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LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

Temporally explicit abiotic depletion potential (TADP) for mineral resource use based on future demand projections

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Abstract

Purpose Assessing the potential impacts (characterization) of mineral resource use in life cycle impact assessment (LCIA) has long been debated. One of the most crucial challenges in the characterization models for mineral resource use is the consideration of the changing demand and availability of in-use stocks in the future, which is relevant to the global population and economy growth as well as the increasing low-carbon technologies. We propose an extended characterization model to assess the potential impacts for arbitrary time horizons, considering future demand changes and the availability of in-use stock: temporally explicit abiotic depletion potential (TADP).

Methods The TADP was developed based on abiotic depletion potential (ADP), which is a widely used characterization model for mineral resource use. While the ADP assesses the potential impacts of mineral resource use based on a natural stock estimate and the current extraction rate, the TADP adopts an average extraction rate for arbitrary time horizons. The average extraction rate was estimated using material flow analysis considering future demand changes and recycling under the five shared socioeconomic pathways (SSPs). TADPs were calculated for six common metals: aluminum, copper, iron, lead, nickel, and zinc.

Results and discussion As a result of calculating TADPs for the term by 2050 ($TADP_{2050}$), compared to iron, all other metals showed larger values of characterization factors for all SSPs than the original ADPs. The $TADP_{2050}$ of copper exhibited the largest difference with ADP among the six metals (approximately 1.9 times), which is mainly attributed to future demand growth. On the other hand, for the longer time perspective, the $TADP_{2100}$ of lead and zinc exhibited larger differences with ADP than copper (approximately 2.8 times for zinc), which is mainly due to a relatively shorter lifetime for lead and a lower recycling rate for zinc. This suggests that the relative significance of the characterization factors of metals varies depending on the temporal perspective.

Conclusions With the proposed characterization model, the potential impacts of mineral resource use can be assessed reflecting future situations for the selected time horizons. The results demonstrate that the consideration of future situations greatly influences the relative significance of the potential impacts of using different mineral resources in the results of LCIA studies. By expanding the coverage of mineral resources and future scenario analysis to other relevant factors, the TADP model can improve the robustness of the assessment and further support decision-making towards sustainable resource management.

Keywords Life cycle impact assessment · Characterization · Mineral resources · Abiotic depletion potential · Temporally explicit assessment · Future demand · Material flow analysis · Shared socioeconomic pathways

1 Introduction

Mineral resource use plays a fundamental role in societal development and is one of the impact categories in life cycle assessment (LCA) (Finnveden et al. 2009). In the characterization step of life cycle impact assessment (LCIA), the potential impacts of the extraction (or use) of different mineral resources are quantitatively assessed and thus can be compared and integrated. Existing characterization methods

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usually assess the consequences of mineral resource extraction as potential impacts (e.g., a decrease in the availability of mineral resources for future generations) (Sonderegger et al. 2020). However, this impact category has been heavily debated and presents several challenges, as in the following.

First, the problem definition of mineral resource use is diverse and the common understanding of it has not been yet gained widely. This has resulted in various characterization models addressing different impact pathways and a lack of consensus for the best model (Dewulf et al. 2015; Drielsma et al. 2016a; Klinglmair et al. 2014; Schulze et al. 2020a, b). Recently, Berger et al. (2020) formulated different questions that stakeholders may have with regard to mineral resource use and developed recommendations on the application-dependent use of methods corresponding to each question, as opposed to focusing on determining the best characterization model. In addition, Poncelet et al. (2022) developed a linkage of impact pathways to cultural perspectives to determine the assessment methods relevant to the scope of the assessment. Furthermore, van Oers et al. (2020a) proposed a calculation approach for characterization factors of mineral resource use depending on the different temporal perspectives of the assessment. In this context, the selection of appropriate characterization models that match the aims of the assessment or the interests of evaluators/stakeholders is essential.

The second challenge involves considering future situations related to mineral resource use. Due to population and economic growth, technological innovation, etc. in the future, supply, demand, and consequently scarcity of mineral resources will no doubt change over time (Lee et al. 2020; UNEP 2013; Yokoi et al. 2018). Many existing characterization models quantify the changing opportunities of future generations in the use of mineral resources (Berger et al. 2020); however, in their assessment, the potential impacts of mineral resource use on future generations are based on parameters drawn from current situations. Given the likeliness of significant changes, including the rapid growth of emerging countries and technological innovation, current situation-based assessments are unable to fully represent the potential impacts of mineral resource use on future generations. Therefore, the incorporation of future situations into the characterization of mineral resources is essential to assess the potential impacts of mineral resource use on future generations.

The third challenge consists of considering the availability of anthropogenic stocks in characterization models (Berger et al. 2020; Klinglmair et al. 2014; van Oers and Guinée 2016). Generally, mineral resources do not physically disappear due to mining of natural stocks, but rather accumulate in society as in-use stocks, part of which can be recycled at the end-of-life stage (Stewart and Weidema 2005). The recovery of mineral resources from anthropogenic stocks will reduce the pressure of natural resource depletion and thus has an important influence on mineral resource availability (Schneider et al. 2011). However, the availability of anthropogenic stocks and the future substitution of primary resource production with secondary resource production have yet to be fully modeled in LCIA, although some studies have partly addressed this issue (Schneider et al. 2011, 2015; Schulze et al. 2020b; Yokoi et al. 2018).

