



Consensus-based framework for the impact assessment of natural resource use in life cycle assessment: generalized impact pathways and recommended methods for abiotic resource use

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Abstract

Purpose This study aimed to establish a consistent framework for assessing the impacts of natural resource use within Life Cycle Assessment (LCA). As part of the outcomes of the UNEP Life Cycle Initiative's GLAM Phase 3 Task Force on Natural Resources, the work defines the safeguard subject, generalized impact pathways applicable across all types of natural resources, and recommended methods for abiotic resource use that aligns with the developed assessment framework for natural resources.

Methods An expert consensus was achieved through a structured evaluation of twenty existing methods using ten criteria, including relevance to the defined safeguard subject, consistency with impact pathways, data quality, and compatibility with Life Cycle Inventory (LCI) databases. The generalized impact pathways were developed to encompass abiotic, biotic and other renewable resources, integrating mechanisms such as dissipation, degradation, and occupation.

Results The consensus-building process resulted in the definition of a common safeguard subject for natural resource use: the potential to make use of the instrumental values of natural resources. Generalized impact pathways were established to consistently describe cause-effect mechanisms across different categories of natural resources. The Future Welfare Loss (FWL) model was selected as the recommended approach for assessing mineral and fossil resource use. Characterization factors (CFs) were recalculated using updated 2018 commodity price data for 81 minerals, 3 fossil resources, and 2 energy carriers. The global annual impact of mineral and fossil resource use (using extraction flows as inputs) was estimated at approximately USD 3,483 billion, equivalent to about 4% of the 2018 global GDP.

Conclusions While the generalized impact pathways are intended to be broadly applicable across natural resource categories, the operational recommendation and updated characterization factors currently focus on mineral and fossil resource use, whereas only interim recommendations could be identified for water resource use and land use assessment. Further methodological refinement is needed for renewable resources. Finally, we encourage LCI databases developers to improve the coverage of mineral and fossil resource dissipative flows in LCI databases to enhance the characterization of resource dissipation.

Keywords Natural resources · International expert consensus · Dissipative flows · Instrumental value · Future welfare loss model · Externality of natural resource use

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1 Introduction

Natural resources, specifically water, land, mineral, fossil and biotic resources, provide services to humans. Natural resources are used by product systems to provide a service (e.g. mobility) as they have instrumental values to humans. For instance, lithium is used in a lithium-iron-phosphate (LFP) battery of an electric vehicle to enhance energy storage, which is essential for the electric vehicle to provide mobility. It is therefore essential to protect the instrumental values of natural resources to meet current and future generation's needs. The concept of instrumental value has been widely discussed in environmental valuation and ecosystem services literature, where natural resources are considered valuable because of the functions and benefits they provide to human societies and ecosystems (e.g., Costanza et al. 1997; Millennium Ecosystem Assessment 2005; Charpentier Poncelet et al. 2022a). Natural resources provide instrumental values through their functions. However, their use for a specific product system could temporarily restrict the access to the values provided from natural resources for other (current and future) users or result in the permanent loss of accessibility to the values of natural resources. In the latest version of the UNEP-SETAC Life Cycle Initiative framework (UNEP 2016; Verones et al. 2017), the instrumental values of natural resources are protected under an Area of Protection (AoP) called "Natural Resources". The cause-effect chains from natural resource use to the loss of instrumental values of natural resources are complex and dynamic and have not been consistently defined across all resource types. In this context, one of the flagship projects led by the Life Cycle Initiative, the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM), has worked to establish generically applicable cause-effect chains and consensus-based impact assessment methods including natural resource use. It focused on mineral resource use during its 2nd phase (2017–2019) as a part of the impact assessment of natural resources AoP. This resulted in the definition of a safeguard subject and cause-effect chains of mineral resource use, aligned with the protection of the instrumental values that mineral resources hold for humans in the technosphere (UNEP 2019; Berger et al. 2020; Sonderegger et al. 2020) using a consensus building processes with international experts and stakeholders (Sonderegger et al. 2017; Berger et al. 2020; Schulze et al. 2020). This achievement represented an important milestone in the development of impact assessment for natural resource use in LCIA; however, a more generalized definition of safeguard subject and cause-effect chains applicable across different natural resource categories was still needed.

The development of methods that are applicable for the overarching assessment of all natural resources is another

challenge for the impact assessment of natural resource use (Klinglmair et al. 2014; Sonderegger et al. (2017)). Various methods for the impact assessment of use of different natural resources exist. Some of these methods explicitly address impacts in terms of the loss of instrumental values of natural resources. Regarding water consumption, Pfister et al. (2009) proposed an assessment method for the lost instrumental values of freshwater due to its consumption based on a backup technology approach for the compensation of consumed water. They adopted the energy demand for producing freshwater by desalination to compensate for the lost value of consumed water. For land, Cao et al. (2015) determined the loss of instrumental values of land by occupation. They characterized six ecological functions of land and monetized in economic values the loss of each of them. Regarding mineral resources, a wide variety of impact assessment methods has been developed, with diverse focuses and underlying theories. Sonderegger et al. (2020) reviewed these existing methods for the impact assessment of mineral resource use and categorized them into four types of methods: depletion methods, future efforts methods, thermodynamic accounting methods, and supply risk methods. This critical review work gave an overview of existing methods for the impact assessment of mineral resource use with categorization of what each method focused on as a problem associated with mineral resource use. Assessment methods within a single category look at similar problems, while methods in different categories adopt different metrics and focus on different impacts (Sonderegger et al. 2020). On the other hand, some methods adopt the same metrics but assess a different category of impact. For instance, the LIME3 method (Yokoi et al. 2024) and the Future Welfare Loss method (Huppertz et al. 2019) assess the externality of mineral resource use in economic units without any compensation of depleted minerals, whereas the SCP method (Vieira et al. 2017) assesses the requirement of additional economic cost for compensation of depleted minerals. These differences between existing methods make it difficult for LCA practitioners to select an appropriate method. To address this issue, Berger et al. (2020) suggested recommended methods corresponding to seven relevant assessment questions, including depletion, changing resource quality, consequences of changing resource quality, externalities, impacts on thermodynamics, potential availability, and potential accessibility.

To tackle these challenges in the impact assessment of natural resource use in LCA, the GLAM 3rd phase task force on natural resources was initiated under the UNEP Life Cycle Initiative in 2020. Within the task force, 59 international experts and stakeholders have joined the discussion on (1) the definition of the safeguard subject of natural resources, (2) the impact pathways of natural resource use, and (3) the development of consensus-based recommendations for

the impact assessment of natural resource use. The novelty of this work does not lie in proposing entirely new impact pathways or characterization concepts, but rather in extending previous GLAM work toward a generalized and consensus-based framework for natural resource use assessment across multiple natural resources. Compared with the previous GLAM Phase 2 work, which primarily focused on mineral resources, the present study develops generalized safeguard subjects and impact pathways intended to conceptually cover mineral, fossil, water, land, and biotic resources, while introducing a transparent consensus-based evaluation process for deriving operational recommendations. In this study, “generalized impact pathways” refer to a conceptual framework intended to consistently represent cause-effect mechanisms across different categories of natural resources, including mineral, fossil, water, land, and biotic resources. The framework is intended to provide conceptual harmonization across resource categories, although fully operational characterization methods are not yet available for all resource types. In Sect. 2, we present the definition of the safeguard subject and the impact pathways associated with natural resource use. Then, we introduce our recommended methods for impact assessment of natural resource use including the process for the evaluation of the existing methods, aligning the defined safeguard subject with plausible impact pathways, in Sect. 3. Sect. 4 summarizes the general recommendations, the limitations of the recommended methods and remaining challenges for the impact assessment of natural resource use.

