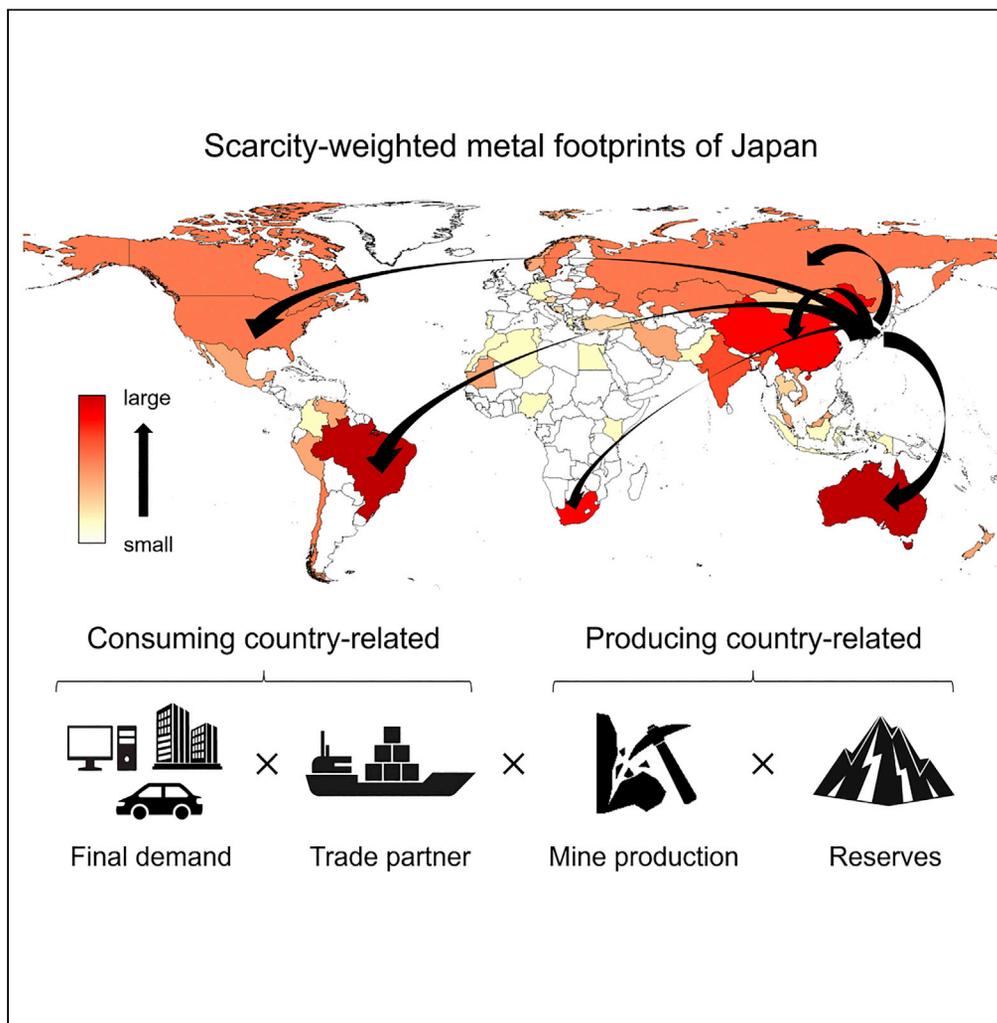


Article

Responsibility of consumers for mining capacity: decomposition analysis of scarcity-weighted metal footprints in the case of Japan



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HIGHLIGHTS

Scarcity-weighted metal footprints (S-MFs) of Japan are analyzed for Fe, Cu, and Ni

S-MFs demonstrate the consuming country-specific responsibility for mining capacity

Decomposition analysis can identify key factors for the consumer's responsibility

The analysis provides the insights on metal supply risks and their alleviation

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Article

Responsibility of consumers for mining capacity: decomposition analysis of scarcity-weighted metal footprints in the case of Japan

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SUMMARY

Metal-consuming countries depend on mining activity in other countries, which may impose potential pressure on sustainable metal supply. This study proposes an approach to analyze the responsibility of consuming countries for mining activities based on the decomposition analysis of scarcity-weighted metal footprints (S-MFs) of Japan. The application results to the Japanese final demand (iron, copper, and nickel) demonstrate the significance of country- and metal-specific conditions in terms of metal footprints and mining capacity in assessing the responsibility of consuming countries. Consuming countries can identify influential factors to reduce their S-MFs based on the decomposition analysis by discriminating the directly controllable and uncontrollable factors for consuming countries, which can help to plan different countermeasures depending on the types of the identified influential factors. The proposed approach supports metal-consuming countries to determine the effective options for reducing the responsibility for the sustainability of metal supply.