The abiotic depletion potential (ADP), first proposed by Guinée and Heijungs (1995), is a widely used characterization model for mineral resource use and one of the recommended characterization models (Alvarenga et al. 2016; Berger et al. 2020; Hauschild et al. 2013). ADP assesses the potential impacts of mineral resource use based on the extraction rate and natural stock estimates. The choice of natural stock estimates implies what is actually assessed by the model (Sonderegger et al. 2020). For example, ADP based on ultimate reserves (UR) assesses the depletion of mineral resources from the very long-term perspective, while the model based on reserves addresses the short-term physico-economic scarcity of mineral resources (Sonderegger et al. 2020). This suggests that ADP can somewhat assess the potential impacts of mineral resource use for different timeframes depending on the choice of natural stock estimate. However, existing ADP models adopt the current extraction rate of mineral resources, which means that future extraction is implicitly assumed to be constant (even though time-series changes in ADP are considered by van Oers et al. 2020b). On the other hand, an extended ADP model has been proposed considering anthropogenic stocks in addition to natural stocks, referred to as the anthropogenic stock extended abiotic depletion potential (AADP) (Schneider et al. 2011, 2015). The updated version of the AADP provided by Schneider et al. (2015) adopts the sum of ultimately extractable reserves (UER) as a natural stock estimate and the anthropogenic stock in the denominator of the characterization model. The AADP is the first model that considers the availability of anthropogenic stocks in the characterization, while it is suggested that the numerator of the AADP is the extraction rate from only the natural stock, and thus, is inconsistent with the denominator (Berger et al. 2020; Schulze et al. 2020b; Sonderegger et al. 2020). In addition, the accumulated extraction rate from 1900 to 2010, with a default dissipation rate of 20%, was adopted as the anthropogenic stock, which does not represent the actual amount of anthropogenic stock available for future generations. Accordingly, a model that considers the availability of anthropogenic stocks and future situations has not yet been fully developed.

In this study, we propose an extended ADP model for the characterization of the potential impacts of mineral resource use on future generations from different temporal perspectives: temporally explicit abiotic depletion potential (TADP). We incorporate material flow analysis (MFA) in the ADP model to consider future demand changes and the availability of in-use stock (i.e., the future substitution of primary resource production with secondary resource production) for different time horizons. The TADP is a model to address the three challenges mentioned above and can be used to assess the depletion potentials of mineral resources considering future situations correspond to the scope of the assessment, which will help LCA practitioners to plan necessary actions towards sustainable resource management. The aim of this work is to develop a framework for TADP calculation and demonstrate the relevance of TADPs to the impact assessment of mineral resource use on future generations from different temporal perspectives in LCIA through the calculation examples of six common metals: aluminum, copper, iron, lead, nickel, and zinc. In addition, we discuss future work required to extend TADPs to other mineral resources towards the practical use of the model in the LCA study.

This paper is structured as follows. The methods are illustrated in Sect. 2, in which we present the derivation of the TADP model (Sect. 2.1), describe the estimation of future annual extraction amounts by using MFA (Sect. 2.2), and describe the selection of the natural stock estimates (Sect. 2.3). The results of calculating the TADPs for different time perspectives are shown and compared to the original ADPs in Sect. 3.1, followed by exploring drivers of difference among metals for TADPs (Sect. 3.2). In Sect. 4, we present sensitivity analysis with different natural stock estimates, comparison with existing the AADP model, and future work towards the practical use of the TADP model in LCIA study. Finally, we present conclusions (Sect. 5).

2 Methods

2.1 Temporally explicit abiotic depletion potential (TADP)

The original ADP is calculated as follows (Guinée and Heijungs 1995; van Oers et al. 2002):

$$ADP_i = \frac{E_i/R_i}{E_{ref}/R_{ref}} \times \frac{1/R_i}{1/R_{ref}} \quad (1)$$

where E_i is the extraction rate of mineral resource i (kg/year), R_i is the natural stock estimate of mineral resource i (kg), and ref represents the reference mineral resource. Equation (1) implies that the ADP consists of two factors: depletion rate (E_i/R_i) and severity of the current 1 kg extraction ($1/R_i$), and represents the relative value of mineral resource i to the reference mineral resource. When natural stock estimates other than UR are used for R_i, the former term (i.e., depletion rate) may not reflect actual depletion since some natural stock estimates, such as reserves and resources, will vary depending on various economic and technological factors (Drielsma et al. 2016b). Accordingly, in such cases, the former term represents the significance of the extraction rate relative to the natural stock estimate. The latter term (i.e., the severity of the current 1 kg extraction) considers the difference in the scale of the natural stock (Guinée and Heijungs 1995). In existing models, the current annual extraction amount is used for E_i, which means that the depletion rate is estimated based only on the current situation. On the other hand, various natural stock estimates can be used for R_i depending on the temporal perspective.

