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Life cycle impact assessment methods for estimating the impacts of dissipative flows of metals

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Abstract

The dissipation of metals leads to potential environmental impacts, usually evaluated for product systems with life cycle assessment. Dissipative flows of metals become inaccessible for future users, going against the common goal of a more circular economy. Therefore, they should be addressed in life cycle impact assessment (LCIA) in the area of protection "Natural Resources." However, life cycle inventory databases provide limited information on dissipation as they only track emissions to the environment as elementary flows. Therefore, we propose two LCIA methods capturing the expected dissipation patterns of metals after extraction, based on dynamic material flow analysis data. The methods are applied to resource elementary flows in life cycle inventories. The lost potential service time method provides precautionary indications on the lost service due to dissipation over different time horizons. The average dissipation rate method distinguishes between the conservation potentials of different metals. Metals that are relatively well conserved, including major metals such as iron and aluminum, have low characterization factors (CFs). Those with poor process yields, including many companion and high-tech metals such as gallium and tellurium, have high CFs. A comparative study between the developed CFs, along with those of the Abiotic Depletion Potential and Environmental Dissipation Potential methods, show that dissipation trends do not consistently match those of the depletion and environmental dissipation potentials. The proposed methods may thus be complementary to other methods when assessing the impacts of resource use on the area of protection Natural Resources when pursuing an increased material circularity. This article met the requirements for a gold-silver *JIE* data openness badge at http://jie.click/badges.

KEYWORDS
circular economy, dissipation, industrial ecology, life cycle assessment (LCA), metals, Natural Resources

1 | INTRODUCTION

1.1 | Context

The dissipation of mineral resources is a major concern for both the economy and the environment. It may hinder the future availability of resources (Mancini, De Camillis, & Pennington, 2013) and lower the quality of the receiving material flow (Nakamura, Kondo, Nakajima, Ohno, & Pauliuk, 2017), therefore increasing our dependency on primary metal extraction (Ciacci, Harper, Nassar, Reck, & Graedel, 2016; Zimmermann, 2017). It can also adversely impact ecosystems and human health (Arvidsson, Molander, & Sandén, 2012; Diaz & Rosenberg, 2014; Lifset, Eckelman, Harper, Hausfather, & Urbina, 2012; Zimmermann & Gößling-Reisemann, 2013). The reduced recycling potential of resources pressures primary production, which often represents a bigger share of deleterious environmental impacts compared to recycling (Ciacci et al., 2016; European Commission, 2016; Nuss & Eckelman, 2014; Van der Voet, Van Oers, Verboon, & Kuipers, 2019). To address these issues, European policies are aiming at using resources more efficiently and closing the material loops within the premises of a circular economy (European Commission, 2011, 2013b, 2015, 2020). The objective of circular economy is to manage resources more efficiently and sustainably to increase the value obtained from resources through strategies such as slowing and closing resource loops (Bocken, de Pauw, Bakker, & van der Grinten, 2016; EEA, 2019; Moraga, Huysveld, De Meester, & Dewulf, 2021).

Dissipative flows (DFs) can result from the use of different types of resources, and the phenomena leading to dissipation may vary among them (Beylot, Ardente, Marques, et al., 2020; Helbig, Thorenz, & Tuma, 2020; Stewart & Weidema, 2005). In particular, metals can remain in the economy for a long time if they are not used in dissipative applications (see, e.g., Ciacci, Reck, Nassar, & Graedel, 2015) and are properly managed across the life cycles of products. Efforts are necessary across all life cycle stages to achieve the best circularity possible, such as proper designs allowing reuse and recycling, efficient transformation processes, and efficient waste collection and recycling processes (Bracquené, Dewulf, & Duflou, 2020; Reuter, van Schaik, Gutzmer, Bartie, & Abadías-Llamas, 2019). However, most metals are lost after just one application, and only a few metals are collected and functionally recycled at an end-of-life recycling rate over 50% (UNEP, 2011). Circularity could hence be improved for all of the metals to retain their value in the economy given additional means and efforts.

Life cycle assessment (LCA) is a recognized assessment tool which allows a holistic assessment of the potential environmental impacts of a product system. The methodology and its application is framed by the ISO 14 040 and ISO 14 044 standards (ISO, 2006a, 2006b). An LCA study generally consists in four main phases: (1) setting a goal and scope; (2) compiling a Life Cycle Inventory in a so-called life cycle inventory (LCI) phase; (3) assessing the potential environmental impacts associated with the inventory in a so-called life cycle impact assessment (LCIA) phase; and (4) analyzing the results. The LCI is a compilation of all of the exchanges between a product system and the environment (i.e., elementary flows: extraction of resources and emissions into the environment), while the LCIA is realized using methods that characterize the potential environmental impacts of these flows using characterization factors (CFs). Three areas of protection (AoP) are typically addressed in the LCIA step: Human Health, Ecosystem Quality and Natural Resources (EC-JRC-IES, 2010; Udo de Haes et al., 1999).

In this paper, we focus on the AoP Natural Resources, which has been subject to scrutiny in recent years (Dewulf et al., 2015; Drielsma, Russell-Vaccari, et al., 2016; Sonderegger et al., 2017). Based on the works of Schulze et al. (2020), Berger et al. (2020) recently consensually defined the damage of mineral resource use on the AoP Natural Resources as "*the reduction or loss [of the potential to make use of the value that mineral resources can hold for humans in the technosphere] caused by human activity*."

The product environmental footprint (PEF) guidelines integrate resource efficiency and circularity concerns in its standardized environmental assessment methodology (European Commission, 2013b; Zampori & Pant, 2019). As a systemic assessment tool, LCA can also support the integration of material circularity concepts (Kalmykova, Sadagopan, & Rosado, 2018; Life Cycle Initiative, 2020; Strothman & Sonnemann, 2017). However, it is limited in doing so, because LCI databases do not allow to track flows that are dissipated inside the technosphere (Beylot, Ardente, Sala, & Zampori, 2020a; Charpentier Poncelet et al., 2019; Zampori & Sala, 2017). Generally, only extraction flows are characterized with LCIA methods for the AoP Natural Resources. This overlooks DFs which may occur in any life cycle phase and generate impacts on the AoP (Berger et al., 2020; Beylot, Ardente, Sala, et al., 2020a; Drielsma, Allington, et al., 2016; Schulze et al., 2020; Stewart & Weidema, 2005; van Oers & Guinée, 2016; Zampori & Sala, 2017). One exception is the environmental dissipation potential (EDP) method, which characterizes the impacts of emissions to the environment on the AoP (van Oers et al., 2020).

DFs represent the real consumption of metals (Helbig et al., 2020). It thus seems desirable to account for DFs in the LCI and characterize them with a consistent LCIA method (Berger et al., 2020; Beylot, Ardente, Sala, et al., 2020a; Charpentier Poncelet et al., 2019; Weidema, Finnveden, & Stewart, 2005; Zampori & Sala, 2017). However, accounting for DFs in inventories would imply important modifications of the existing LCI databases, which are not expected to be feasible in the short term (Beylot, Ardente, Marques, et al., 2020; Beylot, Ardente, Sala, et al., 2020a). Hence, Charpentier Poncelet et al. (2019) proposed two alternatives to account for DFs based on dynamic material flow analysis (MFA) data: either by updating or creating new LCI (option 1), or by integrating the data on dissipation in an LCIA method that can be applied to extraction flows in the LCI (option 2). Helbig et al. (2020) have published such global dynamic MFA data, providing dissipation patterns of metals over the anthropogenic cycle of metals and their anticipated lifetime in the anthroposphere.

1.2 | Objectives

We hereby propose a workaround solution to take dissipation into account in two LCIA methods which can be applied directly to extraction flows quantified in LCI, as per option 2 described above. We specifically address the impacts of DFs of metals on the AoP Natural Resources. The definition of DFs specific to this paper is provided in Section 2.1. To achieve this, a concept and method to integrate time-differentiated measurements of DFs from dynamic MFA data is used to calculate CFs for 18 metals. The dynamic MFA data originates from the work of Helbig et al. (2020). Dissipation patterns are integrated into CFs that can be applied directly to extraction flows quantified in the LCI. Two LCIA methods are developed: the lost potential service time (LPST) and the average dissipation rate (ADR). The resulting sets of CFs are analyzed and compared to those of other LCIA methods in a comparative CF study. While nearly 30 methods exist (Sonderegger et al., 2020), three have been selected for this study: the abiotic depletion potential (ADP) using economic reserves (van Oers et al., 2002), ADP using ultimate reserves (van Oers et al., 2002; van Oers et al., 2019), as well as the EDP method (van Oers et al., 2020). This selection is justified in Section 2.6.