INTRODUCTION

Metals play an essential role in modern human life, and the demand for metals is predicted to increase due to global population and economic growth and the increased adoption of low-carbon technology (Christmann, 2018; Elshkaki et al., 2018; Lee et al., 2020; UNEP, 2013; Watari et al., 2021). Even if metals are not likely to be exhausted on a global scale for the time being (Jowitt et al., 2020), mining capacity is stressed and mining activity may cease on a local scale, which leads to loss of diversity of supply source or need to expand deposits. Supply source diversity is a critical factor for resilient material supply chains, which is addressed in the criticality assessment of metals (Alonso et al., 2007; Graedel and Reck, 2016; Schrijvers et al., 2020; Sprecher et al., 2015). The concept of criticality is generally used to evaluate the probability of supply disruptions (i.e., supply risk) and the vulnerability to supply disruptions for a given material (Achzet and Helbig, 2013; Dewulf et al., 2016; Helbig et al., 2016). As concern for metal criticality has been growing, it is important to use metals so as not to lead to higher criticality in the future. Furthermore, the increasing metal demand may threaten mining capacity on the local scale, which may require access to new or previously uneconomic deposits. The conversion of resources (including uneconomic amounts of metals) to reserves over time in response to the increase in mine production has been observed (Jowitt et al., 2020; Mudd and Jowitt, 2018). However, previous studies have suggested that the development of new and undeveloped deposits may cause environment, social, and governance (ESG) risks in the local sustainability context, thereby resulting in higher supply risks (Jowitt et al., 2020; Lèbre et al., 2019; Northey et al., 2018; Valenta et al., 2019). Given these facts, metal mining in countries with lower mining capacity is concerned about leading to higher supply risks. Therefore, in addition to the assessment of metal availability on a global scale for the long-term, the consideration of mining capacity on the local scale from a short-term perspective is also crucial for the sustainable use of metals.

As mineral deposits are unevenly distributed worldwide, many countries need to rely on mining in other countries through international trade (Galli et al., 2012). Thus, consuming countries (especially high-consumption developed countries) may induce various mining-related issues in producing countries associated with mining activity, such as pressure on mining capacity, which increases the potential risks to local sustainability in mining. Accordingly, consuming countries should recognize the responsibility for mining

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activity in producing countries and reduce the burdens imposed on producing countries. Such displacement of burdens through international trade is a topic of increasing research interest and is often referred to as “consumption-based accounting” or “footprinting” (Hoekstra and Wiedmann, 2014; Wiedmann and Lenzen, 2018).

Several studies have analyzed the dependency of consuming countries on international trade through consumption-based accounting of materials (material footprint), metal-related risks, and their drivers (e.g., Bruckner et al., 2012; Liu et al., 2020; Nansai et al., 2015; 2017; Wiedmann et al., 2015). Among them, Vivanco et al. (2017) and Wang et al. (2020) shed light on the local conditions of mining capacities in addition to induced mining by consumers for metal and fossil fuel, respectively. Regarding metals, Vivanco et al. (2017) introduced an indicator of metal scarcity expressed by the ratio of mine production to availability and incorporated it with metal footprints (scarcity-weighted metal footprint [S-MF]). The S-MF demonstrates how consuming countries induce pressure on mining capacities of producing countries and consequently, the potential risks to local sustainability in mining. Although S-MF can provide insight into the responsibility of consuming countries for pressure on mining capacity, Vivanco et al. (2017) simply summed up the S-MFs for all metals considered. The regional distribution of metal scarcity differs significantly between metals (Yokoi et al., 2020). Therefore, a simple summation of the scarcity-weighted metal amounts may not be indicative of metal-specific conditions of pressure on metal scarcity in mining capacity. Furthermore, the S-MFs induced by consuming countries are determined based on a combination of factors (e.g., consumer demand for metals, trade partners, and metal scarcity conditions in producing countries; see [Transparent methods](#)), making it challenging to plan actions to reduce potential risks represented by the S-MF. Quantitative analysis of the effects of these factors on S-MFs would assist consuming countries in identifying key influencing factors and in implementing initiatives to reduce pressure on producing countries by strategically managing metal use toward lower criticality of metals. However, such an analysis has not been conducted in previous studies.

Here, we focus on Japan as a consuming country. Japan is ranked as the third-largest economy (based on gross domestic product) following the United States of America and China. Japanese economy requires large quantities of various metals, and it relies significantly on the import of metals and metal-based products due to the scarce availability of metals inside the country. Therefore, Japan is among the main countries responsible for induced mining activity in producing countries. Thus, Japan is a suitable subject for a case study analyzing the responsibility for the pressure on mining capacity of producing countries that demonstrates the importance and potential implications of actions by consuming countries toward sustainable metal use.

In this study, we focus on metal scarcity in mining capacity as an influencing factor of metal criticality. This study aims to evaluate the responsibility for pressure on mining capacity of producing countries associated with the final demand of Japan and to identify key factors for consuming countries to reduce their responsibility. We quantify metal mining in producing countries induced by Japanese final demand throughout global supply chains as “induced mine production” (IND) (Nakajima et al., 2019). Then, we assess the S-MFs of Japan for representative metals for different years (2005 and 2011) and adopt a decomposition analysis (Ang, 2005, 2015) to identify factors influencing temporal changes in the responsibility of Japan for sustainability risks in producing countries and opportunities to reduce these risks. For this analysis, we select iron (Fe), copper (Cu), and nickel (Ni) as target metals. These metals are used in large quantities for various applications and are thus vital to the economy (USGS 2020), which means the impacts for the economy are high if their supplies are restricted.

