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Worth of metal gleaning in mining and recycling for mineral conservation

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ABSTRACT

Mitigating mineral extraction is considered to be an important challenge in prolonging resource supplies and protecting the environment at mining sites. This challenge can be faced by retaining metal resources within the anthroposphere with adequate technologies and policies for reducing losses to the environment. In mining and mineral processing, considerable amounts of metals are lost as tailings. In recycling, metal recovery from end-of-life products is limited by economic and technological restrictions. In this study, we evaluate the potential for mitigating mineral extraction by reducing the loss rates in mining and recycling. In this study, global substance flow analysis is conducted for seven metals and the importance of recycling is determined for each metal. Furthermore, the change in potential recycling in the future is discussed in combination with dynamic substance flow analysis. We found that reducing the loss rate in recycling could not fully realize mineral conservation in the year 2000, except in the case of lead. However, we also showed that it will become important as the metal discard increases in the future. The framework of this study supports the sustainable use of metals by introducing the right technologies and policies at the right time.

1. Introduction

Global industrialization and population growth have been consuming much amount of natural resources. To investigate the possibility of human activities continuing in the future, the rates of allowable consumption of a variety of environmental resources, such as forest, land, water, and fossil fuels, have been derived from the environmental capacity. Furthermore, metal minerals are considered as restricted resources because they do not renew in meaningful human timeframes. Although metal elements have high crustal abundances, they can only be economically mined in limited amounts. Therefore, the available amount of a metal mineral is taken as the size of reserves of that metal given in geological documents (Canadian Institute of Mining, 2014; USGS, 2013). Furthermore, a simple index referred to as the static depletion time, calculated as the ratio of reserves to annual mine production, has been used to simply represent the degree of stress of depletion (Goeller and Zucker, 1984). Clearly, the static depletion time is not the time taken to use up all reserves because the threat of mineral depletion will be affected by future changes in the amount of reserves and annual mine production, the metal price, and other economic factors (Yaksic and Tilton, 2009). Nevertheless, the indicator suggests the time buffer within which new solutions need to be developed and is therefore suitable in comparing the stress of depletion between different metals (Wellmer, 2008).

In contrast to other nonrenewable resources like oil and coal, metals can be recycled after the end of their product life. Ideally, metals once mined from the lithosphere can be permanently used within the anthroposphere. However, it is difficult to perfectly separate and recover individual metals embedded in end-of-life (EoL) products because metals are used in products with complex physical and chemical combinations and because of technological and economic limitations. Moreover, metal-containing products are not fully recovered from the residences of consumers. As a result, the end-of-life recycling ratio (EoL-RR) is considered to be low for many metals (UNEP, 2011). Finally, metals not recovered in the waste management process are counted as dissipative losses. Examples of dissipation are sending solid waste to a municipal landfill and incorporating other metals in the smelting process.

Within the life of a metal from mining to dissipation, there is also much loss to the environment in the phase of mining and mineral processing. Through the production of concentrated ores, gangue and tailings are generated and left at the site. Metals contained in these residues will not enter the refining process. Therefore, the amount of metal entering the refining process is to some extent

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decreased compared to the amount extracted from reserves. Improving the yield rate in this phase (which we refer to as the "mining yield rate" here, although it represents the yield rate through mining and mineral processing) is an important issue for not only mineral conservation, but also the prevention of destruction of the land and ecosystem.

Under the limitations of technology and profitability, much effort has been made to increase the EoL-RR and the mining yield rate as far as possible. Still, the recent increase in the need for mineral conservation calls for the improvement of these rates. That is to say, it is necessary to *glean* the metals that have not been *harvested* so far. Technological development in mining, beneficiation, and subsequent extraction/refining processes will increase the gleaning of metals in mining. Meanwhile, development of recycling technology, policies, and systems will increase metal gleaning in recycling.

It is important to note that the potential of loss reclamation must be understood before enhancing these gleaning activities. Clarifying the loss in mining may be comparatively easy by conducting a survey at the mining site. In contrast, how much further recycling is possible is difficult to grasp because the amount of metals embedded in EoL products needs to be clarified. Nevertheless, past studies employing substance flow analysis (SFA) have tackled the estimation of the amount of metal discarded by focusing on the mass balance within the anthropogenic metal cycle (Chen and Graedel, 2012; Graedel et al., 2004). In particular, dynamic SFA is applicable to time-series analysis and provides how much scrap will be available for recycling now and in the future (Hatayama et al., 2007, 2010; Müller et al., 2014).

