock" (arguably a *fund*) in the LCIA method AADP. Conversely, factors representing ecospheric stocks have been argued not relevant in CA (Graedel and Reck, 2016). With this categorization in mind, it seems that similarities in actual temporal scopes between the three methodologies and unclear temporal scopes of specific methods have arisen because of methods' lack of attention to it.

The second benefit concerns the methodological consistency of impact pathway cause-effect chains. As Fig. 1 implies, CFs of midpoint methods assessing impacts of primary extraction should reflect increased rarity in the ecosphere (*fate*) resulting from the elementary flow leaving the ecosphere and potential scarcity arising from users' *exposure* to rarity in the ecosphere (stock). But the CFs do not reflect this cause-effect mechanism if methods combine factors representing ecospheric stocks with either flows and/or funds in the technosphere (flows in GRI and ADP and funds in AADP). Instead, in the case of ADP, which is usually interpreted and recommended as a midpoint LCIA method (Alvarenga et al., 2016; Berger et al., 2020; JRC, 2011; Klinglmair et al., 2014), an implication of combining crustal content (stock) and extraction rates (flow) is that the actual cause-effect chain extends beyond the exposure step. It has been pointed out that including extraction rates (flow) in derivation of CFs can be considered a factor reflecting current importance of resources (Guinée and Heijungs, 1995; JRC, 2011; Klinglmair et al., 2014). In terms of cause-effect chains, the importance of resources corresponds to the effect and damage of scarcity. Therefore, the actual cause-effect chain of the ADP is similar to that of CA. Interestingly, the original intention of the ADP was to assess the "seriousness of depletion" (Guinée and Heijungs, 1995). This can be compared to CA which essentially intends to assess the seriousness of supply disruption. Hence, the actual cause-effect chain scope of the ADP may have been aligned with the initial intended scope of assessing the "seriousness of resource depletion" (provided that current importance of resources can be used as a proxy for long term future importance). It is however misaligned with how it is usually interpreted and recommended, i.e. as a LCIA midpoint depletion method.

The third benefit concerns conceptual and terminological precision. A commonly recurring argument which has fomented the persistent resource debate (see for example (Drielsma et al., 2015; Tilton, 2010; West, 2020)) is that depletion does not happen until resources are dissipated. This argument is indeed relevant, but it muddles two different mineral resource problems: extraction from ecospheric stocks and dissipation from technospheric funds. In focusing on total availability, i.e. the sum of ecospheric stocks and technospheric funds, and the promise of minimizing dissipation from technospheric funds, such "less pessimistic" authors commonly conclude that assessing impacts on ecospheric stocks is irrelevant (Drielsma et al., 2015; West, 2020). We demonstrate in this paper that characterizing mineral resource availability as only a stock problem, as in LCIA (Sonderegger et al., 2017), has limitations in the context of a comprehensive assessment of mineral resource availability. However, we do not agree with the conclusion that assessment of ecospheric stocks is irrelevant as a result of such limitations (Drielsma et al., 2015; West, 2020). Rather, recognizing that mineral resources can pose flow, fund and stock problems clarifies that depletion of ecospheric stocks, dissipation of technospheric funds and technospheric circumstances influencing flows are all distinct and relevant subsets of the question of total mineral resource availability. In other words, the distinction between stocks, funds and flows equips the literature on comprehensive assessment of mineral resource availability with a more accurate terminology. This is essential for reconciling seemingly opposing views in this persistent debate and future work towards purposive and complementary methodologies.

These three benefits suggest that a comprehensive mineral resource assessment could compose distinct and complementary methods which respectively focus on stocks, funds or flows (Fig. 2) instead of inconsistent combinations thereof. The Crustal Scarcity Indicator (Arvidsson et al., 2020) addresses the need for an LCIA method that reflects long term impacts on ecospheric stocks. In line with the recommended future work on methods addressing dissipation (Berger et al., 2020; Beylot et al., 2020; Charpentier Poncelet et al., 2019) technospheric fund methods focusing on urban and landfill mining (Ayres, 1999; Blasenbauer et al., 2020) could be developed. If extraction will increasingly rely on secondary resources, as the vision of a circular economy implies, such methods will become increasingly important as parts of a comprehensive assessment which accounts for both ecospheric and technospheric availability. We should add that the literature focused on quantifying technosospheric funds rather refer to them as *stocks*. But as we have argued, *funds* would be a more accurate term in the context of the AoP-NR. Accessibility for users in the short term is determined by magnitude and location of technospheric flows. Several CA and LCSIA methods currently assess this but mainly with regard to primary technospheric flows. Focusing also on secondary technospheric flows has been suggested a further development of LCSIA methods (Berger et al., 2020).

4. Discussion

The paper contributes in several ways to the literature on assessment of mineral resource availability. The mapping of impact pathways of LCIA, CA and LCSIA methods onto a common cause-effect chain framework allows for increased understanding of how the methodologies can complement each other. In particular, it clarifies how methodologies relate to the fundamental concepts of scarcity and rarity. Importantly, the proposed cause-effect chains are aligned with the definitions of *scarce*, *"deficient in quantity or number compared with the demand"* (Merriam-Webster, n.d.) and *rare*, "*seldom occurring or found: uncommon*" (Merriam-Webster, n.d.). The exposure step represents the meeting point of rarity and demand, denoting that users (technospheric) with a demand are exposed to rarity (either ecospheric or technospheric), thus experiencing scarcity. It follows that the subsequent steps of *effect* and *damage* occur within the technosphere (Fig. 1). This seems to be overlooked by the LCI-UNEP (Sonderegger et al., 2020) who map "additional ore", additional energy" and "additional cost" as cause-effect chain steps occurring outside the technosphere. The categorization of such steps as technospheric is supported by the argument that extraction efforts are part of LCI (technospheric focus) rather than LCIA (ecospheric focus) (Finnveden, 2005).