Here, we introduced the TADP, which considers future situations of mineral resource use, and can be calculated as follows:

$$TADP_{i,T} = \frac{\overline{E_{i,T}}/R_i}{\overline{E_{ref,T}}/R_{ref}} \times \frac{1/R_i}{1/R_{ref}} \quad (2)$$

$$\overline{E_{i,T}} = \frac{\sum_{t_0}^{T} E_{i,t}}{T - t_0 + 1} \quad (3)$$

where $TADP_{i,T}$ is the TADP of mineral resource i for the target year T (-), $\overline{E_{i,T}}$ is the average extraction rate of mineral resource i until the target year T from the evaluation year t_0 (=2010) (kg/year), and $E_{i,t}$ is the annual extraction amount of mineral resource i for year t. In this study, iron was defined as the reference mineral resource (ref). The choice of the reference resource may affect the absolute values of the TADP. However, it is irrelevant to the relative significance of the TADP among mineral resources (van Oers et al. 2020b). The target year T determines the temporal perspective of the characterization factor. The time horizon of the characterization can be chosen depending on the scope of the assessment, which is one of the most characteristic points of TADP. In this study, we selected the time horizon for the calculation of TADPs from 2010 to 2100 to demonstrate the relevance of considering future situations of mineral resources (in particular, TADPs for 2050 and 2100 are shown as typical results in Sect. 3.1). Note that the TADPs do not represent the characterization factors for the relative impacts of the mineral resource extraction in the year T, but the relative impacts of the "current" mineral resource extraction considering the future changes until the year T.

2.2 Future extraction amounts of mineral resources

The future annual extraction amounts of the target resources ($E_{i,t}$), which are required to calculate the average extraction rate ($\overline{E_{i,T}}$) during the defined assessment period, were estimated using MFA. MFA is an effective approach for quantifying and characterizing the anthropogenic flows and stocks of various materials or products at different spatial scales (Bringezu and Moriguchi 2002; Chen and Graedel 2012; Müller et al.` 2014). In a previous study, we projected the future extraction amounts of mineral resources with MFA from 2010 to 2100 (Yokoi et al. 2022a), the results of which were adopted as estimates for the extraction amounts of mineral resources at a certain time during the assessment period in this study. A brief description of the method is provided below (details are also provided in the Supplementary material, as well as in Yokoi et al. 2022a).

Several approaches have been proposed to project the future demands of mineral resources, which can be classified into two approaches: inflow-driven and stock-driven approaches (Watari et al. 2021a). We adopted the stock-driven approach, which first projects future in-use stocks and then determines future demand to meet the projected in-use stock growth (Hatayama et al. 2010; Pauliuk et al. 2013). Future in-use stocks were projected by using logistic regression based on historical in-use stocks estimated by previous studies, with the assumption that the per capita in-use stocks do not increase infinitely and will eventually saturate at a certain level (Watari et al. 2020; Watari and Yokoi 2021). Based on the material cycle model covering processes from natural resource extraction to waste management (Fig. S1), the amount of relevant material flows, such as primary resource extraction ($E_{i,t}$), secondary resource production, and waste flows, were calculated (details of the calculation are shown in the Supplementary material). Given the wide range of possible future situation changes, future demand projections and the corresponding calculations of the characterization factors were conducted based on the five shared socioeconomic pathways (SSPs), which are recently developed future scenarios for socioeconomic situations and are used in various studies, including climate change studies (O'Neill et al. 2014, 2017; Riahi et al. 2017): SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), SSP4 (inequality), and SSP5 (fossil-fueled development). The SSPs describe quantitative and qualitative future socioeconomic situations, including the projection of future population and economic growth in each country used in this study (Figs. 1 and S2). Users can select an appropriate SSP for their assessment, while we suggest adopting the SSP2 (middle of road) as a baseline and other SSPs for sensitivity analysis.

2.3 Natural stock estimates of mineral resources

We focused mainly on the time horizon between 2010 and 2100 in the calculation of TADPs. Thus, resources were used for the natural stock estimate (R_i). Resources are concentrates in such form and amount that ensures economic extraction is currently or potentially feasible and consider medium-term horizon (Mudd and Jowitt 2018; USGS 2022); therefore, they are suitable for the calculation of TADPs in this study. On the other hand, reserves may be suitable if the temporal scope of the assessment is the shorter term (e.g., 10 years), or resources may not fully represent the available amount of mineral resources in a longer-term perspective (e.g., more than 100 years). Therefore, we also calculated the TADPs with other natural stock estimates for sensitivity analysis in the discussion section: reserves, UER, and UR. The data for reserves, resources, UER, and UR were obtained from USGS (2011), Schneider et al. (2011, 2015), and van Oers et al. (2020b), respectively (Table S7).