With regard to the overall structure of this paper, the methods are presented in Section 2, in which we explain the rationale for the methods (Section 2.1), present the impact pathways addressing the fate of metals in the technosphere after extraction in terms of dissipation (Section 2.2), justify the geographical scope and time horizons (Section 2.3), describe the underlying dynamic MFA model (Section 2.4), detail the calculations of the CFs (Section 2.5), and provide the description of the methods selected for the comparative CF study (Section 2.6). In Section 3, we present and discuss the resulting CFs as well as the results for the comparative study and the potential limitations of the developed methods. In Section 4, we provide general conclusions and an outlook on future works for measuring the impacts of the DFs of mineral resources in LCA.

2 | METHODS

2.1 | Rationale of the approach for the development of LCIA indicators for dissipation

For clarity in the following text, we hereby define dissipation-related terms. DFs are "flows to sinks or stocks that are not accessible to future users due to different constraints. These constraints prevent humans to make use of the function(s) that the resources could have in the technosphere. The distinction between dissipative and non-dissipative flows of resources may depend on technological and economic factors, which can change over time" (Beylot et al., 2020a). The state of a resource which is considered as not accessible anymore is branded as "dissipated." An action which triggers DFs is characterized as "dissipative."

It can be said that dissipation generally goes against the commonly accepted objective of a more circular economy. Circularity is here defined as the capacity to keep resources in the economy as part of in-use stocks, in line with Moraga et al. (2021). In theory, a perfect circularity occurs when there are no DFs resulting from the anthropogenic cycle of metals (i.e., all processes have perfect yields of 100%), although there are intrinsic limits to reach perfect yields, such as thermodynamic limits due to the naturally growing entropy of systems and other technological or physical limits to processes (Cullen, 2017; Reuter et al., 2019). The yield of primary production can also be considered to influence the opportunity to make use of resources in the economy.

In this article, we consider DFs to be any flow of an element that is transferred to tailings and landfills, other material flows (through non-functional recycling), or emitted to the environment due to human activity. Non-functional recycling is defined as the "*portion of end-of-life recycling in which the metal is collected as old metal scrap and incorporated in an associated large magnitude material stream as a 'tramp' or impurity elements*" (UNEP, 2011). While it can generally be considered that the flows of most metals emitted to the environment become permanently inaccessible, some that are disposed of as final waste in landfills or tailings could be considered to be potentially accessible in the future (Moraga et al., 2021; Schneider et al., 2011, 2015; Stewart & Weidema, 2005; Zimmermann & Gößling-Reisemann, 2013). Still, elements ending in these stocks are not accessible to be made use of effectively in the economy at least for the duration they remain in them. Moreover, it is unsure whether or not they will at some point in the future become once again accessible, nor when this might be the case. Helbig et al. (2020) highlight that the recovery of elements from, for example, tailings and landfills is currently technically and economically unfeasible in the vast majority of cases. Moreover, Blengini et al. (2019) inventoried a relatively small number of implemented industrial projects recovering metals from these compartments. Hence, in this paper, such flows are considered as DFs based on precautionary principles, in line with the rationale of Zimmermann and Gößling-Reisemann (2013), which has been taken up by Helbig et al. (2020). More generally, such considerations are in line with the literature of life cycle based studies which, in recent years, have increasingly accounted for DFs to final waste disposal facilities and other material flows in the technosphere (in which dissipated resources have low or no function), in addition to DFs to the environment (Beylot et al., 2020; Beylot, Ardente, Sala, et al., 2020a). Figure 1 presents an overview of DFs to the environment and to the technosphere for the main life cycle phases.

DFs are identified for the main life cycle steps: primary production (DF_p), fabrication and manufacturing (DF_f), use phase (DF_u), waste management (DF_c), and recycling (DF_r). Since flows to tailings and landfills are already accounted for as DFs, potential emissions from these two compartments are not further accounted for. One should note that the economy includes the resources whose functionalities are being made use of

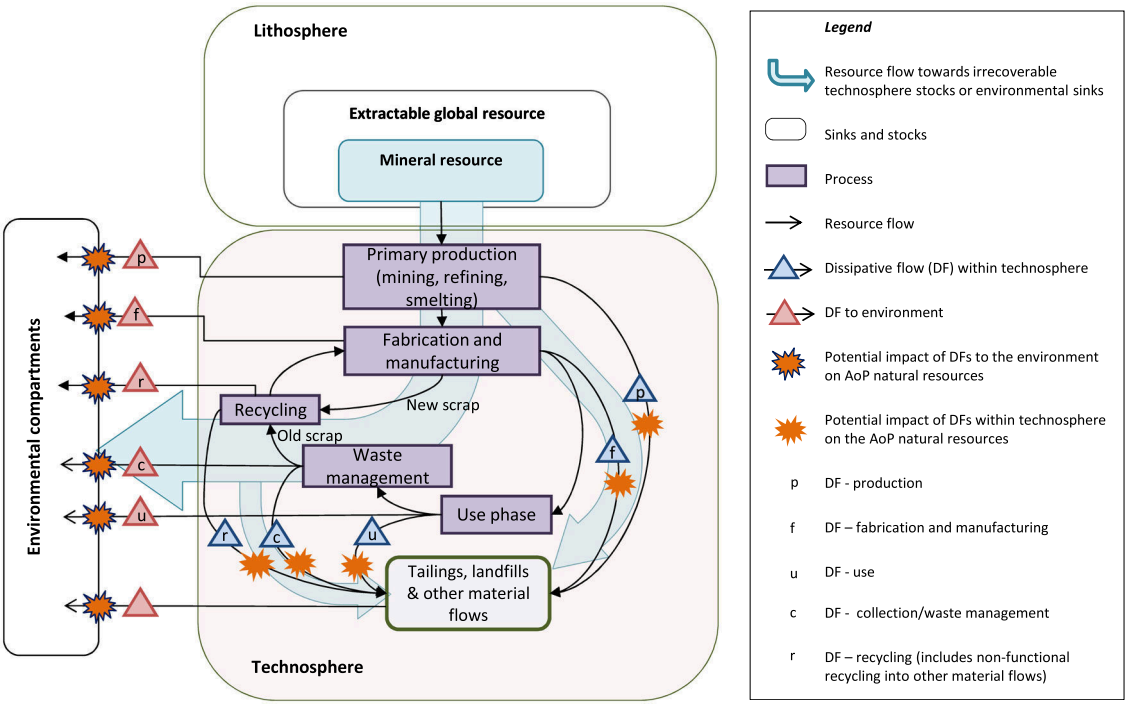

FIGURE 1 Generic anthropogenic cycle for mineral resources from the geological stock to temporary or final stocks and sinks through main processes and their corresponding dissipative flows (adapted from Helbig et al., 2020)

(i.e., in-use stocks), whereas the stocks in the technosphere more broadly encompass resources stored in landfills and tailings in addition to in-use stocks.

Metals accumulate in anthropogenic stocks (e.g., in-use stocks, landfills) and sinks (e.g., environmental compartments) while the geological stocks diminish with the cumulative extraction over time. As illustrated in Figure 1, the fate of metals in the technosphere depends on the yields of the successive processes as well as on the applications in which metals are used (see e.g., Ciacci et al., 2015; Furberg et al., 2019; Zimmermann, 2017). The time dimension is crucial, as the DFs of metals will reach sinks and stocks depending not only on process yields, but also on the product lifetimes. For such reason, it is deemed critical to integrate time in circularity-oriented indicators (Moraga et al., 2021, 2019).