2 Safeguard subject and impact pathways of natural resource use

2.1 Definition of the safeguard subject

In LCA, safeguard subjects within an Area of Protection (AoP) framework represent attributes or entities intended to be protected from the direct and indirect impacts of product systems (Sonderegger et al. 2017). Within each thematic AoP, safeguard subjects specify the targets intended to be protected from damage, while endpoint indicators provide operational metrics for quantifying potential damages along cause-effect pathways. In the context of this study, the AoP is “Natural Resources”, whereas the safeguard subject represents the specific target within this AoP that is intended to be protected. Natural resources are used in different ways and provide diverse values that benefit human life, including instrumental values. Humans make use of the functionality of natural resources in supply, use and end-of-life chains, which may in turn, temporarily restrict access to the instrumental values of those natural resources for other (current

and future) users. In some cases, use of a natural resource may result in the permanent loss of its instrumental values for humans, emphasizing the need to distinguish resources by their renewal dynamics and recovery potential.

Schulze et al. (2020) defined five roles of (perspectives on) abiotic resources depending on the case of abiotic resource use and identified the most relevant perspective through a stakeholder workshop. In parallel, and in line with the perspective, Berger et al. (2020) discussed a safeguard subject for mineral resources together with multiple assessment perspectives for evaluating the potential impacts of mineral resource use. These studies emphasized that the functions and values associated with natural resources in the economy may differ depending on the purposes and situations in which they are used, while the ultimate scope is the protection of the instrumental values that natural resources may hold for humans. The present framework specifically focuses on instrumental values associated with human use of natural resources, while acknowledging that natural resources may also hold other values beyond the scope of the current assessment. These instrumental values may be realized both within and beyond the technosphere (e.g. through ecosystem services such as pollutant assimilation and recreation). We adopted the definition of the safeguard subject for natural resources as the outcome from the previous two works: the potential to make use of the value that natural resources can hold for humans. The conceptual foundation of this definition, including the relationship between instrumental values and other categories of environmental values, is further elaborated in the Supporting Information (Section S2).

2.2 Impact pathways of natural resource use

The functions of natural resources that we value differ depending on the types of resources and the way they are used. Therefore, the damage mechanisms of natural resource use are very complex, which may also be a reason why the question of whether natural resources should be regarded as an AoP at all has been the subject of controversial debate (e.g. Drielsma et al. 2016). In previous studies, the impact pathways of natural resource use were identified and described for the cases of mineral resources (e.g. De Bruille 2014; Dewulf et al. 2015; Drielsma et al. 2016; Sonderegger et al. 2020), freshwater (e.g. Kounina et al. 2013; Pradin-aud et al. 2019) and natural resources in general (e.g. Sonderegger et al. 2017). Particularly, Sonderegger et al. (2017) framed the generalized impact pathways applicable to various natural resources. This was the first ambitious attempt to define the framework of the impact pathways that cover various natural resources based on an extensive review of existing methods. The authors point out the importance of a

method that consistently assesses the impacts of all natural resource use on the AoP “Natural Resources”. Developing a consistent method for the impact assessment of all natural resources is challenging because of the different ways they are used, differences in their availability, and differences in their renewability over different timeframes (e.g., mineral deposits are typically considered non-renewable though even some of these are destroyed and regenerated by tectonic processes over extremely long timeframes). Any impact pathways from the Life Cycle Inventory to estimated damages to the AoP need to be appropriately structured so that they can represent resource-specific cause-effect chains and also be applied to all natural resources.

The impact pathways diagram defined by Sonderegger et al. (2017) is a good basis for developing more detailed impact pathways that can be applied to all natural resources. The aspects of the timeframe of the damage, the ways of use (occupation, translocation, etc.), and the quantification of the lost value (quantity/quality change) seem to be the keys to developing the generalized impact pathways for all natural resources. We categorized pressures (extraction/transformation/translocation) that can give rise to impacts and defined causes (dissipation/ degradation/occupation) that lead to the impacts at midpoint (deprivation of instrumental values) and damages at endpoint (increasing efforts for substitution or non-substitutable damage). Among the various resource flows and stock transitions represented in Fig. 1, dissipation, degradation, occupation, and depletion were identified as the primary impact-generating mechanisms because they directly reduce the accessibility, functionality, or availability of natural resources for current and future users, either

temporarily or permanently. Detailed definitions of these terms and their conceptual distinction are provided in Supporting Information (Section S1).

Figure 1 represents the overall impact pathways diagram that was defined during the discussion in the task force. Natural resources are extracted from accessible stocks in the ecosphere or technosphere (included in the ultimate stocks), and made accessible with functionality for different use (technosphere accessible stocks). Here, ultimate stocks represent the total amount of natural resources existing in the earth system irrespective of their current accessibility, while accessible stocks represent the subset currently feasible for human use from economic, technical, social, and environmental perspectives. Then, natural resources become temporally inaccessible by being occupied for a product system during different terms (technosphere occupied stocks). After occupation in the technosphere, some of the natural resources become accessible again by reuse or recycling and treatment, which may sometimes result in degradation. Others are diffused and disposed as a part of the ultimate stocks. In this framework, dissipative resource use refers to resource flows entering inaccessible ultimate stocks, i.e., stocks that are considered permanently inaccessible within the time horizon relevant to the assessment. Such flows result in a loss of accessibility and instrumental value for current and future users. In contrast, inaccessible stocks in the ecosphere and technosphere may potentially become accessible through future innovation, technological development, or exploitation. The outcomes from GLAM phase 2 called “task force of mineral resources” of the Life Cycle Initiative called for the definition of the concept of

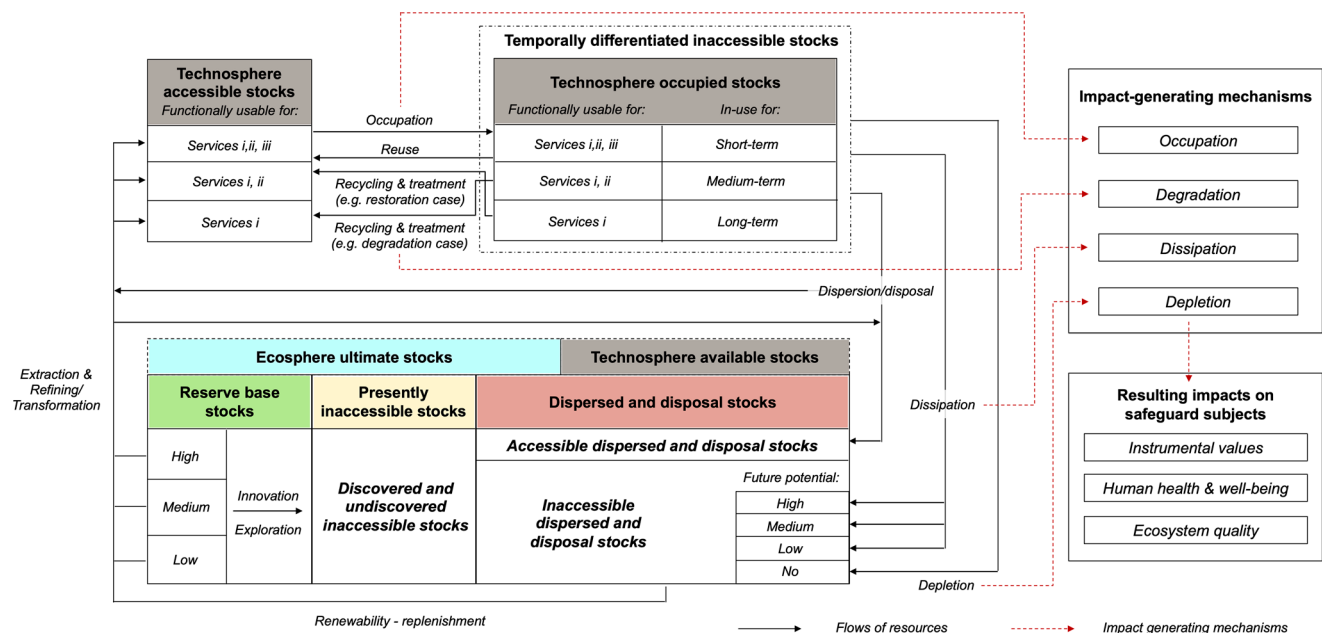


Fig. 1 Generalized conceptual framework of natural resource stocks, flows, and impact pathways associated with natural resource use

dissipative resource use and for its integration in subsequent method developments (Berger et al. 2020). The impact pathways presented in Fig. 1 accounts for this requirement.