Fig. 1 Overview of the five SSPs (O'Neill et al. 2017)

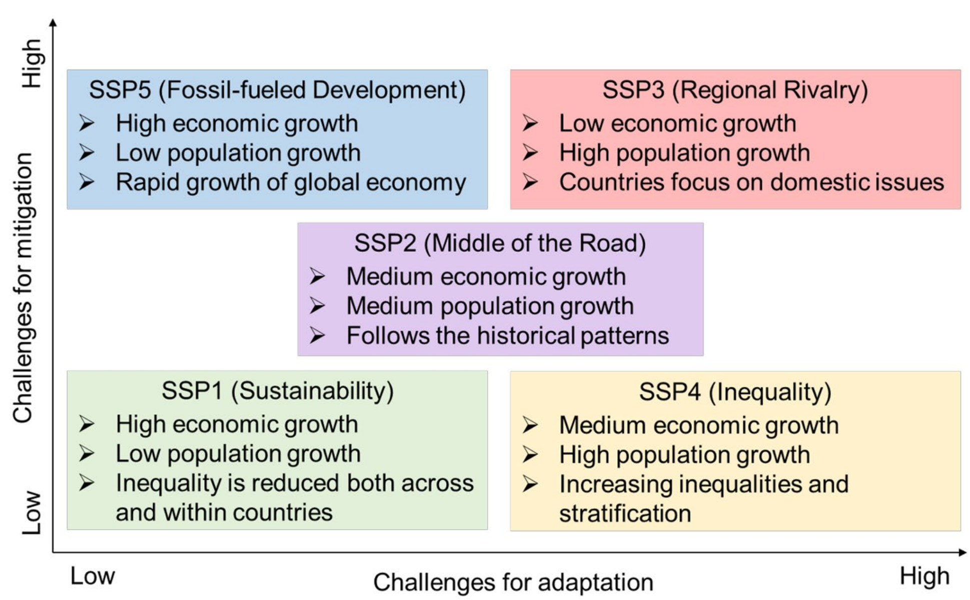

Table 1 The TADPs for the medium-term perspective ($T = 2050$) under the five SSPs

	Al	Cu	Fe	Pb	Ni	Zn
$ADP_{resources}$ [-]	3.9	1.2×10^3	1.0	1.2×10^3	4.9×10^4	1.9×10^3
$TADP_{2050}$_SSP1 [-]	5.5	2.3×10^3	1.0	1.9×10^3	7.3×10^4	3.2×10^3
$TADP_{2050}$_SSP2 [-]	5.4	2.3×10^3	1.0	2.0×10^3	7.0×10^4	3.4×10^3
$TADP_{2050}$_SSP3 [-]	5.4	2.3×10^3	1.0	2.1×10^3	6.7×10^4	3.7×10^3
$TADP_{2050}$_SSP4 [-]	5.6	2.2×10^3	1.0	2.1×10^3	7.3×10^4	3.6×10^3
$TADP_{2050}$_SSP5 [-]	5.6	2.3×10^3	1.0	1.8×10^3	7.7×10^4	3.0×10^3

3 Results

3.1 TADPs for different time perspectives

Table 1 shows the calculated TADPs for the term by 2050 ($TADP_{2050}$) for the five SSPs compared with the original ADPs (the results are also visualized in Fig. S3). The original ADPs were calculated based on the extraction rate in 2010 and resources for a natural stock estimate, which means that the difference between the original ADP and TADP was the time horizon for the calculation of the extraction rate. Compared to iron, all of the other metals evaluated showed larger potential impacts in the calculated $TADP_{2050}$ for all SSPs compared to those of the original ADPs. This is due to the fact that future extractions of iron are not likely to increase significantly, but rather decrease at some points in time for most SSPs, compared with the other metals (Fig. S4). This implies that any existing models assuming constant extraction rates are likely to overestimate the potential impact of iron use compared to other metals. Although the rank of the characterization factors of the metals did not change between ADP and $TADP_{2050}$ in all SSPs (Ni, Zn, Cu, Pb, Al, and Fe in descending order), the relative magnitude of the characterization factors among metals was affected. For example, the $TADP_{2050}$ of copper was approximately 1.9 times larger at the maximum compared to ADP, while the $TADP_{2050}$ of aluminum and nickel was approximately 1.4 times larger relative to that of ADP. The primary metal extraction of copper sharply increased compared with that of other metals in the early twenty-first century (Fig. S4), which led to relatively larger differences between ADP and $TADP_{2050}$ for copper than for other metals.

The difference between ADP and TADP was more remarkable when the time horizon of the assessment was expanded by 2100 (Table 2). Compared to iron, the TADPs of all the other five metals increased from the longer-term perspective ($TADP_{2100}$). Whereas copper showed the most significant differences between ADP and TADP in the assessment by 2050 under most SSPs (Table 1), lead and zinc showed larger differences between ADP and TADP in the assessment by 2100 (by a maximum of approximately 2.8 times for zinc in SSP1). Figure 2 shows the shifts in the ratios of the TADPs of the six metals for different time horizons compared to ADP. Copper typically showed the highest relative significance of the ratio of TADP to ADP by around the mid-century, while the significance of other metals became relatively higher; zinc showed the highest relative significance after the mid-century point. This demonstrates that the relative significance of the characterization factors of the metals varies depending on the temporal perspective of the assessment (drivers of the difference among metals are discussed in Sect. 3.2).