Since metal elements are indestructible, the highest potential instrumental value that a single element of metal can provide to human beings stems from a virtually permanent use of the element in the economy and at its maximum functionality (i.e., without a decrease of quality) (Ayres & Peiró, 2013). Functionality here refers to the contribution of metals to the instrumental value of in-use stocks in the form of products and services in the economy. In the LCA framework, the service provided by resources includes both the background services enabling a product system (such as energy, infrastructure, machinery, and transport), and the functional unit related to the system under study.

The amount of service provided by metals and their potential value for users depend on the total in-use stocks of metals, on their quality, as well as on the applications in which they are used. The latter are intrinsically covered by the functional units in LCA. The two other factors, that is, the total amount of in-use stocks and their quality, can be adversely impacted by human activities through two phenomena:

- DFs, going against circularity principles and resulting in a "*lost potential to make use of the value of resources.*"
- The contamination of the material flow containing the metallic element, leading to a material of lesser quality and resulting in a "*reduced or lost potential to make use of the value of resources.*" For example, impurities exceeding certain thresholds in aluminum alloys can affect their properties such as corrosion resistance (Davis, 2001). Most old aluminum scraps are recycled into cast alloys which in general have higher thresholds for alloying elements than wrought alloys (Classen et al., 2009).

2.2 | Impact pathways

We propose two methods to address the dissipation of metals: LPST and ADR. The studied impact mechanism is based upon the Service Time (ST) of resources, which is here defined as the service provided by a resource as part of in-use stocks in the economy after its extraction from the natural environment, and until it has been dissipated after one or successive applications. The total expected ST, ST_{TOT}, corresponds to the anthropogenic

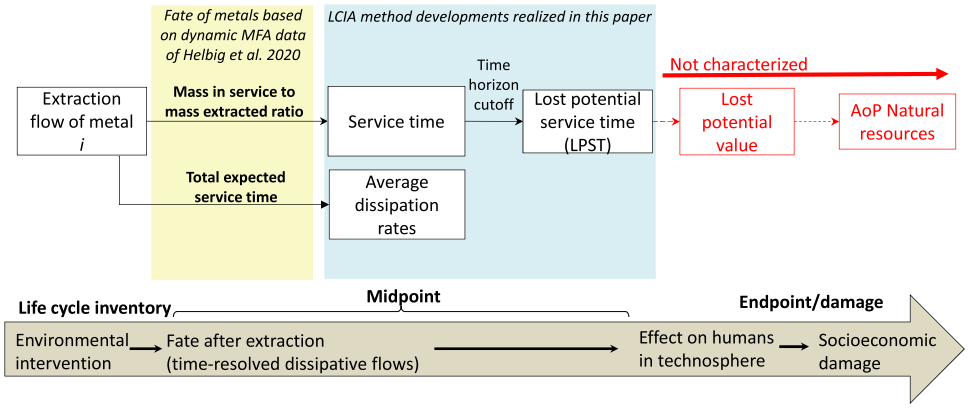

FIGURE 2 Impact pathways for the lost potential service time (LPST) and the average dissipation rate (ADR) methods

lifetime of metals as defined by Helbig et al. (2020). It depends on the yields of processes, dissipative uses, as well as the expected lifetimes of the different applications in which they are used.

The impact pathway addressing the lost potential to make use of metals once they have been extracted from the natural environment is described in Figure 2. The distinction is made between the underlying dynamic MFA data (yellow box) and the developments realized in this paper (blue box).

As illustrated in Figure 2, the LPST potentially induces a socio-economic impact for human beings, which could be assessed by quantifying any reduction or loss of the potential to make use of the value of extracted resources over time. It should be noted that many functions can be provided by a single resource. These functions can change over time (e.g., if copper in a pipe can be recycled in a wire), and each function could be valued differently by its users. At this point, additional research is needed to address this complex issue.

The fate of metals over their lifetime in the anthroposphere is the first step in the impact pathway, which corresponds to the expected ST of resources after extraction based on the current state of the economy. It is calculated based on the DFs of each life cycle phase and the lifetime of end-use applications as measured by Helbig et al. (2020). The ST-integrated mass can be derived year by year based on the data of Helbig et al. (2020), as shown in the "Table S2-2: Stock_from_Extraction" tab in the spreadsheet provided in Supporting Information S2. The LPST can then be measured up to a desired time horizon, at which a cut-off may be placed (see the "LPST" tab in the same spreadsheet). The ST_{TOT} can also be inverted in order to calculate the ADR. Detailed equations for each method are provided in Section 2.4.

The LPST is proposed as a midpoint impact assessment method addressing the lost opportunity to make use of resources once they have been extracted from the lithosphere in relation to a distance-to-target approach, the target being perfect yields for all processes. We call this target the optimum service time (OST). This rationale is similar to that of other circularity-oriented approaches. For instance, Moraga et al. (2021) consider that the maximum in-use occupation is equal to the theoretical maximum use of materials within a given time horizon, while Parchomenko et al. (2020) also use a target system state for the measurement of the material effectiveness of circular economy strategies.

Figure 3 illustrates the concepts of ST and LPST at the time horizon cut-offs of 100 and 500 years with an arbitrary dissipation curve for metal *i*. Some examples of computed dissipation curves from the works of Helbig et al. (2020) are provided in Figure S1-2 in Supporting Information. The grey area over the curve represents the lost ST that could have been provided by this same amount of extracted resources if no dissipation occurred over time. It is thus capped at 1 kg of metal *i* used in the economy per year per kilogram of metal *i* extracted.

The initial mass of metal *i* is below 1 kg due to dissipative flows that do not become part of in-use stocks, including immediate dissipative uses. The yellow area under the curve represents the amount of metal *i* in use over time (i.e., the ST) given the DFs of metal *i* that are expected to result from the successive processes and applications for an initial kg of metal *i* extracted from the ground. The ST thus represents the total amount of in-use functionality provided by a given amount of extracted resources up to a given time horizon. The total expected ST (ST_{TOT}) is equal to the integral of the dissipation curve until the metal is virtually completely dissipated. It has been calculated with a time horizon of 1000 years (Helbig et al., 2020).

We also propose the ADR as a standalone indicator, which provides the global yearly dissipation rate of metals during their anticipated anthropogenic cycle. The ADR can be understood as a weighted ADR per year. The two proposed LCIA methods are intended to enable comparison between the global cycles of metals and to reflect their dissipation potentials within the current state of the economy.

2.3 | Geographical scope and time horizons

It may be considered that the accessibility of resources at the global scale is of most relevance when assessing the impacts of resource use of the AoP, as these resources are often traded on international markets (Schulze et al., 2020). Our indicators are developed using the global scope.

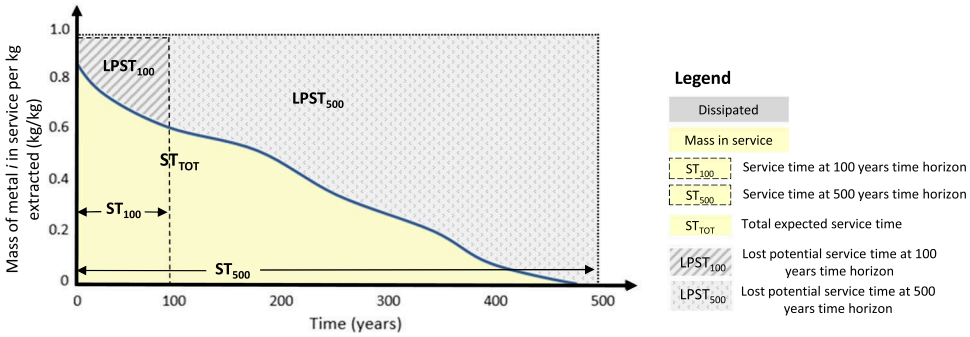

FIGURE 3 Example of an arbitrary dissipation pattern for metal *i* and the associated service time (ST_{TH}) at the time horizons 100 and 500 years, as well as total expected service time (ST_{TOT}). The corresponding lost potential service times (LPST) for these time horizons are illustrated. The ST and LPST at the time horizon of 25 years are not depicted

Selecting the time horizon for the assessment must be done carefully, since it has implications on which generation is to be preferentially protected from environmental damage (Dyckhoff & Kasah, 2014; Sproul et al., 2019). Indeed, different stakeholders might be interested in various time horizons depending on what they value and on their beliefs about the adaptation potential of future societies (e.g., through technological developments) (Hofstetter, 1998).