3 Recommendation of the method for the impact assessment of natural resource use

3.1 Definition of the relevant question to be answered by the recommended methods

In assessing the potential impact of natural resource use, it is crucial to define the relevant question to be answered by the assessment and to select a method that aligns with the objective of the assessment. The approach of Berger et al. (2020) was a bottom-up one, which covered all relevant existing methods covering the diverse issues of mineral resource use. The task force of GLAM3 aimed to recommend a single method for the assessment of impacts to the natural resource AoP at the endpoint level (Verones et al. 2017). In this context, we defined the relevant question that aligns with the defined AoP as follows:

How can we quantify the consequences of reducing the accessibility to the instrumental values of natural resources for current and future users caused by their use in a product system?

The potential to make use of instrumental values is the safeguard subject that we need to protect for natural resources.

The use of the instrumental values of natural resources by one party may be hindered temporarily by the use of natural resources in the technosphere by another party or permanently prevented by the irreversible dissipation of the resource. To quantify the lost potential to make use of the instrumental values of natural resources, we may equate it with the additional efforts needed to compensate for the loss of the instrumental values, or we may simply estimate the lost instrumental values as externalities (see Supporting Information, Section S2, for the typology of values and their relevance to LCA).

3.2 Evaluation of the existing methods for the selection of the recommended methods

3.2.1 Review of existing methods

For the recommendation of the impact assessment model of natural resource use, we reviewed existing relevant methods and selected the best suitable method as the basis of the recommendation. We listed 20 existing relevant methods by the extensive literature review and categorized them into 4 categories depending on their nature in two dimensions: metrics of damage assessment and compensation mechanisms of the damage (Fig. 2).

As a first category (the category 1 in Fig. 2), five methods were categorized as the ones that adopt physical metrics and non-compensation mechanisms. All five of these methods assess the impacts of mineral resource use with the unit of mineral quantity without any efforts for compensation. The

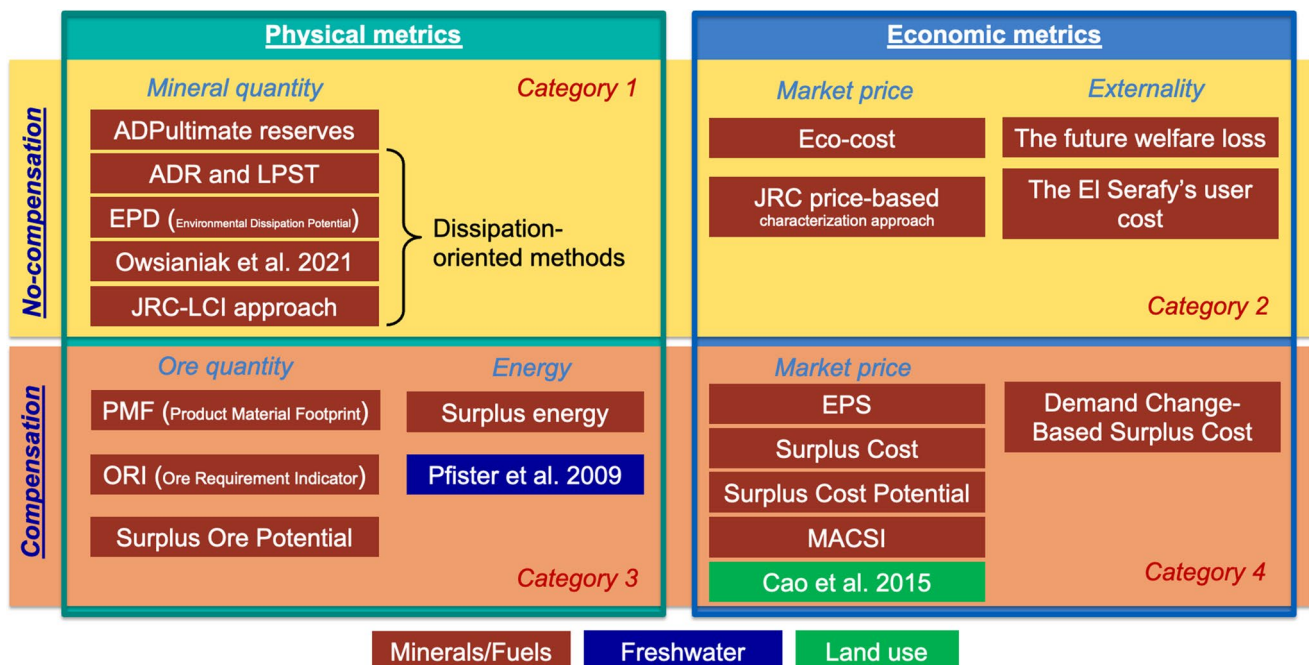


Fig. 2 Overview of the categorization of existing relevant methods for the impact assessment of natural resource use

ADP ultimate reserves method (Guinée and Heijungs 1995) represents the potential long-term depletion of geological mineral stocks based on a static depletion perspective. The characterization factors are calculated from the ratio of annual mine production to the squared ultimate reserves of the target mineral, normalized to antimony as a reference substance. Although the characterization factors themselves are dimensionless because they are normalized to antimony, the method fundamentally represents impacts in terms of relative depletion of mineral quantities. Milà i Canals et al. (2009) also discussed freshwater depletion in LCIA by adapting the conceptual basis of the ADP framework to groundwater depletion. However, because the approach fundamentally relies on the same depletion-oriented characterization logic as the ADP method, it was not treated as a separate methodological category in the present review framework, which focuses on distinguishing different types of impact assessment concepts and mechanisms. The ADR and LPST methods (Charpentier Poncelet et al. 2022b) quantify the potential impact on the basis of the combination of the mass of resources extracted and average dissipation rate obtained from extensive dynamic Material Flow Analyses (MFAs). As in the ADP method, the potential impacts are represented by the mass of a resource that loses instrumental value per year. The Environmental Dissipation Potential (EDP) method (van Oers et al. 2020) applies a generalized framework for impact assessment method development to the problem of dissipative resource use as identified by Schulze et al. (2020) and Berger et al. (2020). As a workable means of estimating changes to the accessible stock of resources over the very long term, the EDP method proposes that all extractions of primary resources may be safely assumed to be dissipated in the very long term. It is acknowledged that no assumption about the far future in any LCIA method can be empirically validated (van Oers et al. 2020; Beylot et al. 2024). This assumption has the convenience of allowing continued use of updated characterization factors (CF) from the ADP ultimate reserves method, only multiplying them by the ‘emissions’ of elements to calculate the potential environmental impact, rather than by the ‘extraction’ of elements. Owsianiak et al. (2021) provided a more detailed definition of dissipative emissions of metals by considering both (i) the concentration of emitted resources in environmental sinks relative to reference accessibility thresholds and (ii) the concentration of the resource in its source of origin, reflecting what is accessible for humans within the considered time span (e.g. equal to the average element concentration in the upper continental crust for the infinite time horizon). However, the operational implementation of the source-related criterion may require additional source attribution information that is not yet systematically represented in current LCI databases.