In order to demonstrate the influence of the TADPs on the results of LCIA, we conducted a case study in which potential impacts of global mine production for the six metals in 2020 are assessed by the ADP and TADPs (Fig. S5). The data for global mine production is derived from USGS (2022). The results show that characterization results by TADPs increase compared to that by the original ADP. In particular, the results by $TADP_{2100}$ significantly increase, mainly driven by the potential impacts of mine production of nickel and zinc. The difference among SSPs is also larger for the results by $TADP_{2100}$, in which the TADPs for SSP1 and SSP5 exhibit the largest potential impacts. These results indicate that the consideration of future situations in the

Table 2 The TADPs for the long-term perspective ($T = 2100$) under the five SSPs

	Al	Cu	Fe	Pb	Ni	Zn
$ADP_{resources}$ [-]	3.9	1.2×10^3	1.0	1.2×10^3	4.9×10^4	1.9×10^3
$TADP_{2100}$_SSP1 [-]	7.7	2.7×10^3	1.0	3.0×10^3	1.0×10^5	5.5×10^3
$TADP_{2100}$_SSP2 [-]	7.0	2.5×10^3	1.0	2.6×10^3	9.4×10^4	4.8×10^3
$TADP_{2100}$_SSP3 [-]	6.0	2.5×10^3	1.0	2.7×10^3	7.0×10^4	4.8×10^3
$TADP_{2100}$_SSP4 [-]	6.9	2.6×10^3	1.0	2.9×10^3	8.4×10^4	5.3×10^3
$TADP_{2100}$_SSP5 [-]	7.6	2.6×10^3	1.0	2.9×10^3	1.0×10^5	5.3×10^3

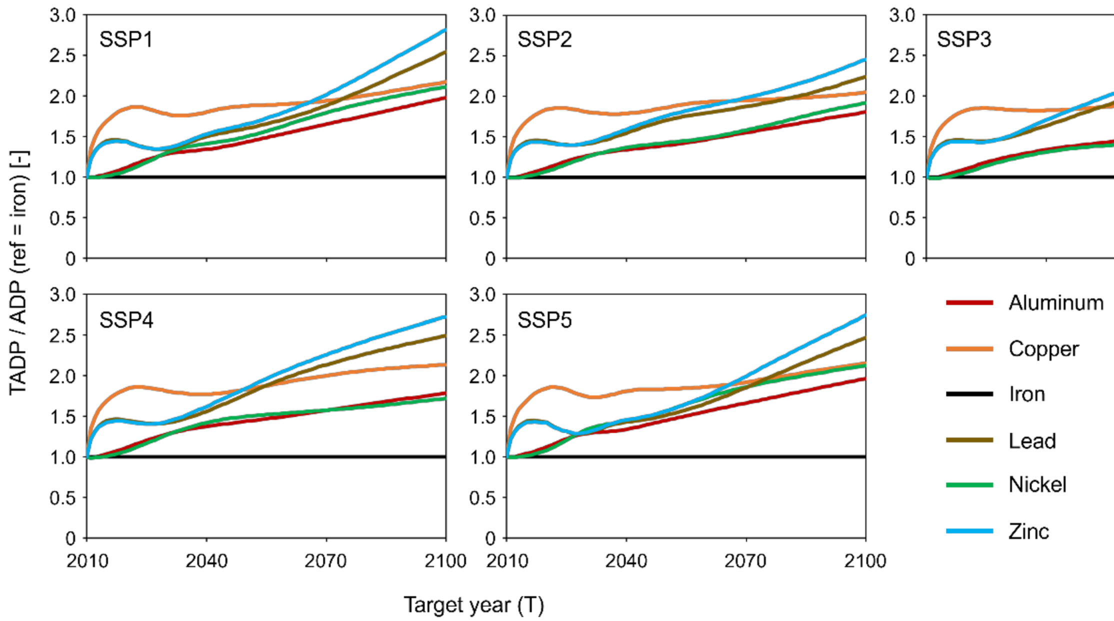

Fig. 2 Shift in the ratios of the TADP to the ADP for different time horizons

calculation of the characterization factors greatly influences the relative significance of the use of different metals in the results of LCIA studies when focusing on a specific time horizon. Therefore, our proposed characterization model can be used to assess the potential impacts of metal use reflecting future situations for the selected time horizon.

3.2 Drivers of difference among metals for TADPs

What causes the difference among metals in TADPs compared to those in ADPs? While ADP refers to the current primary metal extraction, TADP considers the future primary metal extraction growth (Fig. S4). In this study, to estimate future primary metal extraction, we first projected future in-use stock growth, which is determined by a disparity of per capita in-use stock among different income level groups, estimated logistic curve (growth curve) for per capita in-use stock (Fig. S6), and future population and GDP. Then, we determined future demand to meet the projected in-use stock growth by considering lifetime distributions of final products containing the target metals and calculated future primary metal extraction using MFA with assumed recycling rates (see the Supplementary material). Here, we discuss the differences between metals in terms of two related factors: relative changes in in-use stock and total demand, which are shown for the case of SSP2 (middle of the road scenario) in Fig. 3 (the results for the other SSPs are shown in Figs. S7 and S8).