Recently, both the SUPRIM project team and the Joint Research Centre (JRC) of the European Commission have proposed to account for the accessibility of resources over the short-term (25 years) and over a long-term time horizon (a few hundred years, e.g., 500 years in the SUPRIM project) (Beylot et al., 2020; Schulze et al., 2020; van Oers et al., 2020). The JRC suggested taking a short-term perspective of 25 years so that any flow of resources to the environment, final waste disposal facilities and products in use in the technosphere (with low-functional recovery) may be reasonably reported as dissipative (i.e., inaccessible to any future user within 25 years) (Beylot et al., 2020; Beylot et al., 2020b). In the SUPRIM project, it was considered that dissipation results only from emissions to the environment in the long term, as anthropogenic stocks such as tailings and landfills may theoretically become accessible in the future (Schulze et al., 2020; van Oers et al., 2020). This assumption is optimistic about the future technical capacities and economic viability of recovering resources from these deposits and represents the best-case scenario. Moreover, it overlooks potential temporary accessibility issues due to, for example, geopolitics or economic cycles between the short and the long term. Hence, this assumption rather fits the individualist perspective, which is optimistic regarding technological solutions to support human adaptation (Hofstetter, 1998; Huijbregts et al., 2017). In contrast, we conservatively consider that all of the flows to these technosphere compartments remain inaccessible over any time horizon, which could be deemed the worst-case scenario. This may be viewed as most in line with the egalitarian perspective when assessing the impacts over longer time horizons (e.g., 500 years). Indeed, it is a precautionary assessment of the impacts for the future generations considering egalitarians' general aversion for burden shifting and pessimistic view of future technological developments (Hofstetter, 1998; Huijbregts et al., 2017).

In addition to the short-term (25 years) and long-term (500 years) time horizons, we propose a time horizon of 100 years for the midterm. Thus, the LPST method is computed for time horizons of 25, 100, and 500 years to reflect, respectively, the short-, mid-, and long-term impacts of resource use, so that practitioners may choose that which corresponds more closely to the objectives of a given study. These options may allow to compare trade-offs between the impacts assessed with the LPST method and those assessed for other impact categories such as those included in the ReCiPe method (Huijbregts et al., 2017). However, it should be noted that the time horizon of 100 years may become more representative of the hierarchist perspective only if some future recovery from tailings and landfills is considered, as they may believe in human adaptation through technological developments to a certain extent (Hofstetter, 1998; Huijbregts et al., 2017).

Moreover, it may be relevant to consider different time horizons when assessing the impacts of resource use on the AoP Natural Resources along with other methods. For instance, the LPST at a time horizon of 25 years may be complementary to the short-term depletion potentials as measured by the ADP economic reserves (van Oers et al., 2002), while the LPST at a time horizon of 500 years, to the long-term depletion potentials as measured by the ADP ultimate reserves (van Oers et al., 2002, 2019; van Oers & Guinée, 2016). If other time horizons are deemed more relevant to practitioners, other CFs may be calculated with the data supplied in the spreadsheet provided in Table S2-4 in Supporting Information S2 along with the equations below. Contrarily to the LPST method, the ADR method has no time horizon since it integrates the time function as part of its calculation in order to provide a yearly rate of dissipation.

2.4 | Description of the underlying dynamic material flow analysis model

Here we briefly describe the dynamic MFA model developed by Helbig et al. (2020) to compute the global DFs for 18 metals. For a detailed description of the model, the original article of Helbig et al. (2020) should be consulted. Data inputs from global MFA studies are

TABLE 1 Acronyms, symbols, appellation, definitions and units

Acronyms and symbols	Appellation	Definition	Unit
i	Metal i	Metallic elements, e.g., copper (Cu)	—
DF	Dissipative flows	Cf. Section 2.1.	kg
msr_i	Mass in service to mass extracted ratio	Measured ratio of metal i in service (in kg) at a given time t, in relation to 1 kg of metal i extracted	kg/kg = 1
t	Time	Time lapse since extraction	year
Δt	Time length	Time interval in between successive time periods t	year
TH	Time horizon	Time horizon for the LPST indicator (25, 100, or 500 years)	year
ST_{TH}	Service time	Anticipated service time of metal i until a given time horizon, for 1 kg of metal i extracted	Kg year/kg = year
ST_{TOT}	Total expected service time	Total expected service time of metal i in the economy after extraction and until its complete dissipation, for 1 kg of metal i extracted. For example, 1 kg of iron extracted provides an ST_{TOT} of 110 kg year (cf. Table S1-1 in Supporting Information S1)	Kg year/kg = year
omsr	Optimal mass in service to mass extracted ratio	Theoretical optimal ratio between the mass in service in relation to 1 kg of metal i extracted, given perfect yields (1:1)	kg/kg = 1
OST	Optimum service time	Theoretical optimum service time of metal i extracted until a given time horizon given perfect yields, for 1 kg of metal i extracted	Kg year/kg = year
$LPST_{TH}$	Lost potential service time	Total potential impacts due to the lost potential service time of metal i at a given TH for 1 kg of metal i extracted	Kg year/kg = year
CF_{LPST}	Characterization factors for the LPST method	Characterization factors for the LPST method: LPST of metal i in relation to the LPST of iron (Fe) at a given TH	kg Fe-eq./kg
TLPST	Total lost potential service time	Category total for the LPST method	kg Fe-eq.
ADR	Average dissipation rate	Average dissipation rate of metals over their lifetime in the economy	kg/kg year = 1/year
CF_{ADR}	Characterization factors for the ADR method	Characterization factors for the ADR method: ADR of metal i in relation to the ADR of iron (Fe)	kg Fe-eq./kg
TDR	Total dissipation rate	Category total for the ADR method	kg Fe-eq.
m_i	Mass of metal i extracted (inventory data)	Mass of metal i extracted in the life cycle inventory phase	kg

harmonized and run through the model. The data used in the background MFA studies range from 1997 to 2015. The metals used for the study are selected based on the completeness and the data quality of the available MFA models. The harmonization process includes the distribution of the in-use metals within 29 end-use sectors (e.g., manufacturing, transport) for which average lifetimes are harmonized based on peer-reviewed literature. Process yields are calculated for each main life cycle process (cf., Figure 1). These yields are assumed to be the same for every sector and to remain constant over time. Dissipative uses are accounted for. The metals that are expected to be collected and functionally recycled after their application's lifetime are redistributed into the 29 sectors following the initial distribution for each of them.

It is considered that the time required for the different life cycle phases is negligible except for the use phase. DFs for each main life cycle stage are computed in reference to 100 units of a metal entering the use phase. Flows of metals ending in the environment, other material flows through non-functional recycling, and tailings or landfills are all considered as dissipative, concordantly with the rationale presented in Section 2.1.

2.5 | Computation of the characterization factors

For the calculation of CFs, we consider 1 kg entering the (primary) production process instead of 100 units entering the use phase as in the original model. The nomenclature and symbols are the same as in Helbig and colleagues' work (2020), except for "losses" which have been replaced with "DFs" for consistency within this paper. The computational structure of the dynamic MFA related to this article is detailed in Supporting Information S1, while the spreadsheet provided as Supporting Information S2 shows the step-by-step results for the calculations of the CFs for the LPST method (CF_{LPST}) and the ADR method (CF_{ADR}) corresponding to Equations (1)–(8) presented below. Table 1 provides an overview of acronyms and symbols used in the equations.

2.5.1 | Calculations for the LPST method

The fate of a given metal, that is, the expected ST of metal *i* up to a given time horizon, is measured by summing its mass in service ratio (msr) over time up to the delimiting time horizon (TH) for 1 kg extracted, as depicted in Figure 3. It is calculated with Equation (1):

$$\mathrm{ST}_{i,\,\mathrm{TH}} = \sum_{t=0}^{\mathrm{TH}-1} \mathrm{msr}_i\,(t)\,\Delta t \tag{1}$$

where msr_i is the ratio of the mass of metal *i* in service at a given time *t* for 1 kg of metal *i* extracted in $\mathrm{kg.kg}^{-1}$, *t* is the time lapse since extraction in year, TH is the time horizon (25, 100, or 500 years), and $\Delta t = 1$ year. ST is the anticipated service time provided by the initially extracted metal *i* until a given TH, expressed in kg year/kg of metal *i* extracted. The $\mathrm{ST}_{i,\,\mathrm{TOT}}$ is theoretically calculated with an infinitely large TH, and the model in practice was run with 1000 years of time lapse.