RESULTS

Inconsistency between induced mine production and scarcity-weighted mine production

IND by consuming countries has different implications depending on the metal scarcity conditions in producing countries. The global distributions of the IND and scarcity-weighted induced mine production (S-IND) of Japan for 2011 are shown in [Figure 1](#) (the detailed results at a country level are available in [Figures S1](#) and [S2](#)). The countries and regions on which Japan depends for metal supply differ by metals. Japan largely depends on Oceania (e.g., Australia) and Latin America (e.g., Brazil) for Fe (thus, these regions are the largest contributors to the IND of Japan), whereas Fe sourced from Africa (e.g., South Africa) and Asia (e.g., China) has a greater impact on the S-IND of Japan. The same inconsistency between IND and S-IND is observed for both Cu and Ni. Regarding Cu, the significance of North America is lower than that of Latin

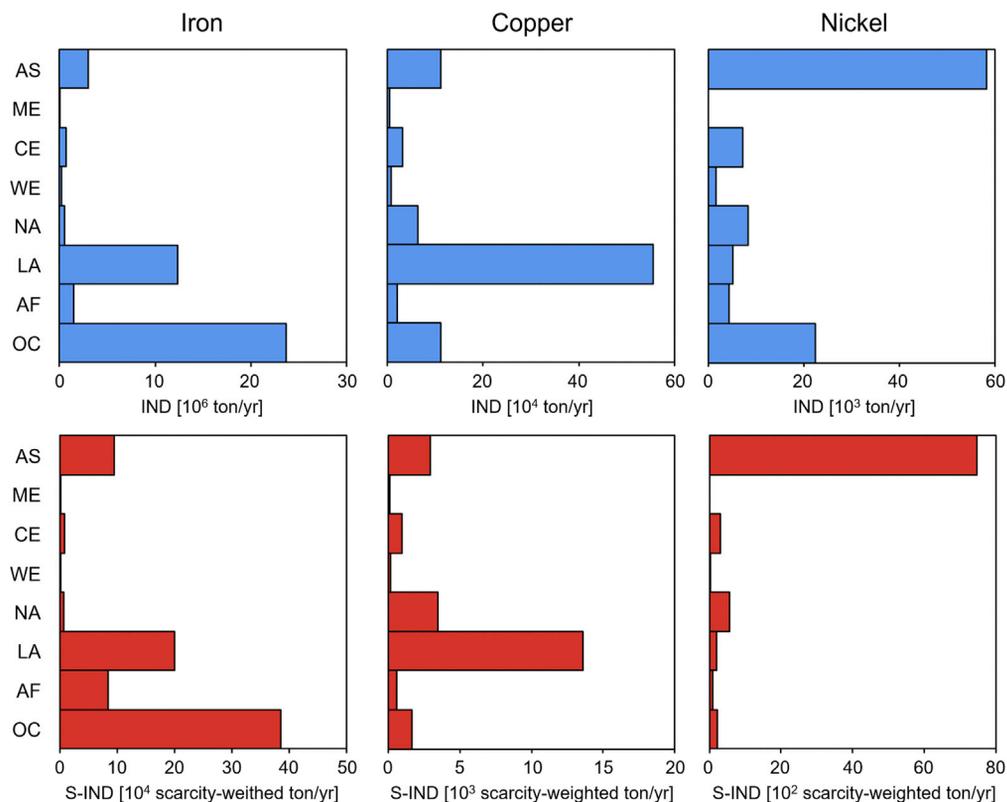


Figure 1. Induced mine production (IND) and scarcity-weighted induced mine production (S-IND) of Japan for Fe, Cu, and Ni in 2011

The upper figures show the amount of mine production induced by Japanese final demand (IND: induced mine production); the lower figures show the induced mine production weighted by country-specific scarcity (S-IND: scarcity-weighted induced mine production). The results of each producing country are aggregated into eight regions. AS: Asia; ME: Middle East; CE: Central Eastern Europe and Russia; WE: Western Europe; NA: North America; LA: Latin America; AF: Africa; OC: Oceania.

America, Oceania, and Asia in terms of IND, whereas North America is relatively more significant than Oceania and Asia in terms of S-IND. The case of Ni is more extreme. The significance of Asia (e.g., Indonesia) for Ni is much greater in terms of S-IND compared with the results for IND. As S-IND is the product of the IND and country-specific scarcity (CS) of a producing country, countries with large INDs and/or high CSs usually show large S-IND values. Figure 2 shows the relationship between IND (horizontal axis) and CS (vertical axis) in each producing country and represents S-IND via the size of a bubble. The countries with large INDs show high significance in S-IND, as do some countries with small INDs but high CS, highlighting the impact of CS on S-IND values. In the case of Fe, Japan induces a large amount of mine production in Australia and Brazil, which results in a large S-IND in both countries. In contrast, the IND of Fe in South Africa and China is relatively minimal; however, the S-IND in South Africa and China cannot be disregarded. If Japan continues to procure Fe from these countries with a relatively high CS, low mining capacity in these countries will increase the ESG risks associated with the development of new and undeveloped deposits. Therefore, the S-IND analysis of Japan at the producing country level can add another relevant aspect of metal supply risk with the analysis of IND. In addition to the direct comparison of the S-IND between different countries, the significance of the S-IND of Japan in a producing country needs to be discussed by comparing it with the total S-IND in a producing country, which is demonstrated in the next section.