With regard to the temporal changes in in-use stocks from 2010 (Fig. 3), nickel exhibited the largest increase by 2100, while iron exhibited the smallest increase. Our projection of future in-use stocks was based on the assumption that per capita in-use metal stock growth in all countries follows that in a high-income level group and saturates at the current per capita in-use stock level of a high-income level group (validity of this assumption will be discussed in Sect. 4). Thus, the larger gaps in current per capita in-use stock level between high-income and other income level groups (i.e., the disparity in per capita in-use stock level) result in a larger increase in future in-use stocks. Table S8 shows the differences in per capita in-use stock among the income level groups for the six metals, suggesting a correlation between the disparity in per capita in-use stock level and future in-use stock growth, as shown in Fig. 3.

Although an increase in in-use stock results in additional metal input, and thus an increase in total demand, the relative change in total demand exhibited different trends (Fig. 3). Lead, which showed the third smallest increase in in-use stock, exhibited the largest increase in total demand by 2100. This was mainly attributed to a relatively shorter lifetime for the end-use of lead (Table S4): a shorter lifetime resulted in additional metal input in the short term to sustain even the same level of in-use stock, which means a relatively larger demand growth compared to in-use stock growth (Fig. S9). As shown in Fig. 3, the relatively long lifetime for the end-use of iron (Table S3) restrained the increase in total iron demand compared to the other metals.

In addition to total demand growth, factors relevant to recycling (i.e., waste flow and old scrap collection rate) also affected the relative change in primary metal extraction. Both lead and nickel showed steady increases in the total demand and reached the highest level of all metals in 2100,

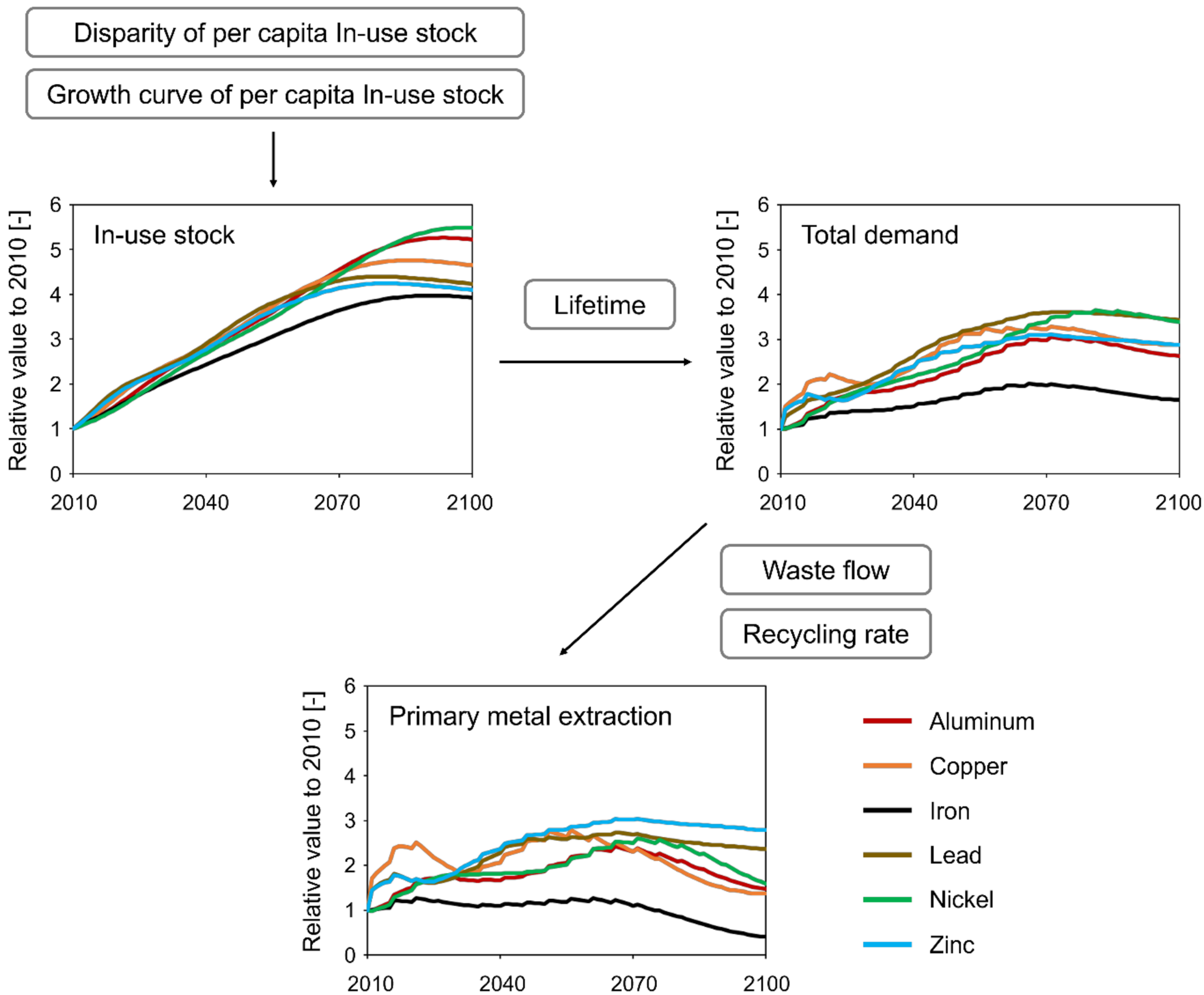

Fig. 3 In-use stock, total demand, and primary metal extraction for SSP2. The values are represented as the relative values to those in 2010, and determinant factors specific to respective estimated values are additionally indicated