In the theoretical optimal conditions (i.e., with perfect yields), the optimal mass in service ratio (omsr_i) is of 1 kg in service for 1 kg extracted for each time step in Equation (1). Thus, each kg of metal *i* extracted provides 1 kg year of ST for each year *t*. The OST for the initially extracted metal *i* until a given TH is calculated with Equation (2):

$$\mathrm{OST}_{\mathrm{TH}} = \sum_{t=0}^{\mathrm{TH}-1} \mathrm{omsr}\,(t)\,\Delta t = \mathrm{omsr}\cdot\mathrm{TH} = 1\ \mathrm{kg}\cdot\mathrm{TH/kg} \tag{2}$$

where $\Delta t = 1$ year. The OST is measured in kg year/kg of metal *i* extracted.

The LPST measures the difference between the target OST and the expected ST at a given TH for the same amount of extracted metal *i*, as shown in Equation (3):

$$\mathrm{LPST}_{i,\mathrm{TH}} = \mathrm{OST}_{i,\mathrm{TH}} - \mathrm{ST}_{i,\,\mathrm{TH}} \tag{3}$$

where the LPST is again measured in kg year/kg of metal *i* extracted. The LPST will always be smaller than the delimiting time horizon.

The characterization factors for the LPST method, CF_{LPST}, are calculated as the ratio between the LPST of metal *i* and the LPST of the reference substance iron (Fe) at a given TH. Fe was chosen as the reference substance because it proved to have the highest $\mathrm{ST}_{\mathrm{TOT}}$ within the model from the set of 18 metals (Helbig et al., 2020). Equation (4) provides the $\mathrm{CF}_{\mathrm{LPST}}$:

$$\mathrm{CF}_{\mathrm{LPST}_{i,\mathrm{TH}}} = \mathrm{LPST}_{i,\,\mathrm{TH}}/\mathrm{LPST}_{\mathrm{Fe,\,TH}} \tag{4}$$

where the $\mathrm{CF}_{\mathrm{LPST}}$ are given in kg Fe-eq./kg.

The total impact score for dissipation as measured with the LPST method is named the total lost potential service time (TLPST). It is obtained by summing the mass of the flow of metal *i* extracted in the LCI (m_i, in kg) multiplied with their corresponding $\mathrm{CF}_{\mathrm{LPST}}$, for *n* metals covered in the method (i.e., 18 metals), as shown with Equation (5):

$$\mathrm{TLPST}_{\mathrm{TH}} = \sum_{i=1}^{n} m_i \cdot \mathrm{CF}_{\mathrm{LPST}_{i,\mathrm{TH}}} \tag{5}$$

where the total lost potential service time, TLPST, is expressed in kg Fe-eq.

2.5.2 | Calculations for the ADR method

The ADR is calculated with the inverse of the total service time $\mathrm{ST}_{\mathrm{TOT}}$ of metal *i*, calculated with a hypothetical infinite time horizon (here calculated as 1000 years) and is therefore independent of the TH chosen for the LPST, as shown in Equation (6):

$$\mathrm{ADR}_i = 1/\mathrm{ST}_{\mathrm{TOT}_i} \tag{6}$$

where ADR is measured in kg/kg year. The ADR can be understood as an average yearly dissipation rate, since the $\mathrm{ST}_{\mathrm{TOT}}$ integrates the anthropogenic lifetime of metals given their time-dependent dissipation patterns. For instance, iron provides an $\mathrm{ST}_{\mathrm{TOT}}$ of 110 kg year per kg extracted, hence on average about 0.9% (= 1/110) of its in-use stock is dissipated per year. A mathematical demonstration backing up this claim is provided in

the Section 3 of Supporting Information S1. The ADR would take extreme values of only 0.001 kg/kg year if the ST_{TOT} was 1000 kg year/kg, and up to 52 kg/kg year if the ST_{TOT} was only a week.

The CFs for the ADR method, CF_{ADR}, are calculated with Equation (7):

$$CF_{ADR_i} = ADR_i \,/ADR_{Fe} \tag{7}$$

where CF_{ADR} are measured in kg Fe-eq./kg.

The total potential impacts related to the expected dissipation rates of metals is obtained by summing the mass of the flow of element *i* extracted (m_i, in kg) with their corresponding CF_{ADR}, as shown in Equation (8):

$$TDR = \sum_{i=1}^{n} m_i \cdot CF_{ADR_i} \tag{8}$$

where the total dissipation rate, TDR, is measured in kg Fe-eq.

2.6 | Comparative study of characterization factors

The CFs developed for 18 metals are compared with those of the ADP method using economic reserves (van Oers et al., 2002) and ultimate reserves (van Oers et al., 2019), as well as those of the EDP method for the long-term environmental dissipation of elements (van Oers et al., 2020). The ADP economic reserves method is selected as suggested by the Life Cycle Initiative's Taskforce on Mineral Resources to measure potential availability issues due to physico-economic scarcity of resources in a shorter time horizon than the ADP ultimate reserves (Berger et al., 2020). The ADP ultimate reserves method is chosen as it is recommended by the same taskforce to assess the relative changing opportunities of future generations to use mineral resources, due to the contribution of a product system to the depletion of mineral resources (Berger et al., 2020; Berger et al., 2019; Sonderegger et al., 2020). This method is also currently recommended to assess the impacts of mineral resource use in the PEF (European Commission, 2013a; Zampori & Pant, 2019). Finally, the EDP method (van Oers et al., 2020) is considered as it is the only other known LCIA method addressing the impacts of dissipation on the AoP Natural Resources that has been published in a scientific paper. Although the JRC has also suggested a framework to address dissipation at the unit process level (Beylot, Ardente, Marques, et al., 2020), it was not selected for the study since it implies modifications of the LCI and has a different framework than typical LCIA methods.

The ADP methods relate a yearly production rate of a substance *i* to its reserves. The "economic reserves" correspond to "reserves" published by the United States Geological Survey (USGS), while the "ultimate reserves" are estimated from the crustal content of each substance (van Oers et al., 2002; van Oers & Guinée, 2016). The CFs are computed by dividing the production rate with the reserve of mineral *i* for a given year and relating it to Sb equivalents (van Oers & Guinée, 2016), as shown in Equation (9):

$$CF_{ADP_i} = \frac{DR_i/R_i^2}{DR_{Sb}/R_{Sb}^2} \tag{9}$$

where DR_i is the global extraction rates of mineral *i*, in kg year^{-1}, DR_{Sb} is the global production rates of the reference substance antimony, R_i is the economic reserves or ultimate reserves of mineral *i*, and R_{Sb} is the corresponding reserves of antimony. The ADP economic reserves considered in this paper uses production and reserves for the year 1999 (van Oers et al., 2002), while the updated ADP ultimate reserves consider production data for the year 2015 (van Oers et al., 2019). Finally, the CFs for the EDP method are calculated using the same equation as the latest ADP ultimate reserve method, but using copper as the reference substance instead of antimony (van Oers et al., 2020).