Nevertheless, the approach remains broadly compatible with existing emission-based elementary flow structures used in current LCI datasets. The JRC-LCI approach (Beylot et al. 2021) involves reporting what is termed as “dissipative resource flow” at the unit process level. This approach identifies the dissipative flows of resources to three key areas: (i) environment, (ii) final waste disposal facilities, and (iii) products-in-use in the technosphere. These resources are deemed to be not providing any significant function anymore (including due to non-functional recycling). The JRC-LCI approach considers both elementary (dissipative) flows, from the technosphere to the ecosphere, and (dissipative) flows within the technosphere. Owsianiak et al. (2021) and Beylot et al. (2021) proposed classification frameworks for identifying and distinguishing dissipative resource flows within LCI databases rather than characterization methods providing alternative characterization factors with specific units. These approaches primarily address the inventory-level definition of dissipative resource use and therefore complement, rather than replace, LCIA characterization models for resource use assessment. The unit of the impact using each of these two methods depends on its combination with an appropriate impact assessment method. As both these methods focus on the mass of dissipated resources, they are categorized in this category 1 (Fig. 2).

The methods in the category 2 of Fig. 2 quantify the consequences of compensating the lost values of resources in a physical metric of ore quantity or energy, which the methods in category 1 do not account for. Three methods assess the impact of resource use by accounting the mass of resources required for compensation. The Product Material Footprint (PMF) method (Mostert and Bringezu 2019) assesses the potential impact by considering the extracted amount of raw materials that is further processed and used in production and consumption, the volume of final emissions and waste, and the associated bundle of environmental impacts. The unit of the CFs is dimensionless, but the original parameter of the indicator has the unit of metal mass. The Ore Requirement Indicator (ORI) method (Swart and Dewulf 2013) assesses the potential impact of resource use by considering the changes to ore requirements based on past data on ore requirements for mining so that the value of lost resources is compensated by additional ore mining. The Surplus Ore Potential (SOP) method (Vieira et al. 2017) estimates the additional amount of ore that would need to be mined per additional unit of resource extracted, based on grade–tonnage relationships of known mineral deposits in the years 2000–2013 assuming that higher-grade ores are extracted first and without explicitly accounting for competing factors such as technology and economic considerations that are known to be important and influential. As with other resource depletion models, this representation is

subject to uncertainties related to the complex dynamics of mineral supply (e.g., Northey et al. 2018). Apart from these methods based on physical metrics, two methods adopt the energy requirement for compensation of the lost values of resources. The surplus energy method (Goedkoop and Sprimmsma 2001) assesses the energy requirement for additional mining which is averaged for future based on the grade tonnage relationships. Pfister et al. (2009) focuses on freshwater resources and the consequence of its consumption. The method assumes the freshwater consumption exceeding renewability needs to be backed up by desalination, and the energy requirement of desalination to compensate for the same volume of freshwater is determined as the damage of water consumption in the method.

The methods in the category 3 of Fig. 2 assess the economic loss from resource use without any compensation of the lost values. Two approaches assessing the impact based on the market price of resources and the externality in the market were reviewed. Both the Eco-cost method (Vogtländer et al. 2001) and the JRC price-based characterization approach combined with the JRC-LCI approach (Beylot et al. 2020; Ardente et al. 2023) assess the lost instrumental values of resources using their market price (a measure of exchange value) as a proxy for the instrumental value provided by resources in diverse economic sectors. On the other hand, three methods quantify the lost economic value associated with depleted resources for other potential users. The future welfare loss method (Huppertz et al. 2019) calculates the cumulative economic loss as the underestimation of the resource price in the market compared to the optimal price for sustainable use until depletion. El Serafy's user cost method (El Serafy 1989; Yokoi et al. 2024) also assesses the economic loss of resource use for other potential users. This method assumes that the potential damage to be quantified is due to overuse of a resource, which is quantified by calculating the difference between the expected value of permanent income generated from resource utilization and the present value of the resources based on market prices. Cao et al. (2014) evaluates the lost economic values of ecosystem services due to land use by quantifying the lost functions in biophysical units and converting them into economic values estimated by virtually setting the market.

In contrast to category 3, the methods in category 4 of Fig. 2 represent the consequences of compensating for the lost values of resources. The EPS method (Steen 2016) assumes that the function of used resources will be replaced by alternative energy/materials, and the procurement cost of the alternative in the market is determined as the damage. Three methods focus on the increased cost of resource production with a change in resource quality, which mainly targets mineral resources. The surplus cost method (Goedkoop et al. 2001; Ponsioen et al. 2014) estimates the increased

cost of mineral production to compensate for the lost values of resources by the integration of additional increase of mining cost with a change of resource quality divided by the sum of production. The surplus cost potential (Vieira et al. 2016 b) method adopts the similar approach that estimates the increased cost of resource production based on a cumulative tonnage-cost relationship over a period characterized by very high growth in mineral demand and mineral price increases that significantly distorted short-term mineral markets (Berger et al. 2020). The Demand Change-based Surplus Cost (DCSD) method (Yokoi et al. 2018) assesses the additional cost for the compensation of the lost resources by considering future primary resource use changes due to future changes in total demand and secondary resource use. As a different approach to assess the economic loss from resource use, the MACSI method (De Bruille 2014) estimates the additional cost to pay by unadapted users to take back the access to lost services from resources.

As shown in the above, the listed existing relevant methods focus on the potential impact of resource use from diverse perspectives, including differences in the impact metrics adopted and consideration of compensation consequences. To determine the most suitable method for addressing the defined question and its associated impact pathways, we established evaluation criteria and a scoring system for the listed methods, which will be explained in detail in the following section.

3.2.2 Evaluation criteria and scoring

The evaluation criteria were developed through iterative discussions within the GLAM Phase 3 Task Force based on previous methodological discussions conducted in earlier GLAM activities and related LCIA evaluation studies (e.g., Sonderegger et al. 2017, 2020). The criteria were intended to reflect key methodological and practical requirements for LCIA methods addressing natural resource use, including scientific robustness, environmental relevance, operational applicability, transparency, reproducibility, and stakeholder acceptance. The following 10 criteria were defined for transparent and consistent evaluation of the existing methods (Table 1). Previous review studies have provided important overviews and categorizations of existing methods for natural resource use assessment (e.g., Sonderegger et al. 2020; Berger 2024). In contrast, the objective of the present evaluation was not only to compare methods themselves, but also to assess their consistency with the safeguard subject, generalized impact pathways, and operational requirements for LCIA implementation defined within the present consensus-based framework.