whereas the relative changes in the primary metal extraction differed between lead and nickel: nickel exhibited a decline in primary metal extraction after 2070, unlike lead. This was due to differences in waste flow growth for these metals, as determined by the total demand growth and lifetime (Fig. S10). Nickel showed a relatively larger increase in waste flow in the late twenty-first century than lead, resulting in increases in secondary metal production which substitutes primary metal extraction. On the other hand, the relative change in primary metal extraction for zinc reached the highest level most of the time, even though in-use stock and total demand growth exhibited different trends. This is due to the relatively low recycling rate for end-use of zinc, the majority of which has a relatively low zinc content, such as galvanizing and brass, making zinc recycling challenging (Ma et al. 2011) (Table S6).

In summary, the disparity in per capita in-use stock among income level groups, lifetimes of metal-containing products, and recycling rate were considered the main determinants of relative changes in primary metal extraction, and consequently TADPs compared to ADPs. Although the relative change in the in-use stock of zinc was the second smallest after iron, a relatively shorter lifetime and lower recycling rate for the end-use of zinc resulted in the largest increase in primary metal extraction and TADPs compared to ADPs for zinc from a long-term perspective. On the other hand, the relatively smaller disparity in per capita in-use stock level, longer lifetime, and higher recycling rate for iron led to relatively lower TADPs for iron.

4 Discussion

This study incorporates MFA into LCIA methods to introduce the TADP, which is an extended ADP model. The TADPs can assess the potential impacts of mineral resource use from different temporal perspectives while taking account of future changes in resource demand and recycling. Considering future situations, the changes in the relative significance of metals by TADPs compared to the original ADPs were found to have a significant effect on the results of LCIA studies. Furthermore, we found that time perspective affected the relative significance of TADPs for different metals. For the short- and medium-term perspectives by around 2050, metals with relatively rapid growth of demand, such as copper, exhibited greater increases in the TADPs compared to the original ADPs, while for the longer-term perspective by 2100, metals with relatively short lifetimes and/or lower recycling rates, such as lead and zinc, exhibited greater increases in the TADPs. In addition to assessing the potential impacts associated with products or services in LCA based on TADPs or as a complement to ADPs for sensitivity analysis with arbitrary time horizons corresponding to the scope of the assessment, the TADPs can be incorporated in criticality assessment. It assesses the significance of raw materials in terms of supply risks (i.e., likelihood of supply disruptions), vulnerability (i.e., economic consequences), and, in some approaches, environmental implications and is often discussed in relation to LCA (Cimprich et al. 2019; Glöser et al. 2015; Schrijvers et al. 2020). Insights derived from ADPTs will support the criticality assessment in terms of supply risks. Furthermore, the TADPs suggest effective measures to alleviate the potential impacts of metal use in future scenarios. The TADPs for the short- and medium-term perspectives can identify metals that need improvement in resource efficiency as a crucial factor for the reduction of potential impacts, while those for a longer-term perspective can identify metals that need improvement in the lifetime and/or recycling rate.

Although we adopted resources as a natural stock estimate for TADPs in this study since resources represent metal availability for the medium-term horizon, there are several other options for natural stock estimates. As previously mentioned, the choice of natural stock estimates is known to have a great effect on the calculation of ADP and is thus controversial (Sonderegger et al. 2020). Therefore, we explored the effect of natural stock estimates by calculating ADP and TADP using different natural stock estimates (Tables S9–S11). Based on the UER and UR, which represent very long-term metal availability, the effect of natural stock estimates was greater than that of future metal extraction changes (i.e., the difference between ADP and TADP), especially for aluminum. On the other hand, ADPs based on reserves exhibited relatively similar results to those of resources. Regarding aluminum and zinc, the effect of future metal extraction changes was greater than that of changes to reserves.