3 | RESULTS AND DISCUSSION

3.1 | Overview of service times for the 18 studied metals

As a result of the yields of processes and application lifetimes for each metal, various patterns can be observed for the studied metals. The results from Helbig et al. (2020) (also reported in Tables S2-1 and S2-2 in Supporting Information) show that after 25 years, several metals (aluminum, iron, chromium, copper, and silver) still have significant amounts in the use phase (>40%) while most others are already expected to be almost completely dissipated (cobalt, gallium, germanium, selenium, indium, tin, tellurium, tantalum, and tungsten). After 100 years, around 10% of the extracted silver, chromium, and copper are expected to remain in the economy, along with about 20% of nickel and 40% of aluminum and iron. After 500 years, only

TABLE 2 Total expected service times (based on the anthropogenic lifetimes calculated by Helbig et al. (2020)), average dissipation rates (ADR), lost potential service time (LPST) with time horizons of 25, 100, and 500 years, and the associated characterization factors for the LPST and ADR methods

						Characterization factors (midpoint)			
	ST_{TOT} (based on Helbig et al., 2020)	ADR	LPST25	LPST100	LPST500	CF_{ADR}	$CF_{LPST}25$	$CF_{LPST}100$	$CF_{LPST}500$
metal i	kg.yr/kg	kg /kg.yr	kg.yr/kg			kg Fe-eq./kg			
Fe	110	0.00908	3.93	34.8	391	1.00	1.00	1.00	1.00
Al	98	0.0102	5.72	41.7	403	1.12	1.46	1.20	1.03
Ni	58	0.0171	7.53	54.7	442	1.89	1.92	1.57	1.13
Cu	45	0.0222	6.42	59.3	455	2.45	1.64	1.70	1.16
Ag	40	0.0248	6.77	62.9	460	2.73	1.72	1.81	1.18
Cr	32	0.0316	11.8	71.3	468	3.48	3.01	2.05	1.20
Zn	16	0.0614	13.6	83.8	484	6.76	3.47	2.41	1.24
Pb	14	0.0731	13.8	86.3	486	8.05	3.52	2.48	1.24
Re	13	0.0795	16.2	87.5	487	8.75	4.12	2.51	1.25
Sn	11	0.0891	14.5	88.8	489	9.82	3.70	2.55	1.25
Ta	8	0.122	17.4	91.8	492	13.5	4.43	2.64	1.26
W	5	0.204	20.2	95.1	495	22.5	5.14	2.73	1.27
Co	3	0.346	22.1	97.1	497	38.1	5.64	2.79	1.27
In	3	0.396	22.5	97.5	497	43.6	5.73	2.80	1.27
Te	0.7	1.36	24.4	99.3	499	150	6.20	2.85	1.28
Se	0.5	2.06	24.5	99.5	500	227	6.25	2.86	1.28
Ga	0.1	8.18	24.9	99.9	500	901	6.34	2.87	1.28
Ge	0.05	18.6	24.9	99.9	500	2046	6.35	2.87	1.28

about 1% of aluminum and iron are expected to remain in the economy. A more detailed analysis of the ST for the different metals is provided in section 2 in Supporting Information S1.

3.2 | Characterization factors

Table 2 presents the ADR and LPST as well as their corresponding midpoint CFs calculated for the ADR and LPST methods for 18 metals.

The CF_{LPST} and CF_{ADR} represent different readings of the global dissipation patterns after extraction. The two methods are not meant to be complementary, but rather provide different readings of the same data. The CF_{LPST} provide an indication of the lost opportunity to make use of a single initially extracted kg of metal as part of in-use stocks in the economy with regard to a target of theoretical perfect yields. Using the LPST method may become more relevant if it is associated with the actual value of its use as part of an endpoint impact model, as suggested in Section 2.2. On the other hand, the ADR rather focuses on flows occurring during the lifetime of metals and provides a direct reading of global dissipation rates, which makes it practical to use as a standalone indicator providing generic dissipation rates to compare metals. The CF_{ADR} have no specified time horizon because the expected lifetime of resources is integrated in the calculation of the ST_{TOT}.

For example, Fe is relatively well preserved in the economy compared to other metals, with an average product lifetime of about 40 years for all sectors combined, a small percentage of dissipation in use, and a combined yield of about 80% for the collection and recycling processes (Helbig et al., 2020). In comparison, gallium is mostly dissipated at the production phase (>99%) for technical and economic reasons (Helbig et al., 2020; Løvik et al., 2015, 2016). This results in relatively high CF values for gallium for the ADR, LPST25, and LPST100 methods (901, 6.34, and 2.87 kg Fe-eq./kg, respectively). Figure S1-2 in Supporting Information S1 presents examples of dissipation curves underlying the ST_{TOT} of aluminum, cobalt, and gallium along with their respective ADR, LPST, and CFs. Figure 4 presents the CF_{ADR} plotted against the CF_{LPST} at the time horizons of 25, 100, and 500 years. It is possible to distinguish roughly between three groups of metals (major, variable, and highly dissipative) which are further discussed in section 2 in Supporting Information S1.

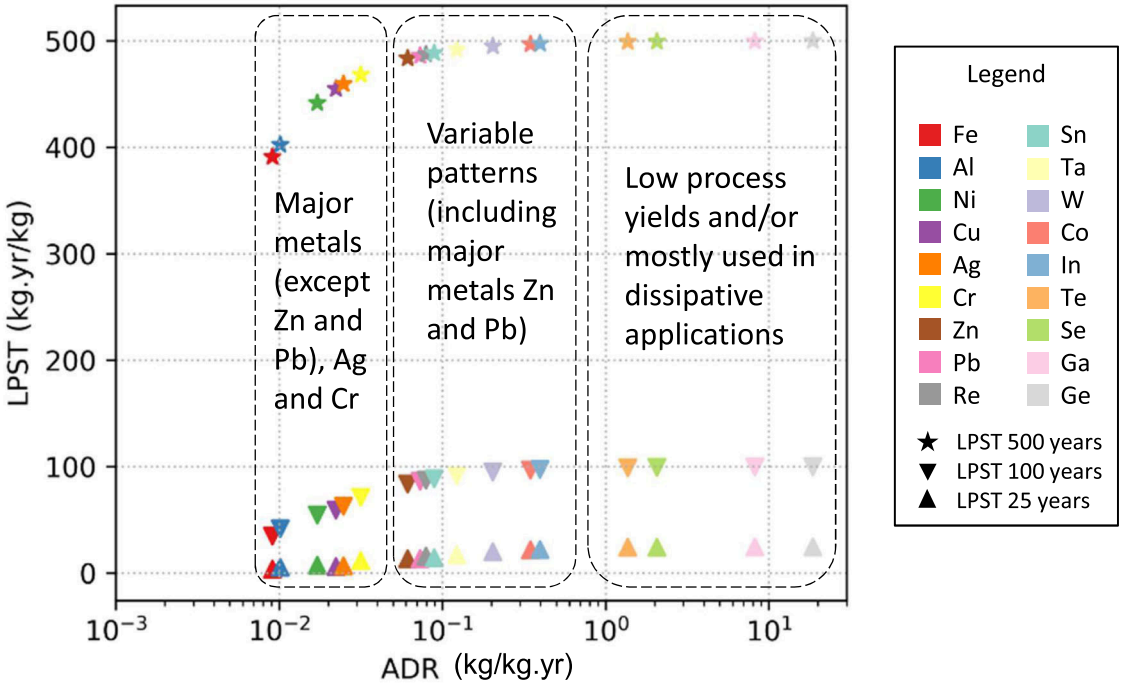

FIGURE 4 Average dissipation rates (ADR) of 18 metals (*x*-axis) scatter plotted against their lost potential service times at the time horizons of 25, 100, and 500 years (LPST25, LPST100, and LPST500, respectively) (*y*-axis). The metals are classified into three rough categories described in Supporting Information S1. Underlying data used to create this figure can be found in Table S1-2 in Supporting Information S1