Relative significance of Japanese responsibility for pressure on mining capacity

Consuming countries induce different amounts of mine production in the countries from which they source metals. Therefore, the dependency on producing countries in terms of the S-IND is specific to consuming countries, which can be demonstrated by the share of the S-IND in a producing country to the total S-IND of

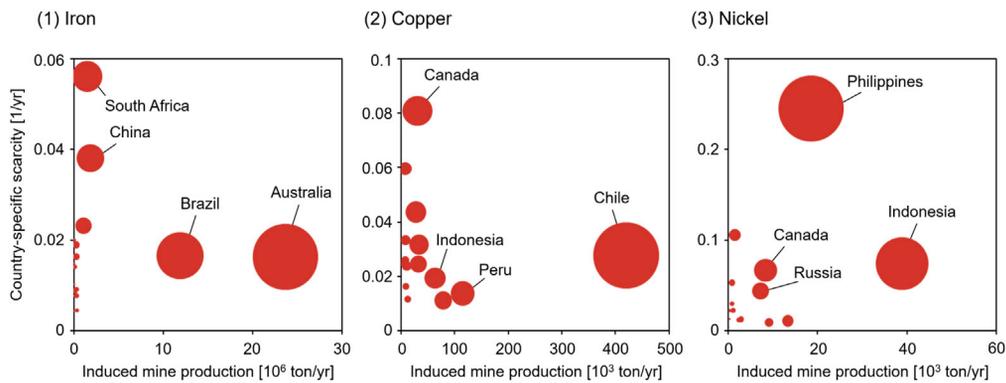


Figure 2. Bubble charts of induced mine production (IND) versus country-specific scarcity (CS) in 2011

The size of the circles represents the scarcity-weighted induced mine production (S-IND) of Japan for each producing country.

a consuming country (i.e., S-MF) as the responsibility of a consuming country for a producing country. By comparing the shares of Japan and the world total (all consuming countries), we demonstrate for what countries Japan has relatively higher responsibility compared with other consuming countries. Figure 3 shows the relative significance of Japanese responsibility for the S-IND in producing countries compared with the world total. The relative significance of Japanese responsibility for the S-IND is the highest in Australia, followed by Brazil and South Africa for Fe; Papua New Guinea, Philippines, and Indonesia for Cu; and Indonesia, Zimbabwe, and New Caledonia for Ni. On the other hand, the metal scarcity of these producing countries is different among metals (Figures S3 and S4). Regarding Fe and Cu, the metal scarcity of these countries is fairly low except for South Africa for Fe. On the contrary, scarcity for Ni is relatively high in Indonesia and Philippines compared with that in other producing countries, whereas Japan depends on the Ni extraction in these countries.

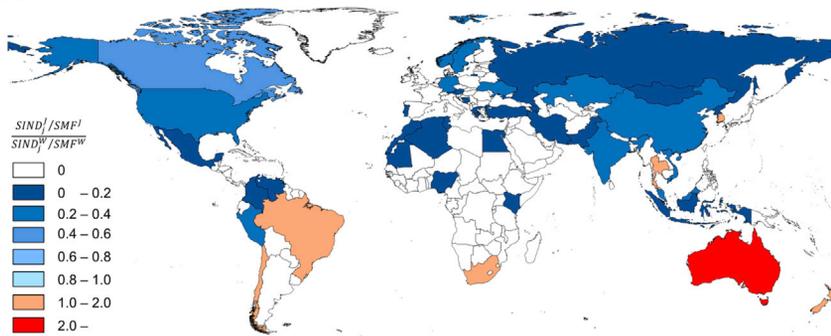
The dependency on producing countries and their conditions of metal scarcity affect the relative significance of Japanese responsibility for the S-MF as a total. In the case of Fe and Cu in 2011 (Tables S1 and S2), the Japanese share of the total world S-MF (Fe: 2.91%, Cu: 5.10%) is smaller than that of the IND (Fe: 3.38%, Cu: 5.60%), indicating that Japan induces mine production in producing countries with relatively low scarcity compared with the world average of consuming countries. On the contrary, in the case of Ni (Table S3), the Japanese share of the total world S-MF (6.58%) is larger than that of the IND (5.55%). This is because Japan procures Ni from countries with relatively high scarcity than does the average consuming country. Therefore, the choice of trade partners for metal and metal-containing products supply, which is associated with the composition of producing countries, is an important factor for the S-MF of consuming countries, along with the amount of induced mine production and the scarcity conditions in producing countries.

Influential factors on the scarcity-weighted metal footprints

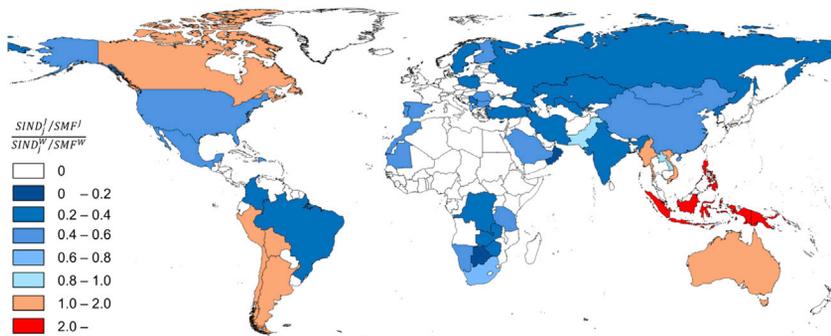
The S-MFs of consuming countries are determined based on various factors (induced mine production, choice of trade partners, and scarcity conditions in producing countries) that can temporally vary. Decomposition analysis is effective in identifying factors that influence temporal change in the S-MFs, which can support planning actions to reduce induced pressure on producing countries in terms of strategic management of metals. Figure 4 shows the results of the decomposition analysis of S-MFs changes in Japan between 2005 and 2011 for Fe, Cu, and Ni (results of S-MFs in 2005 are shown in Tables S4, S5, and S6). D_{tot} values (black bar chart) represent changes in the S-MFs for 2005 and 2011. The values of other factors indicate their contribution to S-MF changes.