The first two criteria were defined to test suitability to the defined question to be answered and associated impact

Table 1 Evaluation criteria and description

Criterion	Description of each criterion
1. Relevance to the question to be answered	Does the method appropriately represent the potential impacts on the safeguard subject corresponding to the assessment question defined in the Sect. 3.1?
2. Consistency of the impact pathways to the task force (TF) developed impact pathways	Is the cause-effect chain consistent with regards to what is proposed within the work of TF, including appropriate justification of links between fate, exposure, and effect modeling steps?
3. Robustness of the assumption	How sufficiently robust are the assumptions used for characterizing the potential impacts on the AoP?
4. Quality of the data used in the CF calculation (precision)	How precise is the data used for the CF calculation?
5. Quality of the data used in the CF calculation (representativeness)	How representative is the data used for the CF calculation?
6. Quality of the data used in the CF calculation (up-to-date)	How up-to-date is the data used for the CF calculation?
7. Representativeness of the damage	Is the damage for all affected users covered properly? (geographical coverage/temporal coverage/technological coverage)
8. Consistency/compatibility of the metrics with various impact categories	Are the metrics of the damage applicable across different natural-resource-related impact pathways (e.g. minerals use, freshwater consumption, land occupation/transformation etc.)?
9. Availability of the CFs	Are the CFs readily applicable in case studies?
10. Compatibility of the CFs with LCI databases	Are the CFs compatible with the elementary flows of existing LCI databases?

pathways. Criteria 3 to 6 were designed to secure the robustness and quality of the assessment by the selected method in terms of its assumptions and the data used. Criteria 7 and 8 were set to test coverage of all relevant users and resources. Criteria 9 and 10 were set for the sake of securing feasibility, promotion of practical application of recommended methods being one of the primary objectives of the GLAM project:

For the evaluation of the existing methods in response to the above criteria, we also set the scoring system with four grades of recommendation level. First, we defined the general requirement for each level of recommendation from the highest level, recommendable, to the lowest level, not recommendable:

- Recommendable: There are no major concerns for recommendation.
- Acceptable: There are some issues that are not critical but can be solved in further development.
- Less recommendable: There are some critical concerns that may not be easily solved in further development.
- Not recommendable: There are some critical concerns that can not be technically solved.

According to the defined general requirement, the criteria-specific scoring requirements were defined for each criterion in detail (Table S3). These requirements were designed through intensive discussion and consensus building within the task force. All the listed existing relevant methods were reviewed and evaluated for the defined 10 criteria with 4 recommendation levels. The evaluation criteria, scoring requirements, and minimum requirements were discussed and established independently from the final

evaluation outcomes of individual methods, in order to provide a transparent and consistent basis for comparison and recommendation.

3.2.3 Results of the evaluation of the existing methods and selection of the recommended methods

Table 2 summarizes the results of the evaluation of the existing methods for each criterion. The evaluation process was conducted iteratively through preliminary assessments and subsequent consensus discussions within the Task Force. For each method, preliminary evaluations were primarily prepared by Task Force members with sufficient methodological expertise, while avoiding assigning the lead preliminary evaluation to developers of the respective method. The preliminary evaluation results were subsequently reviewed and discussed collectively by the Task Force members, including method developers, in order to ensure consistency and transparency across methods and criteria. Final evaluation outcomes shown in Table 2 were determined through consensus-based discussions among the Task Force members. The broad participation of experts with different methodological backgrounds was considered important to critically examine assumptions, strengths, and limitations of the evaluated methods from multiple perspectives. Similar evaluation processes including in-depth critical analysis have been conducted in parallel (for example, by Beylot et al. (2024)). These sometimes involved different subsets of Task Force members, and their results have not always fully aligned with the evaluation carried out by the Task Force as a whole, reflecting different scopes and objectives as compared to the consensus building process presented in this article.

Table 2 The results of the evaluation of the existing methods

Method	1. Relevance to the question to be answered	2. Consistency of the impact pathways to the TF developed impact pathways	3. Robustness of the assumption	4. Quality of the data used in the CF calculation (precision)	5. Quality of the data used in the CF calculation (representativeness)	6. Quality of the data used in the CF calculation (up-to-date)	7. Representativeness of the damage	8. Consistency/compatibility of the metrics with various impact categories	9. Availability of the CFs	10. Compatibility of the CFs with LCI databases
ADP ultimate reserves	C	B	A	B	B	D	A	C	A	A
ADR and LPST	B	B	A	B	B	C	A	C	B	C
EDP (Environmental Dissipation Potential)	C	B	C	B	B	C	A	C	A	A
Owsianiak et al. (2021)	B	B	B	NA	NA	NA	NA	B	NA	A
JRC LCI approach	B	B	B	NA	NA	NA	NA	B	NA	A
PMF (Product Material Footprint)	C	B	C	A	A	A	A	C	B	A
ORI (Ore Requirement Indicator)	C	B	C	B	B	C	A	C	A	A
Surplus Ore Potential	C	B	C	B	B	C	A	C	B	A
Surplus energy	B	B	C	C	C	C	A	B	A	A
Pfister et al. 2009	B	B	A	A	C	C	A	A	A	A
Eco-cost	A	B	B	C	C	C	A	A	B	A
JRC price-based characterization approach	A	B	C	C	C	A	A	A	A	A
The future welfare loss	A	B	B	C	C	B	A	A	A	A
The El Serafy's user cost	A	B	C	C	C	B	A	A	B	A
Cao et al. 2015	A	A	B	C	C	C	A	A	B	A
EPS	A	B	B	C	C	B	A	A	B	A
Surplus cost	A	B	C	C	C	C	A	A	A	A
Surplus cost potential	A	B	C	B	B	C	A	A	B	A
Demand-Change-Based Surplus Cost	A	B	C	B	B	C	A	A	C	A
MACSI	A	B	D	C	C	C	B	A	A	A
Minimum requirement for recommendation	B	C	B	C	C	C	A	B	B	A

A: Recommendable
 B: Acceptable
 C: Less recommendable
 D: Not recommendable
 NA: Not applicable

As shown in Table 2, all methods have their own advantages and disadvantages according to different criteria. Regarding relevance to the question and consistency/compatibility of the metrics, methods based on physical metrics

tended to receive relatively lower recommendation levels because physical quantities alone cannot fully represent the instrumental values associated with natural resources, although they can capture important aspects related to

physical depletion or dissipation of resources. In contrast, methods based on economic metrics were considered to align more directly with the value-oriented interpretation of the defined safeguard subject. On the other hand, regarding robustness of the underlying assumption and data quality of the calculation, the opposite tendency is observed because of the weaknesses and limitations of the underlying assumptions of the methods based on economic metrics.

More generally, no single method performed strongly across all evaluation criteria, highlighting the trade-offs between conceptual consistency with the defined safeguard subject, methodological robustness, and practical applicability. In particular, many methods received relatively low evaluations regarding their data currency and representativeness of the underlying data, reflecting the difficulty of maintaining globally representative and continuously updated datasets for natural resource assessment. By contrast, compatibility with existing LCI databases was generally evaluated positively for many methods, indicating that practical implementation within current LCA frameworks is already feasible to a certain extent. An exception is represented by the ADR and LPST methods. Their lower evaluation regarding compatibility with current LCI databases reflects not a lack of inventory data availability but the potential inconsistency between the assumptions embedded in the dynamic MFA models and those represented in product system LCIs (Beylot et al. 2024).

These trade-offs between the evaluation results according to the different criteria made selection of recommendable methods less straightforward. On the other hand,

according to the aim of the GLAM3 project, we aimed to identify and further refine/update methods that could best fit to the defined relevant question to be answered, its associated impact pathways, high availability of CFs and compatibility with existing LCI databases. The task force therefore discussed the significance of each criterion and agreed to define the minimum requirement for each criterion shown in Table 3. In particular, the minimum requirement for consistency with the generalized impact pathways was intentionally set at the “Less recommendable” level because many existing operational LCIA methods for natural resource use were originally developed before the generalized framework proposed in the present study. Requiring a higher threshold for this criterion would have excluded most operationally mature methods currently available despite their scientific robustness and practical applicability in other evaluation dimensions.