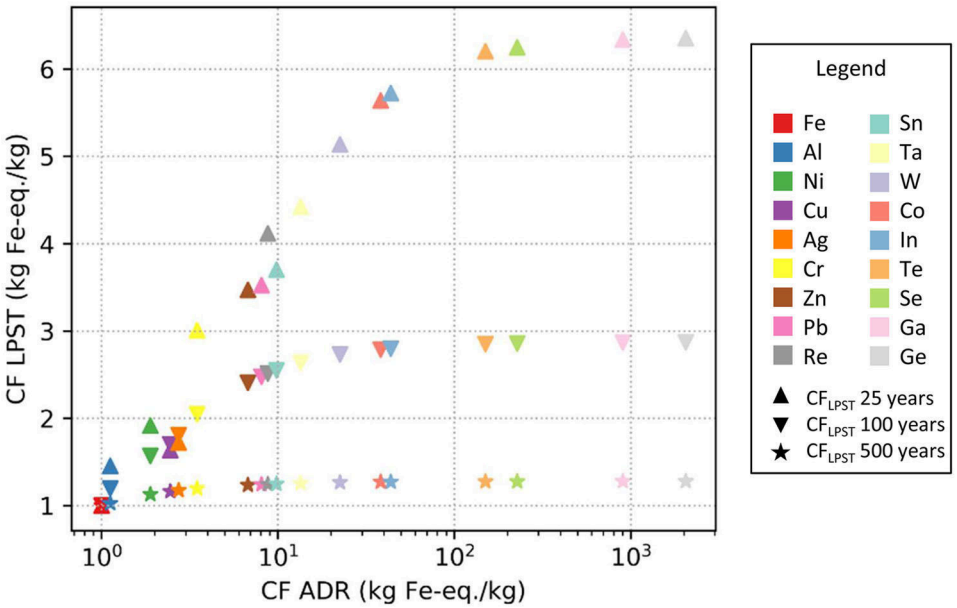

FIGURE 5 Characterization factors for the ADR method (*x*-axis) scatter plotted against characterization factors for the LPST method at the time horizons of 25, 100, and 500 years (*y*-axis). Underlying data used to create this figure can be found in Table S1-3in Supporting Information S1

It can be observed that the relative ranking between substances is mostly identical between the methods. A few CFs have slight changes in their relative ranking because of the irregular shape of the ST curves due to long-lived applications (>25 years) or highly dissipative uses of a metal in its first applications (as it is the case for, e.g., selenium).

Figure 5 presents the relative CF_{ADR} plotted against the relative CF_{LPST} for the same three time horizons. The CF_{ADR} are rather well differentiated compared to the CF_{LPST}, which are increasingly similar over longer time horizons. This reveals that the CF_{ADR} are most sensitive to the lifetime of applications and the yields of processes for each of the metals, which underlay their ST_{TOT}, are highly influent on the CF_{ADR}, while the CF_{LPST} are

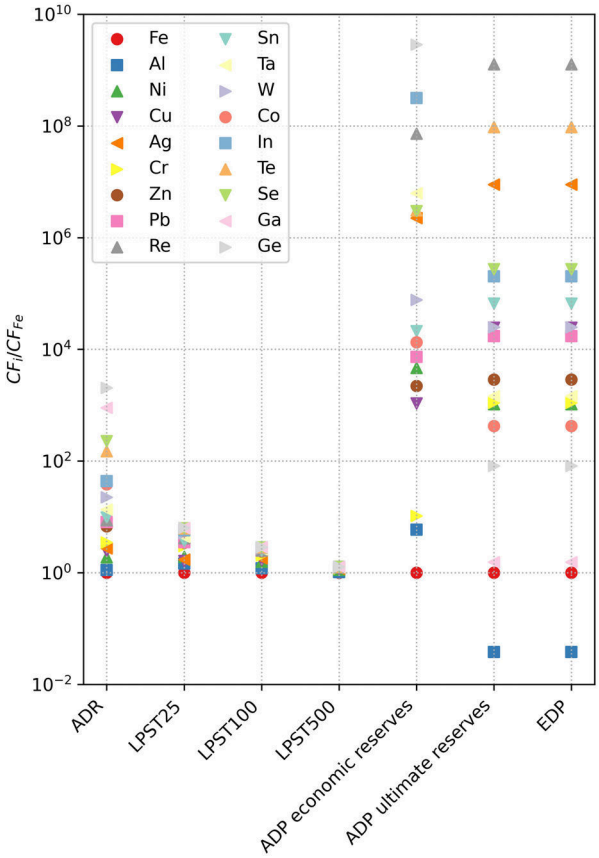

FIGURE 6 Normalized characterization factors for the 18 elements covered in the ADR method and LPST method for the time horizons of 25, 100, and 500 years, as well as the corresponding CFs for the ADP economic reserves, ADP ultimate reserves, and EDP methods. The characterization factors are normalized with the characterization factor of iron for each method. Underlying data used to create this figure can be found in Table S1-4 in Supporting Information S1

also strongly influenced by the length of the time horizon. Indeed, as most studied metals are dissipated rather rapidly after their extraction, the yearly LPST is increasingly similar for all metals until they are completely dissipated, at which point they increase equally for each subsequent year. This explains why the CF_{LPST} are less distinct over longer time horizons.

3.3 | Comparative study of methods and their characterization factors

Using the Life Cycle Initiative's terminology to describe the impacts of different LCIA methods (Berger et al., 2020; Berger et al., 2019), the ADR method indicates the relative changing opportunities for future generations to use mineral resources due to the current ADRs of metals, and the LPST25, LPST100 and LPST500 methods, the relative lost opportunity to make use of the potential value of mineral resources in the economy due to dissipation over the short, mid, and long term, respectively. The EDP method (van Oers et al., 2020) addresses the lost opportunity to make use of the potential value of mineral resources due to environmental dissipation in the long term.

The ADR, LPST, and EDP methods each aim to address dissipation, though with important differences between them. The ADR and LPST methods consider dissipation in the environment and in the technosphere, while the EDP considers only the emissions to the environment as dissipation in the long term. The CFs for the EDP method are calculated with the $M_{i,t}/R_i^2$ ratio, M being the global extraction of an element *i* for a year *t* (assumed to be equal to the global environmental emission in the long term) and R, the ultimate reserve for each element (van Oers et al., 2020). *In fine*, the EDP factors are calculated with the ratio between global long-term environmental dissipation (all applications combined) and squared ultimate reserves (R_i^2), which are multiplied with the emission flows of the LCI. Contrastingly, the ADR and LPST methods are based on the anticipated dissipation patterns in the technosphere (all applications combined) related to an extracted kg of resource, which are multiplied with the extraction flows of the LCI.

The CF_{ADR} and CF_{LPST} for the 18 metals covered in this article are depicted in Figure 6, along with the corresponding CFs for the ADP economic reserves (van Oers et al., 2002), ADP ultimate reserves (van Oers et al., 2019), and EDP (van Oers et al., 2020). Since

the analyzed methods use different reference substances, the CFs for each method were normalized based on their respective CF for iron (Fe).

The CFs for the ADP ultimate reserves and EDP methods are equal once they are brought back to iron equivalents because of their similar equations. However, their LCIA step differs in that CFs for the ADP ultimate reserves apply to extraction flows while those of the EDP method apply to emission flows. The CFs for the ADP economic reserves spread over 9 orders of magnitude, while those for the ADP ultimate reserves and EDP methods spread over 10 orders of magnitude. They each provide a greater differentiation in between metals in comparison to the LPST and ADR methods, which are spread over factors of 1, 3, and 6 for the LPST500, LPST100, and LPST25 methods, respectively, and 4 orders of magnitude for the ADR method. The impacts of dissipation in the long term might be overestimated for some metals in all of the studied methods, as some flows that are considered as DFs in the technosphere (and even the environment) could possibly become once again accessible in the long run.

The CFs for aluminum and iron are the lowest two in all methods, indicating relatively low depletion and dissipation potentials. Other widely used metals, such as chromium, nickel, zinc, and lead, also appear in the lower end of CFs across methods. On the other hand, selenium, indium, and tellurium consistently appear on the higher end of the spectrum for all methods. Gallium and germanium have the highest CFs for the LPST and ADR methods, primarily due to their very low yields of extraction, while their CFs for the ADP ultimate reserves and EDP methods are relatively low. This is explained partly because of the consideration of the net yearly production in their calculation, which disregards the uneconomical fraction of extracted minerals from the crust. Indeed, the elements which are not consistently targeted by extractive processes, such as many companion metals, are extracted but not "produced." When the reserves are corrected accordingly with the current economic feasibility of their extraction, that is, when economic reserves are considered rather than ultimate reserves, CFs change drastically. For instance, the CF for germanium is the third lowest CF for the ADP method when considering ultimate reserves, but the highest CF when the economic reserves are considered instead. In both cases, one should be careful when interpreting the ratio between production and various reserves, especially for low value metals or by-product metals for which extraction exceeds demand (West, 2020).