The S-MFs (D_{tot}) for Fe and Ni increase in 2011, whereas that for Cu decreases. Regarding the factors that consuming countries can control (D_{IT} and D_{IS}), the decrease in the IND associated with the final demand of Japan in 2011 contributes to the lower S-MFs for all target metals (induced mine production effect: D_{IT}), whereas trade partner choice effect (D_{IS}) decreases the S-MFs for Fe but increases those for Cu and Ni. The reduction of induced mine production directly leads to decreased S-MF values, whereas the

(1) Iron



(2) Copper



(3) Nickel

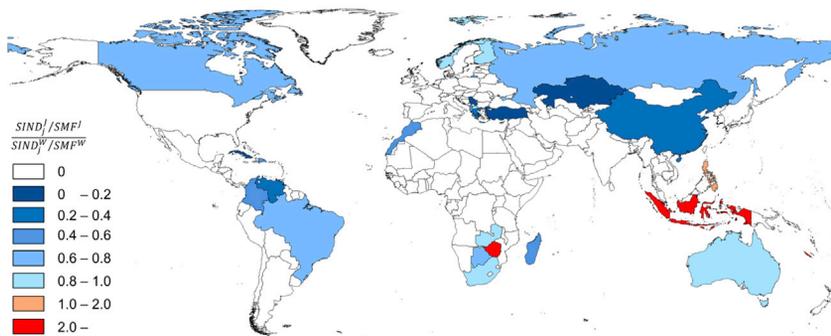


Figure 3. The relative significance of scarcity-weighted induced mine production (S-IND) in each producing country to the scarcity-weighted metal footprint (S-MF) of Japan compared with that of the world total for 2011
If a producing country shows a value larger than 1.0, the relative significance of S-IND in the producing country to the S-MF of Japan is higher than that of the world total. That is, Japan has a higher responsibility for the S-IND in the country compared with the world average.

composition of producing countries affects S-MFs more intricately depending on scarcity conditions in producing countries. The decomposition analysis results regarding the trade partner choice effects (D_{IS}) demonstrate whether the choice of trade partner in 2011 is better than that in 2005. However, S-MFs could potentially be reduced further through different choices. To explore the potential for reducing S-MFs by changing the composition of producing countries, the virtual S-MFs (S-MF') are additionally calculated based on the assumption that Japan induces mine production of these metals in producing countries corresponding to the share of the world average (Table 1). If Japan followed the world average composition of producing countries, the S-MF for all target metals could have been reduced by changing the choice of producing countries in 2005 (Table 1). On the other hand, whereas the Japanese S-MFs for Ni in 2011 could be potentially reduced by following the world average composition of producing countries, those for Fe and Cu in 2011 would increase by shifting the composition of producing countries from Japanese case to the world average case. This indicates that the Japanese composition of producing countries for Fe

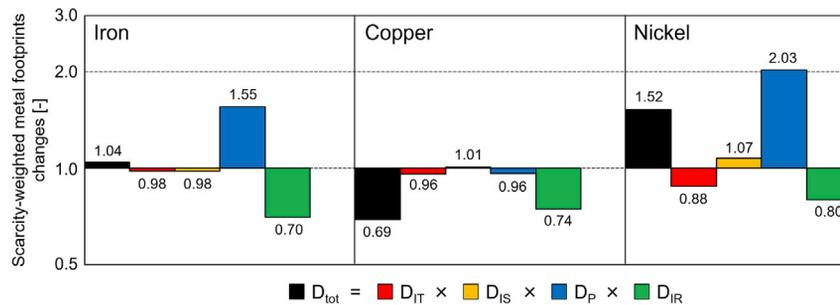


Figure 4. Decomposition analysis of changes in the scarcity-weighted metal footprints of Japan between 2005 and 2011

The vertical axis is displayed in logarithmic scale with base 2. D_{tot} values (black bar) are the ratios of the scarcity-weighted metal footprints (S-MFs) of Japan in 2005 and 2011. Values for other factors (D_{IT} , D_{IS} , D_P , and D_{IR}) represent their contributions to S-MF changes. The product of these values is equal to the ratio of the S-MFs in 2005 and 2011 (D_{tot}). D_{tot} : changes in the scarcity-weighted metal footprints of Japan; D_{IT} : induced mine production effect; D_{IS} : trade partner choice effect; D_P : mine production effect; D_{IR} : reserves effect.

and Cu in 2011 is better than the world average. On the other hand, the decomposition analysis results (Figure 4) show that the trade partner choice effect (D_{IS}) contributes to the changes in the S-MFs in both directions: reduction for Fe and increase for Cu. Thus, the Japanese composition of producing countries for Cu improves S-MF values in 2011 (relative to the world average; Table 1), whereas the Japanese choice of trade partners for Cu has a further reduction potential of the S-MFs in 2011 compared with 2005.

Factors associated with producing countries (D_P and D_{IR}) contribute more significantly to S-MF changes than do consuming country-related factors in all cases for the target metals (Figure 4). For both Fe and Ni, the mine production effect (D_P) significantly contributes to increases in S-MF values, although the reserves effect (D_{IR}) decreases S-MFs. For Cu, D_P leads to a slight decrease in S-MFs, whereas D_{IR} contributes to S-MF decreases more significantly. Both D_P and D_{IR} are beyond the direct control of consuming countries, whereas it is important for consuming countries to closely observe the situations in producing countries to reduce their responsibility for potential risks associated with mining activity.