If there is large room for recovering metal losses, then gleaning is effective for mineral conservation. However, if there is little room for reclamation, the blind action of gleaning should be shelved. In constructing a strategy for mineral conservation, it is important to determine which metals are worth gleaning in mining or recycling. In this study, we clarify the potential of metal gleaning in the year ca. 2000 for seven major metals: iron, aluminum, copper, zinc, lead, nickel, and silver. The potential of metal gleaning is indicated for mining and EoL recycling according to an analysis of global substance flow. The effectiveness of gleaning is then represented as the expected extension of the static depletion time. Finally, the dynamic change in the gleaning potential of iron is illustrated in combination with the dynamic SFA.

2. Methodology

2.1. Measuring the potential of gleaning in SFA

In evaluating the gleaning potential, the generating losses in the mining and recycling stages must be understood. In the past SFA framework, the anthropogenic metal cycle was generally divided into four life-cycle stages: "production," "fabrication & manufacturing," "use," and "waste management & recycling" (Chen and Graedel, 2012). SFA clarifies the amounts of metal flows between these processes using statistical data, original survey data, and mathematical formulae that satisfy the mass balance for each process.

In this study, we adhered to the traditional framework and organized the SFA according to the schematic diagram shown in Fig. 1. Here we integrated the processes of metal production and product manufacturing as "production & manufacturing." In this procedure, the flow of new scrap, generated in the fabrication and manufacturing process, was included in the integrated process because it usually returns to the production process. In Fig. 1, the destination of the metal loss is expressed as "Expended stock" (Kapur and Graedel, 2006).

According to the scheme of Fig. 1, we organized data for flows of iron, aluminum, copper, zinc, lead, nickel, and silver. For these seven metals, there have been many global SFA studies as listed in Chen and Graedel (2012). However, of course, the calculation methods, data sources and year of the analysis were diverse among those studies. For the purpose of a comparative analysis of the gleaning potential among metals, it was preferable to use data obtained with a consistent approach. With high regard for consistency, therefore, we used data provided by Rauch et al. (2009) despite the oldness of the data. Another benefit of the data by Rauch et al. (2009) was that the study estimated the amount of landfill and old scrap recovery for each metal, which are often lacking in other SFA studies. As a result, the worldwide amount of each flow in the year ca. 2000 was calculated as listed in Table 1. The table also gives the amount of reserves of each metal in 2000 obtained from the US Geological Survey (2002). The reserve of bauxite reported by the US Geological Survey was converted to that of aluminum by multiplying with a conversion factor of 0.23, which was determined by assuming 43.4% Al_2O_3 content in bauxite ore. (IAI, 2004).

2.2. Exploring the effectiveness of gleaning

From Fig. 1 and Table 1, the depletion time (DT), EoL-RR (r), and mining yield rate (y) are calculated as:

$$\mathrm{DT} = R/P, \tag{1}$$

$$r = 1 - L/D, \tag{2}$$

$$y = 1 - W_P/P. \tag{3}$$

The recovery of old scrap is then obtained as:

$$\text{Old scrap recovery} = rD. \tag{4}$$

The mass balance for the production & manufacturing process is given by:

$$P + rD = I + W_P, \tag{5}$$

and it thus follows from Eq. (3) that:

$$P = (I - rD)/y. \tag{6}$$

Therefore, Eq. (1) is finally expressed as:

$$\mathrm{DT} = yR/(I - rD). \tag{7}$$

The equation indicates the expected extension of DT when y and r are increased by gleaning activities.

From Eqs. (2) and (3) and Table 1, the mining yield rate and EoL-RR in ca. 2000 were estimated (as shown in Table 2). In this study, we evaluated the effectiveness of gleaning in mining and recycling as the increase in DT with increases in y and r from the current levels. In this methodology, DT has a linear relationship with y. Meanwhile, the effectiveness of the increase in r (i.e., gleaning in recycling) depends on the availability of old scrap. Through gleaning in recycling, P can be greatly reduced when a there is a sufficient amount of metals in EoL products. Conversely, even the absolute gleaning of metals in EoL products cannot contribute to a notable reduction in P when D is far smaller than I.

2.3. Tracking dynamic changes in the effectiveness of gleaning

Metal demand has rapidly increased in developing countries from the twenty-first century onwards. Dynamic SFA studies have estimated that metals consumed in the 2000s and 2010s will be available as old scrap in the future, thereby greatly reducing the amount of primary metal (Pauliuk et al., 2013). This means that gleaning in recycling will become more effective in the future.