Of the studied methods, two sets have relatable objectives and methods. First, the ADP economic reserves and the LPST25 methods both aim to characterize the potential impacts of resource use in the short term by multiplying the CFs with extraction flows in the LCI. The CFs for Fe, Al, Cu, Cr, Ni, Pb, and Zn appear in the lower half of the ranking for both methods, while the CFs of Sn, Re, Ta, W, In, Te, Se, and Ge are consistently amongst the higher half of the studied CFs, Ge being the highest in both methods. This suggests that many metals are both highly dissipated and with high physico-economic scarcity potentials (according to the ADP economic reserves method). They would likely be flagged in LCA studies of product systems that require relatively large extraction flows of these metals. Interestingly, low demand or economic interest for some metals may explain both the high dissipation rates (as measured in this paper), and their high production to economic reserves ratio, because few efforts are put into exploring and/or recovering them during primary production and recycling (West, 2020).

Second, the ADP ultimate reserves and the LPST500 methods both aim to characterize the potential impacts of resource use on the long term by multiplying the CFs with extraction flows in the LCI. The comparison between both methods shows that the CF_{LPST} provide a relatively small differentiation between metals, and thus that the impact scores for the LPST500 method would mostly align on the LCI values for extraction. Assessing the actual value of the ST of metals, as proposed earlier, could allow to better distinguish between the different metals. Contrastingly, the CFs for the ADP ultimate reserves method as such are well differentiated and provide some idea of the long-term geological depletion potentials.

Finally, it could be possible to interpret results given by the different ADP methods and the ADR or LPST methods altogether when assessing impacts on the AoP Natural Resources, similarly to how it can be done for multiple impact categories on other AoPs (e.g., the impacts of toxicity, respiratory disease, on the AoP Human Health). For instance, looking only at the CFs for the ADP ultimate reserves method, one could conclude that the extraction of rhenium and tellurium should be primarily avoided, whereas the CF_{ADR} suggest that germanium and gallium are the most problematic metals in terms of dissipation rates and should be primarily addressed.

3.4 | Limitations of the ADR and LPST methods

The LPST and ADR methods offer a simplified solution to account for dissipation using current LCI, as suggested for the short-term agenda to account for dissipation in LCA proposed by Beylot et al. (2020b). However, the methods present some limitations due to the workaround framework that was developed to anticipate dissipation based on extraction flows in the inventories. First, in the case where extraction data comes from LCI databases using allocation procedures, there could be an alignment (i.e., double counting or discounting) between the allocation of primary production to multiple product systems in the database and the recycling considered for the calculation of the CFs. Second, global average yield values for all supply chains and applications making use of an element are considered in the computation of CFs, providing averaged values which are element specific rather than application specific. These may differ from the actual process yields considered in the LCI databases. Third, as the CFs are meant to be applied to extraction flows, the results provide no specific differentiation between the processes that contribute most to the dissipation of metals along the life cycle of a specific product system.

These limitations may prove to be restrictive for the applicability of the proposed methods depending on the practitioner's objectives for a given LCA study. We insist that, when dissipation patterns for the different metals are well known by the practitioner for a specific process or product

system, it is likely that foreground data would allow to calculate dissipation potentials that contradict those suggested in our generic global model. In this situation, practitioners could prefer to calculate their own CF values based on their own product lifetime and DFs rather than use the CFs developed for our methods. The computational structure provided in section 1 of Supporting Information S1 gives a useful basis to do so. Moreover, other process-centric approaches such as suggested by the JRC (Beylot et al., 2020), or product-centric assessments such as the approach proposed by Moraga et al. (2021) could also provide alternatives to address dissipation as defined in this article, that is, including DFs occurring within the technosphere. The approach suggested by the JRC is detailed and its operationalization in LCI databases is discussed with an application to a case study in Beylot et al. (2020a) and Beylot et al. (2020c). Yet, any potential routine application of that approach may require large-scale changes of LCI databases, justifying the development and use of interim approaches such as those developed in this article. Finally, all the aforementioned limitations ultimately support the need for detailed information on DFs made available in LCI before the dissipation of minerals can be operationalized in a consistent LCIA framework, as suggested by the JRC (Beylot et al., 2020a; Zampori & Sala, 2017).

Moreover, we would like to highlight that there might be a mismatch between what is defined and considered as a resource in widespread LCI databases and the ADR and LPST methods, especially concerning the potentially co-produced elements (e.g., gallium). Such problem has already been highlighted regarding the definition of mineral resources of the mining industry, which may differ from that used in different LCIA methods (Drielsma et al., 2016). Indeed, in the ADR and LPST methods, all of the extracted elements are accounted for, in line with the proposition of the Taskforce on Mineral Resources (Berger et al., 2020), whereas the industry may consider uneconomically extractible elements in a given context as valueless rock (gangue), and thus not as a resource per se (CRIRSCO, 2019; Drielsma, Russell-Vaccari, et al., 2016). For instance, LCI databases such as ecoinvent consider resources to be the targeted elements in the ore when the mineral ore is valued only for its metal content (Classen et al., 2009; Weidema et al., 2013), which seems to somewhat align with the definition of resources of the mining industry. However, some elements contained in the ores that are not valuable economically today could potentially be so in the future. For example, gallium (a by-product of aluminum production) is overabundant in aluminum ores today in comparison to the current demand; however, an increasing demand for gallium along with a lower primary production of aluminum could lead to an insufficient production capacity of gallium in the future (Løvik et al., 2015, 2016). Thus, efforts should be spent on clearly identifying what are considered as resources in the LCI databases and how these resources compare to the definition of resources in the AoP Natural Resources. This investigation could allow to identify which flows of elements are to be considered as DFs, and eventually to allocate the impacts of dissipation to the processes that are actually responsible for these DFs (e.g., the aluminum production process may be responsible for DFs of gallium).

4 | CONCLUSION AND OUTLOOKS

A conceptual framework to address dissipation of abiotic resources in LCA based on Charpentier Poncelet et al. (2019) was developed into an LCIA method and applied with a set of dynamic MFA data collected by (Helbig et al., 2020). This demonstrates that (1) it is possible to uptake data obtained from other fields of research such as MFA to fill information gaps in the LCA framework, (2) the information can be used in an impact assessment method, and (3) an impact assessment method can provide information on the degree of circularity of a global metal cycle. As previously stated, the primary objective of the ADR and LPST methods is to provide a temporary solution to overcome limited knowledge on the dissipation patterns of metals in LCA, because much of the DFs as defined in this paper can occur within the technosphere and are not tracked in LCI.

Moreover, conceptual advances relating the dissipation of resources to the AoP Natural Resources have been proposed with the concept of ST in the technosphere, which could be complemented with quality aspects of resources. The ST could also eventually be aligned with the lost service provided by ecosystems in the ecosystem services framework (see discussion on ecosystem services in, e.g., Maia de Souza et al., 2018; Rugani et al., 2019).

The LPST method provides a midpoint step in the impact pathway which exposes the lost potential service provided by the different metals due to dissipative flows occurring from extraction and onwards up to a given time horizon of 25, 100, or 500 years. The LPST method is the first step in an impact pathway to the AoP Natural Resources. As a next step, the quantification of the potentially lost value due to the lost service time for each element should be investigated, leading to an endpoint damage to the AoP. Contrastingly, the ADR method provides an indication of the dissipation potentials of the different metals, which are conceptually hardly linkable to an endpoint damage by themselves.

Using the LPST or the ADR methods, designers and LCA practitioners can anticipate how the composition of their products (i.e., quantities and types of metals) influences the potential impacts of their system due to the potential dissipation. The comparative study between CFs of different methods demonstrates that their CFs can be combined to provide a more thorough panel of information when analyzing the potential impacts of resource use on the AoP Natural Resources. Still, the aforementioned limitations of the developed methods should be kept in mind.

In addition to addressing these limitations, future works should focus on increasing the number of metals covered by the ADR and LPST methods. The possible recovery of metals from hibernating anthropogenic stocks (e.g., tailings and landfills) and possible scenarios of technological development leading to increased process yields could also be further addressed. Lastly, additional efforts could be spent on extending the concept and the method to other types of minerals such as aggregates, or to other materials like plastics whose dissipation has led to impacts such as marine litter.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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