DISCUSSION

In this study, we adopt S-MFs as an indicator representing responsibility of consuming countries for pressure on mining capacity. We demonstrate the inconsistency between mine production and scarcity-weighted mine production of Fe, Cu, and Ni induced in producing countries by Japanese final demand. This implies the integration of the scarcity in mining capacity into metal footprints as the S-MF enables to quantify the potential pressure on mining capacity of metals that cannot be represented by metal footprint indicators (non-weighted by scarcity) adopted in previous studies (e.g., Bruckner et al., 2012; Wiedmann et al., 2015). The scarcity in mining capacity is dependent on conditions in producing countries, and the composition of producing countries is specific to consuming countries. Thus, the responsibility for pressure on mining capacity differs between consuming countries corresponding to the dependency of metal mining on producing countries, as demonstrated by the analysis of the relative significance of the consuming country's responsibility. In addition to the importance of country-specific conditions, the analysis of the S-MFs in this study sheds light on the relevance of metal-specific conditions to the pressure on mining capacity by demonstrating the differences of consuming country's responsibility for pressure on mining capacity among metals. The country-specific scarcity varies more largely for some metals not considered in this study (e.g., Al, Sb, REE, Sn, and W) than for the target metals (Fe, Cu, and Ni) (Yokoi et al., 2020); therefore, metal-specific conditions may be more important for other metals. However, the results of this study indicate the relevance of country- and metal-specific scarcity-weighted footprint analysis in assessing a consuming country's responsibility for pressure on mining capacity of producing countries, an angle not fully investigated in previous studies.

The S-MFs of consuming countries are determined based on multiple factors (e.g., the consumer demand for metals, trade partners, and the conditions of metal scarcity in producing countries). We decompose the S-MFs into four factors and classify these factors as consuming country related or producing country

Table 1. Comparison of the actual scarcity-weighted metal footprint (S-MF) and virtual S-MF (S-MF') of Japan

		Iron	Copper	Nickel
2005	S-MF (scarcity-weighted ton/year)	7.50×10^5	3.40×10^4	5.85×10^3
	S-MF' (scarcity-weighted ton/year)	6.47×10^5	3.28×10^4	5.58×10^3
	S-MF'/S-MF	0.86	0.96	0.95
2011	S-MF (scarcity-weighted ton/year)	7.81×10^5	2.35×10^4	8.90×10^3
	S-MF' (scarcity-weighted ton/year)	9.19×10^5	2.61×10^4	7.35×10^3
	S-MF'/S-MF	1.18	1.11	0.83

The S-MF' is indicative of the S-MF in a case where the share of producing countries of Japan is the same as the world average.

related. The decomposition analysis quantifies the contributions of each factor to S-MF changes for each metal, and the results can support to consider effective options for reducing the responsibility of consuming countries depending on metals. Regarding consuming country-related factors (the induced mine production and the trade partner choice), consuming countries can potentially take direct actions to lower the risks associated with induced mine production via the improvement of resource efficiency and recycling rates, the development of substitute materials, and longer lifetime of final products (Graedel, 2017). When there is more potential to reduce the S-MFs by changing trade partners, understanding the mining capacity conditions in producing countries will support decision-making. For example, a previous analysis of country-specific scarcity of producing countries suggested the potential for substitution of mine production for several metals in some countries with relatively large capacity in reserves at lower pressure from mine production (Yokoi et al., 2020). On the other hand, producing country-related factors (mine production and reserves in producing countries) cannot be directly controlled by consuming countries. In the case of Japan analyzed in this study, producing country-related factors demonstrate a larger contribution to S-MF changes than do the consuming country-related factors for three target metals. However, whereas consuming countries have little power to change producing country-related factors unilaterally, mine production in a producing country is the sum of the mine production induced by consuming countries. Thus, consuming countries can affect mine production in producing countries by recognizing their responsibility of induced mine production for pressure on mining capacity of a producing country. Regarding the reserves effect, consuming countries may contribute to increasing the reserves to alleviate scarcity in mining capacity by supporting mine development. However, as mentioned in previous studies (Jowitt et al., 2020; Valenta et al., 2019), the development of new or previously uneconomic orebodies may cause ESG risks; therefore, it is crucial that development consider local sustainability.

The ESG risks associated with the development of new or previously uneconomic orebodies include the level of political governance in producing countries. The issue of the political governance is recognized as a country risk in criticality assessments, and indicators that represent political risks (e.g., the World Governance Index and the Global Political Risk Index) are adopted to assess the stability of metal supplies (Achzet and Helbig, 2013; Bach et al., 2016; Gemechu et al., 2015). A large S-IND in a producing country (as a part of S-MF) implies an elevated potential for leading to ESG risks associated with the development of new or previously uneconomic orebodies to secure metal supply sources; however, such risks may not occur in all producing countries with large S-INDs. In the case of Japan, Ni-producing countries with large S-INDs demonstrate relatively high political risks, whereas the political risks in Fe- and Cu-producing countries with large S-INDs are relatively low (Figure S5). The stability of metal supply is an important issue in resource securement for governments, industries, and companies; therefore, the S-MFs can contribute to stability assessments by quantifying the potential pressure on the stability of metal supply in terms of the availability of reserves. In these senses, the country risk indicators can complement the S-MFs in terms of the potential ESG risks and provides further insights into the criticality of metals.