The availability of anthropogenic stocks was introduced into the characterization model for the first time in the AADP model, which was proposed by Schneider et al. (2011) and subsequently updated by Schneider et al. (2015). The AADP model considers the current anthropogenic stock but does not consider future demand changes, lifetime, or recycling rate, which are specific to each metal. On the other hand, the TADP proposed in this study does not consider the relative amount of in-use stock compared to the natural stock estimate but considers the future availability of in-use stock and its relative amount compared to primary metal extraction. We calculated the AADP-based characterization factors for the six target metals based on our estimates of in-use stocks (Table S12). It is noted that we considered the waste flows from in-use stock in addition to primary metal extraction in the numerator of the AADP for the sake of consistency with the denominator (the calculation of AADP is described in the Supplementary material). The $AADP_{resources}$ for copper and zinc are almost the same as the $ADP_{resources}$, which means that the effects of considering waste flows and in-use stocks were similar to those for iron. These results differ from those obtained by TADPs, where copper and zinc showed higher values than ADPs when considering future demand changes and recycling. Furthermore, nickel exhibited lower $AADP_{resources}$ than $ADP_{resources}$, mainly due to the relatively large in-use stock compared to a natural stock estimate (i.e., resources). On the other hand, the TADPs assessed the five metals (aluminum, copper, lead, nickel, and zinc) as more significant than iron compared to AADPs because of the consideration of future primary metal extraction changes.

Here, we mention some limitations and future works of this study. Firstly, our approach for projecting future metal demand takes into account future changes in population and GDP but does not account for other factors, including technological development and increasing low-carbon technologies. Furthermore, the number of mineral resources for characterization factors should be expanded for a more comprehensive assessment of mineral resources, which requires more intensive efforts, particularly for MFA studies. This study aimed to introduce the extended characterization model and thus calculated the characterization factors for a limited number of mineral resources for the first attempt. For practical use of the TADP model in LCA studies, the characterization factor should be calculated for various metals and non-metal elements. In particular, the demands for some metals that are closely related to low-carbon technologies are expected to increase significantly (Sovacool et al. 2020; Watari et al.

2021b). The TADP model has the potential to reflect such increases in future metal demands. Thus, the incorporation of future demand projections considering technology-related factors with TADP and expanding the number of characterization factors will be important elements to consider in future studies. In projecting future demands and extending covered mineral resources, it is essential to construct consistent and widely agreed future scenarios over different mineral resources. This is challenging work, while adopting widely used scenarios developed by international organizations, such as SSPs and energy scenarios of the International Energy Agency, can be a feasible way.

Secondly, this study is based on an assumption that per capita in-use metal stock in all countries saturates at the current level of a high-income level group, i.e., convergence of per capita in-use stock level. Regarding global income inequality, previous studies have suggested both convergence and divergence and this issue has been still debatable (Milanovic 2012; Paprotny 2021; Pritchett 1997). On the other hand, regarding metal use, the intensity of use hypothesis, which assumes that the intensity of use (metal use per GDP) initially rises and then falls with the economic growth due to economic transition, substitution, and technological development, was suggested (van Vuuren et al. 1999). A recent study shows that the international inequality in per capita in-use metal stocks has been decreasing over time (Watari and Yokoi 2021), and several studies have projected future metal demands based on the assumption of the convergence of per capita in-use stock level (e.g., Hatayama et al. 2010; Pauliuk et al. 2013; Yokoi et al. 2018). However, the stock saturation assumption has not yet been demonstrated with clear evidence, and it is conceivable that the per capita in-use metal stock level in a high-income level group will increase further because of the introduction of low-carbon and/or other metal-intensive technologies (Wiedenhofer et al. 2021). On the contrary, per capita in-use stock level may possibly decrease, which is implied for specific sectors in a developed country (Yokoi et al. 2022b). Since per capita in-use stock level is one of the influential factors to future metal demand, exploring the discussion for convergence or divergence of in-use stock level, as well as income inequality, is significant future work.

Thirdly, the natural stock estimate can be improved to reflect future risks associated with mine development. Although resources represent the amount that economic extraction is currently or potentially feasible, they do not consider environmental, social, and governance (ESG) risks newly occurring by the development of new and previously uneconomic deposits (Jowitt et al. 2020). Recent studies have addressed ESG risks that may limit future metal supply (Lèbre et al. 2019, 2020; Northey et al. 2017; Valenta et al. 2019; Watari et al. 2020). With natural stock estimates considering future ESG risks, this characterization model could be reinforced by considering a more realistic availability of mineral resources.

Finally, the TADP model has the advantage of being able to consider a variety of future scenarios. While this study adopted the five SSPs as future scenarios, additional future scenarios for relevant factors, including technological development, low-carbon technology deployment, energy transition, promoting recycling, and lifestyle changes, could also be considered. Furthermore, in conjunction with integrated assessment models, including material flow modeling, TADP can assess the potential impacts of mineral resource use in line with knowledge from different domains.

5 Conclusions

This study proposed the TADPs as an extended characterization model for the potential impacts of mineral resource use to account for future situations of primary metal extraction from different time perspectives. The developed TADP model sheds light on the significance of the consideration of future situations in the assessment of the potential impacts of mineral resource use and will give LCA practitioners additional insights regarding possible future risks in their LCIA studies in the context of sustainable metal management. In order to operationalize the TADPs in the LCA study, extending the number of covered mineral resources is essential. To do so, projecting future demands of various mineral resources under consistent and widely agreed future scenarios over different mineral resources, as well as considering the effects of increasing low-carbon technologies on future demands, is a significant future work.

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Data availability The datasets generated during and/or analyzed during the current study are available in the supplementary excel file and from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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