Another difference between this paper and the literature concerns the cause-effect chain for LCSIA methods. Sonderegger et al. (2020) suggest that vulnerability is separated from "impaired function" and "additional costs". This seems to contradict the CA literature, where these factors rather reflect vulnerability. In this respect, the cause-effect chain suggested in this paper bears stronger resemblance to that of Cimprich et al. (2019) except for a few differences. Importantly, the explicit use of cause-effect chain steps provides a common framework for AoP-NR methodology. Considering the prevalent terminological and methodological ambiguity in the literature this is much needed.

Further, neither the SUPRIM project (Schulze et al., 2020a, b) nor the LCI-UNEP (Berger et al., 2020; Sonderegger et al., 2020) considers the potential usefulness of distinguishing between stocks, funds and flows of mineral resources. Neither do they explicitly promote keeping ecospheric and technospheric factors separate in distinct methods as a way to align actual and intended scopes. Consequently, their recommendations differ from ours in some respects. For instance, the LCI-UNEP discusses benefits and drawbacks of including extraction rates in LCIA methods (Sonderegger et al., 2020). Despite the drawbacks, the ADP method is given the highest level of recommendation of all 27 methods reviewed (Berger et al., 2020; Sonderegger et al., 2020). This recommendation clearly differs from the recommendations of this paper, considering how the combination of flows and stocks in the derivation of the CFs of the ADP has been shown to result in methodological inconsistency and unclear temporal scope.

However, the consideration of stocks, funds and flows suggested in this paper needs to be elaborated on in future research, especially since they are relative terms. As pointed out by Sonderegger et al. (2017), how to define clear boundaries between these categories is an open question. In addition, the temporal scope has implications for whether a flow can be considered dissipated or not (Beylot et al., 2020). With a short term scope, all metals which are not functionally recycled can be considered dissipated (Beylot et al., 2020). With a medium or long term scope, however, it cannot be excluded that even such non-functionally recycled flows may become functional again (Beylot et al., 2020). Thereby, the temporal scope has implications for the categorization of mineral resource compartments as stocks, funds and flows. Future work could aim to clarify which compartments are best described by which category and in what temporal scope.

5. Conclusions

By comparing the three methodologies within a common framework, it can be clarified that, predominantly, scarcity is caused by: ecospheric rarity and non-foreseeable demand in LCIA, and technospheric rarity and foreseeable demand in CA and LCSIA methods. More specifically, the predominant intended scopes can be summarized as follows:

- Depletion LCIA methods reflect the potential of current product systems to deplete ecospheric stocks, and ultimately cause potential scarcity in the long term future.
- Future efforts LCIA methods include what is reflected by depletion methods, i.e. potential scarcity, and add potential consequences of scarcity in terms of substitution to lower grade ores and associated increased costs.
- LCSIA methods reflect the potential of technospheric circumstances to disrupt supply of technospheric flows and thereby cause scarcity in the short term future.
- CA methods include what is reflected by LCSIA methods, i.e. potential scarcity, and add potential consequences of scarcity in terms of substitution to other resources and associated increased costs.

Thus, there is a symmetry between depletion and LCSIA methods, which both assess *scarcity*, and between future efforts methods and CA methods, which both assess *consequences of scarcity*, for either future generations (LCIA) or the system under study (CA and LCSIA). This straightens out the terminological and methodological ambiguity which has caused important concepts such as scarcity, criticality and depletion to be muddled by method developers (see SI) and practitioners (Berger et al., 2020).

The comparison also reveals that there are unintended similarities in temporal scopes between LCIA, CA and LCSIA methods. Although the predominant intended temporal scopes are long term in LCIA and short or medium term in CA and LCSIA methods, the actual scopes of all of them are predominantly short to medium term or incongruent. The underlying reason for this is a lack of distinction between mineral resource stocks, funds and flows. This distinction has three principal benefits. First, it creates better alignment between intended and actual temporal scopes within methods and between methodologies. Second, it resolves methodological inconsistency with regard to impact pathway cause-effect chains. Third, it equips the literature with a more accurate terminology. Thereby, it is concluded that a more prominent distinction between mineral resource stocks, funds and flows is essential for aligning intended and actual scopes of individual methods and methodologies. This in turn is essential for a comprehensive mineral resource availability assessment consisting of individually purposive and mutually complementary parts.

Based on these conclusions, it is recommended that: long term scopes (as predominantly assessed in LCIA) are addressed by methods focusing on ecospheric stocks; short term scopes (as predominantly assessed in CA and LCSIA methods) are addressed by methods focusing on factors which represent, or can influence, magnitude and location of technospheric flows. Further, funds of mineral resources in e.g. products in use, end of life products and landfills are relevant in different temporal scopes. In line with discussions on accounting for dissipation in LCA (Beylot et al., 2020) and the expected growing reliance on secondary resources with the advent of a more circular economy (Blasenbauer et al., 2020) technospheric fund methods focusing on e.g. urban and landfill mining (Ayres, 1999) could be useful additions to a comprehensive assessment of mineral resource availability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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