Proposed approaches and findings in this study will support consuming countries to realize their responsibility for mining capacity of metals and to manage their supply chains toward sustainable metal use. Nevertheless, there are still multiple tasks that need to be tackled in the future. First, this study focuses on the mine production of three metals (Fe, Cu, and Ni) induced by Japan as a basis for further studies. Analysis of other consuming countries will enable us to understand the performance of each consuming country relative to others, which is expected to contribute to international coordination and resource governance for lower supply risks and

sustainable metal use (Ali et al., 2017). In addition, we simply decompose the consuming country-related factors on S-MFs into induced mine production and trade partner choice effects; however, induced mine production could be further decomposed into other factors, such as resource productivity and the usage rate of recovered materials, which describe the performance of society. A detailed analysis of the factors that control demand for metals in consuming countries requires more intensive data collection; incorporating these indicators into decomposition analysis of S-MFs would reveal the performance of consuming countries in detail and provide information to plan more detailed initiatives for improvement. Furthermore, a higher-resolution analysis at the mining site level of producing countries is crucial, as our analysis suggests that producing country-related factors are highly significant for the three target metals. As mining activity varies by mining site, such detailed analysis will provide more useful support for consumer decision-making to reduce the potential risks for mining in producing countries.

Limitations of the study

This analysis adopts a global link input-output model, which is a hybrid multiregional input-output (IO) model based on Japanese IO tables (Nansai et al., 2009), to estimate induced mine production of Japan. The target years of this analysis are limited to years for which Japanese IO tables are published (2005 and 2011). In addition, data availability and uncertainty are also limitations. Data for mine production and reserves are available from different sources, which are not necessarily completely comparable. Improving data reliability and quantifying data uncertainty are future tasks for data development.

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Ryosuke Yokoi (r.yokoi@aist.go.jp).

Materials availability

This study did not generate new unique reagents.

Data and code availability

The data used in this study are available from the corresponding author.

METHODS

All methods can be found in the accompanying [Transparent methods supplemental file](#).

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at <https://doi.org/10.1016/j.isci.2020.102025>.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.Y., K. Nansai, K. Nakajima, T.W., and M.M.; Methodology, R.Y. and M.M.; Investigation, R.Y., K. Nansai, and K. Nakajima; Formal Analysis, R.Y.; Writing – Original Draft, R.Y.; Writing – Review & Editing, R.Y., K. Nansai, K. Nakajima, T.W., and M.M.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Supplemental Information

**Responsibility of consumers for mining
capacity: decomposition analysis of scarcity-weighted
metal footprints in the case of Japan**

Ryosuke Yokoi, Keisuke Nansai, Kenichi Nakajima, Takuma Watari, and Masaharu Motoshita

Transparent Methods

Metal extraction in each country induced by the Japanese economy

Multiregional input-output (MRIO) models have been adopted to calculate footprint indicators for various environmental problems such as climate change (Hertwich and Peters, 2009), damage to biodiversity (Lenzen et al., 2012), and material extraction (Bruckner et al., 2012; Wiedmann et al., 2015). For the Japanese footprint study, Nansai et al., 2009 developed a global link input-output (GLIO) model, which is a hybrid (mixed unit) MRIO model and specialized for a detailed description of the relationship between the Japanese economy and other countries. Nansai et al., 2015 developed an approach to quantify the metal extraction induced by the Japanese economy by incorporating global metal flows associated with international trade between 231 countries (estimated in Nansai et al., 2014) into the GLIO model. Using this approach, Nakajima et al., 2019 estimated the Fe, Cu, and Ni extraction induced in each country by the Japanese domestic final demand in 2005 and 2011; these estimates were adopted in this study. The GLIO model is based on Japanese input-output (IO) tables, which allows the incorporation of global metal flows with high resolution traded commodity data. The analysis is conducted for 2005 and 2011, as these are the years for which Japanese IO tables were published (which is a limitation of this paper). The metal extraction estimates are expressed not as ore-based weights but as content-based weights. A list and detailed descriptions of the 231 considered countries and regions are available in a previous paper (Nakajima et al., 2019).

Scarcity-weighted metal footprints of Japan

According to van Oers and Guinée, 2016, scarcity describes the state in which “the amount available for use is, or will soon be, insufficient (“demand higher than supply flow”).” However, this term is used in different contexts depending on which stage of the supply chain is being considered. When focusing on ore stocks, scarcity is assessed in association with the long-term availability of geological stocks (e.g., extractable global resources); in this context, scarcity is often referred to as “geologic scarcity” (Harmsen et al., 2013; Henckens et al., 2014). On the other hand, scarcity is assessed in the context of supply risk when focusing on the metal user side (Bustamante et al., 2018; Graedel and Erdmann, 2012). This study primarily investigates potential threats to local sustainability in mining induced by Japanese final demand through international trade. Therefore, we focus on the short-term availability of current supply sources and current mining activities. Accordingly, in this paper, “scarcity” is used to represent the ratio between mine production and short-term availability. Here, we adopt the country-specific scarcity indicator using the following equation (Yokoi et al., 2020).

$$CS_{i,j,t} = \frac{P_{i,j,t}}{R_{i,j,t}} \quad (1)$$

where $CS_{i,j,t}$ refers to the country-specific scarcity of metal i in country j for year t (1/yr), $P_{i,j,t}$ refers to the mine production of metal i in country j for year t (ton/yr), and $R_{i,j,t}$ refers to the reserves of metal i in country j for year t (ton). While Vivanco et al., 2017 used reserve base values (which includes reserves, marginal reserves, and subeconomic resources; USGS, 2020) to calculate scarcity indicators within the scarcity-weighted metal footprints (S-MFs), reserves values are used in this paper because we focus on the short-term availability of metals. Reserves are the amount of resources that can be economically extracted at a given time (USGS, 2020) and are influenced by various factors including metal prices and mining technology. Therefore, reserves can fluctuate over time and are not suitable for assessing long-term availability (Calvo et al., 2017; Drielsma et al., 2016a). Nevertheless, reserves data is “direct evidence of current resource availability” and is thus appropriate for the assessment of short-term availability (Drielsma et al., 2016b). The data on mine production and reserves by country are derived from the U.S. Geological Survey (USGS, 2006, 2012).