As a result of introducing the above minimum requirement for each criterion, five methods were selected as candidates for GLAM recommendation: Pfister et al. (2009) was selected for water resource use, Cao et al. (2015) for land use, the Eco-cost, the future welfare loss, and the EPS for abiotic resource use. Pfister et al. (2009) and Cao et al. (2015) were identified as the most suitable currently operationalized methods for water resource use and land use, respectively, within the present review framework. However, the task force agreed that these recommendations should still be regarded as interim because the scientific maturity of impact assessment methods for these resource categories is still limited, particularly regarding the robustness

Table 3 Minimum requirement for each criterion for recommendation

Criterion	Minimum requirement	Description of minimum requirement level
1. Relevance to the question to be answered	Acceptable	Can fully answer by the support of other methods or modification: either current or future effects.
2. Consistency of the impact pathways to the task force (TF) developed impact pathways	Less recommendable	One mechanism of the fate model is covered but not part of the one recommended within the TF (e.g. extraction instead of occupation, dissipation, degradation and depletion) or no effect model is described and/or the proposed cause-effect chain is not justified.
3. Robustness of the assumption	Acceptable	The assumptions are recognized through peer reviews in scientific journals but there are some unanswered scientific questions within TF.
4. Quality of the data used in the CF calculation (precision)	Less recommendable	The quality of the data is not good but fair enough in precision.
5. Quality of the data used in the CF calculation (representativeness)	Less recommendable	The quality of the data is not good but fair enough in precision.
6. Quality of the data used in the CF calculation (up-to-date)	Less recommendable	The quality of the data is not good but fair enough in precision.
7. Representativeness of the damage	Recommendable	Affected users are mostly covered and a plausible impact mechanism is given, but one of the aspects (geographical/technological) is not satisfied for the chosen timeframe (current or future).
8. Consistency/compatibility of the metrics with various impact categories	Acceptable	The metric is relevant to many natural resources but not comparable/aggregatable for different resources (e.g. minerals, freshwater, land, soil, non-metallic minerals, fossil fuels, wood, biomass, etc.).
9. Availability of the CFs	Acceptable	Some flows are covered.
10. Compatibility of the CFs with LCI databases	Recommendable	Fully compatible without modification by the user.

of characterization models. Thus, further methodological development and exploration of additional approaches are required, particularly for the development and refinement of characterization factors for water resource use and land use assessment. In this study, an “interim recommendation” refers to a method that is currently considered the most suitable operational option within the available scientific knowledge and evaluation framework, while recognizing that further methodological development, validation, and scientific consensus are still required before a fully established recommendation can be made. For abiotic resource use, the Eco-cost and EPS methods are very similar. The Eco-cost assesses the lost instrumental values of resources using their market price, while the EPS assumes that the lost instrumental values of resources are proportional to the market price of virgin resources needed to compensate for their use. Therefore, both methods generally account the lost instrumental values of resources with the market price of resources. The future welfare loss method calculates the cumulative economic loss from underestimation of the resource price in the market until depletion, which considers the resource price but captures the opportunity cost for both current and future users of resources. For the Eco-cost and EPS methods, the critical concerns raised by the task force were the timeframe of the assessment and their similarities with life cycle costing. Natural resources are common goods for all current and future users; therefore, current use of natural resources may affect resource accessibility across generations, which the task force considered an important perspective for impact assessment. Although the Eco-cost, EPS, and Future welfare loss methods were all evaluated as recommendable regarding coverage of affected users within their respective assessment timeframes, the Future welfare loss method was considered to align more explicitly with the safeguard subject defined in this study because it consistently captures opportunity costs affecting both current and future users within a single assessment framework. Thus, the task force concluded to select the future welfare loss method for abiotic resource use for development of characterization factors and recommendation by the GLAM project. This recommendation does not replace the question-dependent recommendations proposed in Berger et al. (2020), but rather represents a generalized operational recommendation within the broader safeguard-subject framework developed in the present study.

Moreover, the JRC-LCI approach is a classification method to be applied before characterization. The JRC-LCI approach involves reporting and classifying dissipative flows of mineral resources to a number of (receiving) compartments, at the unit process level in mass units. As such, it may be used in combination with any impact assessment that applies consistent system boundaries. The same may be

said for the LCI classification approach described by Owsianiak et al. (2021).

3.3 Updated characterization factors of the recommended method for mineral and fossil resource use

3.3.1 Data and calculation of the updated characterization factors

For providing the characterization factors based on the recommended method for mineral and fossil resource use, we recalculated the characterization factors by following the original equation of the characterization factor by the future welfare method (Huppertz et al. 2019) with the updated resource price data:

$$CF_i = c_{p,i} \times NRP_i \quad (1)$$

where CF_i denotes the characterization factor of mineral and fossil resource i [USD/kg]; $c_{p,i}$ denotes the price correction factor of abiotic resource i [dimensionless]; NRP_i denotes the net resource price that represents the net cost for extraction of resource i [USD/kg]. Conceptually, the net resource price is derived from the difference between market price and extraction cost. However, due to limited availability of commodity-specific extraction cost data, extraction costs for many resources were estimated using market-price-based assumptions following Huppertz et al. (2019). The price correction factor $c_{p,i}$ is derived from the following equation and determined by the annual social discount rate r_s and the annual market discount rate r_m :

$$c_{p,i} = \frac{\int_0^{T_i} df_{r_s}}{\int_0^{T_i} df_{r_m}} \quad (2)$$

where T_i denotes the depletion time of abiotic resource i . Economically, the price correction factor expresses the extent to which current market prices underestimate the long-term social value of natural resources due to differences between private and social discounting perspectives. Following Huppertz et al. (2019), the social discount rate and market discount rate used in this study were 3% and 5.5%, respectively. Though depletion time T_i likely varies across abiotic resources, Huppertz et al. (2019) argue the differences in resulting impacts become negligible in the long term and therefore define 300 years as the default T_i for all abiotic resources. We retained these original parameter values and updated only the commodity price data used for recalculating characterization factors.

For the calculation of the NRP_i , we referred to the historical market price data of abiotic resources as implemented to compute the JRC price-based characterization factors (Ardente et al. 2023). The average market price of 88 commodities during 30 years during 1989 to 2018 was used as input data for estimating the net resource prices (NRPs), together with extraction cost assumptions following the original Future welfare loss framework (Huppertz et al. 2019). A 30-year period was used to smooth short-term price fluctuations and better represent long-term economic signals related to resource scarcity. The reference year 2018 was selected to maintain consistency with the JRC price-based characterization framework and to avoid distortions associated with exceptional short-term market fluctuations observed in more recent years, such as those related to the COVID-19 pandemic and subsequent geopolitical disruptions. Because the price correction factor $c_{p,i}$ is dimensionless, the resulting characterization factors retain the unit of the net resource price (2018 USD/kg). Nevertheless, periodic future updates of the database and characterization factors will be necessary to maintain the operational relevance of the method. The list of commodities for this calculation is shown in Table S2. Based on the calculated CFs, the normalization value (NV) is also calculated by multiplying the

annual mine production (in this case, extraction) volume of each abiotic resource (Energy Institute; NEA 2020; USGS 2020) with the corresponding CF:

$$NV_i = AP_i \times CF_i \quad (3)$$

Where NV_i denotes the annual total impact of producing abiotic resource i [USD/year]; AP_i denotes the annual production of abiotic resource i [kg/year].

3.3.2 Results of the updated characterization factors and normalization

The calculated CFs for 20 main commodities in terms of annual impact are summarized in Fig. 3. Coal, iron ore, lime, bauxite, and phosphate rocks show relatively low CFs owing to their relatively low market price, and some metals such as gold, platinum, and silver show higher CFs. At the same time, it can be observed that the CFs contain a certain range of uncertainty which mainly comes from the market price variation. The fact that net price for production differs across commodities is one of the controlling factors of this method.

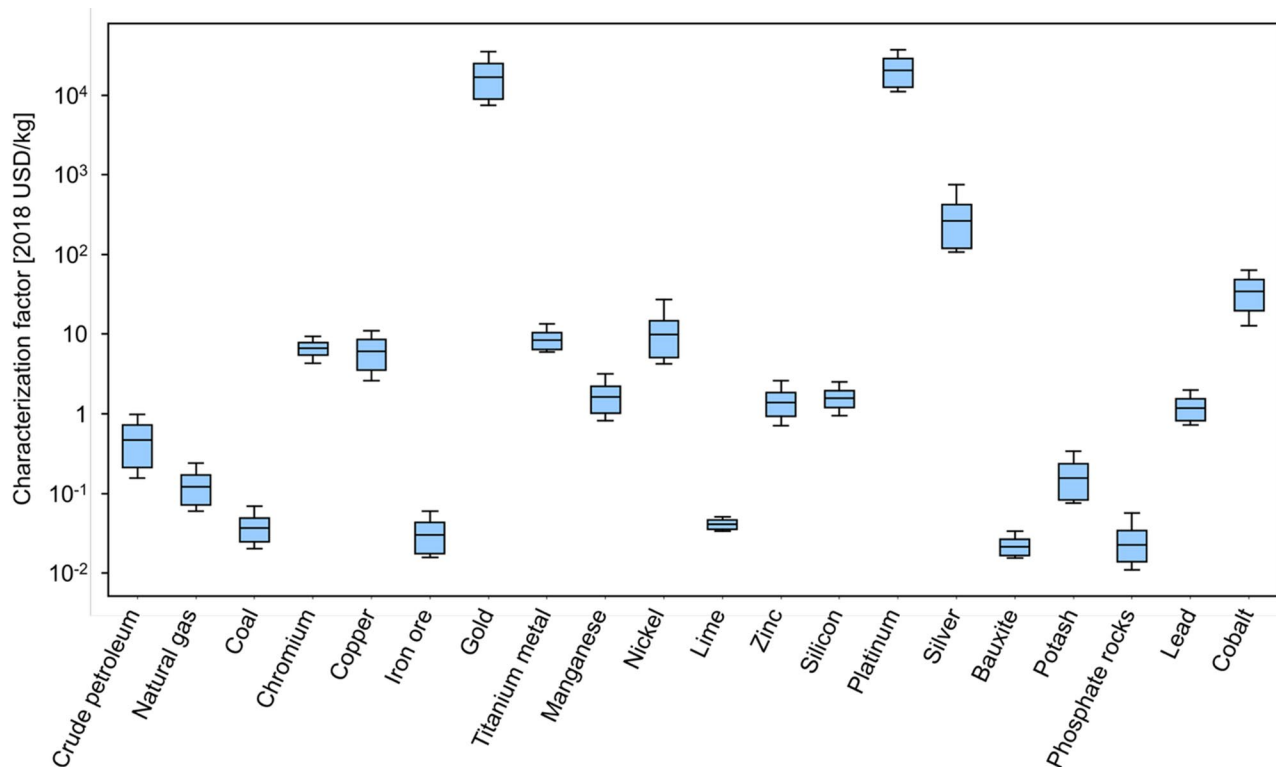


Fig. 3 Characterization factors of the top 20 commodities contributing to the annual impact. Note that the vertical axis is shown on a logarithmic scale. The top, upper box edge, middle line, lower box edge, and bottom whisker represent the CFs calculated using the maximum price over the 30-year period, the mean price + standard deviation (SD), the

mean price, the mean price – SD, and the minimum price, respectively. A list of characterization factors for all target commodities and the corresponding price basis is provided in the Supporting Information (Table S4)

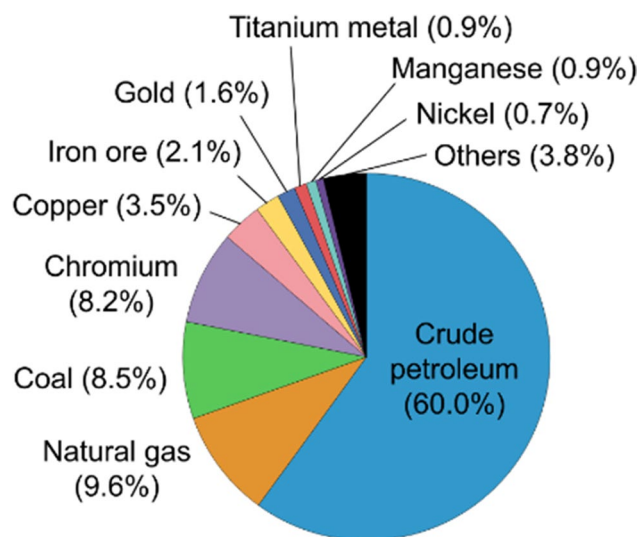


Fig. 4 Breakdown of the annual impact (3,483 billion [2018 USD/year]) of abiotic resource use

Metals tend to show higher values of the CFs compared with fossil resources and other minerals such as rocks. However, the total impact of current activities shows a different tendency, which can be observed by the results of normalization in Fig. 4. The estimated total impact is accounted as 3,483 billion [2018 USD/year], which accounts for around 4% of the world Gross Domestic Product (GDP) in 2018. Fossil resources such as crude petroleum, natural gas, and coal dominate around 78% of the total impact. Although the CFs of these fossil resources per se are relatively smaller than those of minerals, the significance of annual production volume results in the dominance in the annual impact of abiotic resource use. Apart from fossil resources, chromium, copper, iron ore, gold, and titanium metal are indicated as the main drivers of the total annual impact. In particular, chromium and copper are key resources owing to the significance of their CFs.

3.3.3 Interpretation of characterization and normalization results

The normalization results indicate that a limited number of resources dominate the overall impact results, particularly crude petroleum and several metal resources with relatively high characterization factors. Such concentration reflects both the scale of global extraction and the economic assumptions embedded in the FWL model, where market prices and extraction costs act as proxies for the instrumental values associated with resource accessibility.

In particular, some minerals, e.g. chromium and copper, contribute a relatively large share of the total annual impact despite lower production volumes compared with bulk materials such as iron. This result is mainly explained by

the comparatively high characterization factor of those minerals in the FWL method, reflecting the combined effects of commodity price and extraction cost assumptions. The characterization factors based on the FWL method are highly influenced by the extraction cost of resources which generally relates to the commodity price. Thus, resources with higher commodity price tend to show larger characterization factors and normalization values irrespective to their smaller mine production (see Table S4). On the other hand, crude petroleum accounts for the largest contribution to the total normalization results. The dominance of crude petroleum in the normalization results should not be interpreted as indicating that the FWL method functions merely as an “oil price indicator.” The normalization results reflect the combined influence of the characterization factor and the very large global extraction volume of crude petroleum. In contrast, some mineral resources such as chromium exhibit comparatively high contributions despite much smaller extraction volumes because of their relatively high characterization factors within the FWL method. The normalization results therefore reflect both the scale of resource extraction and differences in the economic valuation embedded in the characterization model.

Compared with the original characterization factors of major resources reported by Huppertz et al. (2019), the updated factors calculated in the present study generally preserve the similar magnitude and relative tendencies among resources, while some changes are observed due to updated 2018 commodity price data (Table S5). The update therefore primarily represents an operational refinement and expansion of coverage rather than a fundamental modification of the underlying characterization model.

4 General recommendations, limitations and challenges

The generalized impact pathways defined in this study are intended to conceptually cover multiple categories of natural resources. However, operational consensus-based recommendations could currently only be established for mineral and fossil resource use due to the differing levels of methodological maturity and data availability across resource categories. While mineral and fossil resources fit well within the proposed framework, renewable resources like water, land, forest and other biotic resources, may need some modifications of the generalized impact pathways. For example, water and forest resources may be temporally depleted, while they will be regenerated in the natural system without any interventions from human beings. During the regeneration of such resources, both quantity and quality of regenerating resources may change. In the current framework, such

replenishment processes are conceptually represented by the “Renewability – replenishment” flow in Fig. 1. However, explicit operationalization of regeneration dynamics for renewable resources should be further discussed for the definition of resource-specific impact pathways.

4.1 To which extent do the selected methods answer to the question to be answered?

The recommended methods by this taskforce should enable us to either evaluate *the requirements of additional efforts to compensate for the lost values or the lost values per se*. The FWL method is recommended as it is estimated to be the best proxy to evaluate the lost use values of natural resources. As a result, extraction cost-adjusted market price of natural resources is a proxy indicator for the lost use values of natural resources. This assumes that the use value of natural resources is captured by the market price of resources.

4.2 Resource coverage of the recommended methods

Regarding the characterization model of the impact assessment of mineral and fossil resource use, we have selected the future welfare loss model by updating the commodity price for the year of 2018 from the original model (Huppertz et al. 2019). This model covers 81 minerals, 3 fossil resources, and 2 energy carriers for the assessment of the potential impacts of their use at global level. This model satisfies the requirements for recommendation in all evaluation criteria, which endorses the legitimacy of the model as the best available model of the existing studies.

4.3 Update requirements and limitations of the recommended methods

For the improvement of the coverage of target resources, the data of market price and extraction cost of mineral and fossil resources will be required. In particular, the CFs for most of mineral and fossil fuels were derived not from the real extraction cost but the estimated extraction cost on the basis of the assumption according to the original study (Huppertz et al. 2019) due to the limited availability of the data of commodity-specific extraction cost.

Apart from these data-related limitations, particularly regarding the availability and representativeness of extraction cost and market price datasets, there are two methodological questions to be solved in future research. First, the model assumes that the socially optimal valuation of abiotic resource use evolves over time according to a social discount rate, resulting in a divergence from observed

market prices based on private discount rates. The Future welfare loss method interprets this divergence as reflecting the opportunity costs imposed on current and future users through resource depletion. However, the legitimacy of assuming resource valuation based on a social discount rate remains a normative and debated assumption. Different assumptions regarding social discounting may substantially influence intergenerational valuation of resource depletion impacts. Inconsistencies between simplified economic models and real-world resource economics have been discussed in the literature (Reynolds 2013; da Cunha and Missemmer 2020). Second, the depletion time of abiotic resources is set as 300 years for all resources as a default of the model (Huppertz et al. 2019). This setting of the parameter implies that all resources would never be depleted or dissipated until 300 years. It may be true to some extent, because reserves vary depending on the advancement of the production technologies and market price. In particular, this model assumes the increase of market price with time, which may result in the expansion of reserves. However, this is also a strong assumption that is not yet verified. Besides this question, if we select the resource-specific depletion time for the CFs, abiotic resource with short depletion time will result in lower CFs as seen from Eq. 2. Sensitivity analyses regarding depletion time assumptions were already performed in the original FWL study by Huppertz et al. (2019), including comparisons using resource-specific depletion times and alternative upper-bound assumptions (e.g., 50-year limits). These analyses showed that the recommended base case using long-term convergence of discount factors generally provides an upper-bound estimate, while resource-specific depletion times resulted in lower characterization factors for many resources. These remaining methodological questions should be solved by further research together with the improvement of the coverage of resources. From the perspective of the generalized impact pathways proposed in this study, the systematic characterization of elementary flows entering inaccessible stocks (i.e., dissipative resource flows shown in Fig. 1) is considered an important direction for future LCIA development and implementation, particularly through improved inventory modelling and reporting of dissipative flows. The magnitude and direction of the resulting bias may vary substantially depending on the resource and application context. Applying characterization factors directly to extraction flows may overestimate impacts for resources with high recycling rates and low dissipative losses, whereas impacts may be underestimated for resources predominantly used in dissipative applications, such as phosphorus in fertilizers or zinc in galvanizing applications (Beylot et al. 2020, 2021, 2024). This reflects a broader tension between approaches that prioritize compatibility with currently available LCI databases and those that

advocate explicit modelling of dissipative flows through revised inventory structures (Beylot et al. 2024).

Regarding mineral resources, the Task Force recognizes that, in conceptual alignment with the defined impact pathways (Fig. 1), the recommended characterization factors are most consistently applicable to dissipative flows of mineral resources, as these represent permanent losses of accessibility and instrumental value. However, current LCI databases predominantly report mineral resource use as elementary flows “extracted from ground”, while systematic identification and reporting of dissipative flows (e.g., following Owsianiak et al. 2021 or JRC-LCI approaches) are not yet widely implemented. The additional contextual information, such as the origin and prior accessibility of the emitted resources, is often needed to determine whether such flows represent genuinely dissipative losses of accessible resources and instrumental value.

In this context, we consider the application of the recommended characterization factors to extraction flows as an operationally pragmatic approach under current LCI practice. In typical product LCA applying an avoided burden or substitution approach for end-of-life allocation, primary extraction is partly offset by recycling a part of input resource. This effect may differ under cut-off allocation approaches, where credits are instead associated with the use of secondary materials. The net primary resource demand is reflected in the results, thereby partly mitigating potential overestimation associated with applying the factors directly to extraction flows.

Nevertheless, for improved conceptual consistency, future methodological developments should explicitly link characterization factors to quantified dissipative flows, once these are systematically available in LCI databases. The concept of dissipative mineral resource flows has been developed in recent years in scientific literature. Several approaches have recently been proposed to define and quantify dissipative flows of natural resources, including concentration-based thresholds, dynamic material flow approaches, energy-based criteria, and accessibility-oriented concepts (Beylot et al. 2021; Owsianiak et al. 2021; Charpentier Poncelet et al. 2022c; Greffe et al. 2023; Santillan-Saldivar et al. 2023; Dewulf et al. 2024). However, no consensus has yet been reached regarding how dissipative flows should be consistently identified and represented within LCA practice. Beyond the remaining conceptual questions, a key challenge for operationalizing dissipation-based approaches is the systematic reporting of dissipative resource flows in LCI databases, including appropriate inventory nomenclatures and data structures. Progress in this area is likely to be essential for the practical implementation of dissipation-based resource assessment approaches in future LCA practice (Beylot et al. 2024). At this stage, the operational

update and provision of characterization factors are limited to mineral and fossil resource use, whereas the ultimate goal of this TF is the provision of a comprehensive method that covers impacts from other mechanisms relevant to natural resources, including degradation. Interim recommendations were also identified for water resource use and land use assessment. In this context, two methods satisfy the requirements for recommendation in all evaluation criteria: Pfister et al. (2009) for water, Cao et al. (2015) for land use. However, the applicability of these recommended models could not be fully discussed due to the limitation of time at this stage of the TF work. Particularly, water is not traded in the market explicitly, which makes it difficult to determine the economic value of water in the same way as other resources. The development of a cross-cutting and internally consistent assessment framework that can coherently assess impacts associated with different natural resources, rather than relying solely on resource-specific and independently developed approaches, remains an important future challenge for LCIA methodology development.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper, its supplementary information file.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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