The S-MFs of Japan are calculated using the following equation (Vivanco et al. 2017).

$$SMF_{i,t}^J = \sum_j SIND_{i,j,t}^J = \sum_j (IND_{i,j,t} \times CS_{i,j,t}) \quad (2)$$

where $SMF_{i,t}^J$ refers to the scarcity-weighted metal footprint of Japan for metal i for year t (scarcity-weighted ton/yr), $SIND_{i,j,t}^J$ refers to the scarcity-weighted induced mine production (S-IND) of Japan for metal i in country j for year t (scarcity-weighted ton/yr), and $IND_{i,j,t}$ refers to the induced mine production of Japan for metal i in country j for year t (ton/yr), which is estimated by the GLIO model (see the previous section). In addition, worldwide S-MFs ($SMF_{i,t}^W$) are also calculated as reference values for comparison with S-MFs of Japan using the following equation.

$$SMF_{i,t}^W = \sum_j SIND_{i,j,t}^W = \sum_j (P_{i,j,t} \times CS_{i,j,t}) \quad (3)$$

Decomposition analysis

To identify factors driving the changes in the S-MF of Japan for each metal between 2005 and 2011, we adopt the logarithmic mean divisia index (LMDI) decomposition approach, which is one of the index decomposition analysis (IDA) approaches (Ang et al., 1998; Ang, 2005). IDA approach is adopted for analyzing the contribution of factors to changes in quantity or intensity indicators, such as

energy consumption, CO₂ emissions, and energy efficiency (Ang, 2015). LMDI approach is a recommended approach among IDA approaches owing to its theoretical foundation, adaptability, ease of use and result interpretation, and perfect decomposition (Ang, 2004). Although it has been mainly adopted in energy consumption and CO₂ emission analyses (Ang, 1995; Ang and Zhang, 2000), it has increasingly been applied in other areas, including material use (Pothen and Schymura, 2015), land requirements (Kastner et al., 2012), and water footprints (Xu et al., 2015).

In this study, the S-MF of Japan in Eq. (2) is rearranged as follows:

$$\begin{aligned}
 SMF_{i,t}^J &= \sum_j \left(IND_{i,j,t} \times \frac{P_{i,j,t}}{R_{i,j,t}} \right) = \sum_j \left\{ IND_{i,tot,t} \times \frac{IND_{i,j,t}}{IND_{i,tot,t}} \times P_{i,j,t} \times \frac{1}{R_{i,j,t}} \right\} \\
 &= \sum_j (IT_{i,t} \times IS_{i,j,t} \times P_{i,j,t} \times IR_{i,j,t})
 \end{aligned} \tag{4}$$

where $IT_{i,t}$ denotes the total induced mine production by Japan worldwide for metal i and year t (ton/yr), $IS_{i,j,t}$ denotes the share of induced mine production by Japan in country j to the total induced mine production by Japan worldwide for metal i and year t (-), and $IR_{i,j,t}$ denotes the inverse of reserves in country j for metal i and year t (1/ton). $IS_{i,j,t}$ represents the choice of producing countries by Japan. $P_{i,j,t}$ and $IR_{i,j,t}$ are associated with the conditions of local mine production and reserves, which determine the country-specific scarcity. Therefore, the first two parameters ($IT_{i,t}$ and $IS_{i,j,t}$) represent factors that Japan can directly control to reduce the S-MF (referred to as “consuming country-related factors”), while the latter two ($P_{i,j,t}$ and $IR_{i,j,t}$) represent factors that are dependent on conditions in the producing countries that Japan cannot directly control (referred to as “producing country-related factors”).

The LMDI approach is classified into two types of decomposition forms: additive decomposition and multiplicative decomposition (Ang, 2015). In additive decomposition, the arithmetic change of the aggregate indicator is decomposed. In multiplicative decomposition, the ratio change of an aggregate indicator is decomposed. Because the results of these two types of decomposition can be converted to each other, the choice of the decomposition forms depends on the desired presentation and interpretation of the results. In this study, multiplicative decomposition is adopted to analyze the ratio of S-MFs in 2011 to 2005. Based on Eq. (4), changes in the S-MFs of Japan (D_{tot}) are decomposed into four factors: the induced mine production effect (D_{IT}), trade partner choice effect (D_{IS}), mine production effect (D_P), and reserves effect (D_{IR}).

$$D_{tot} = \frac{SMF_{2011}^J}{SMF_{2005}^J} = D_{IT} D_{IS} D_P D_{IR} \tag{5}$$

The contributions of each factor to the change in the S-MF of Japan between 2005 and 2011 are calculated using the following equations (Ang, 2005).

$$D_{IT} = \exp \left(\sum_j \frac{(SIND_{j,2011}^J - SIND_{j,2005}^J) / (\ln SIND_{j,2011}^J - \ln SIND_{j,2005}^J)}{(SMF_{2011}^J - SMF_{2005}^J) / (\ln SMF_{2011}^J - \ln SMF_{2005}^J)} \ln \left(\frac{IT_{2011}}{IT_{2005}} \right) \right) \quad (6)$$

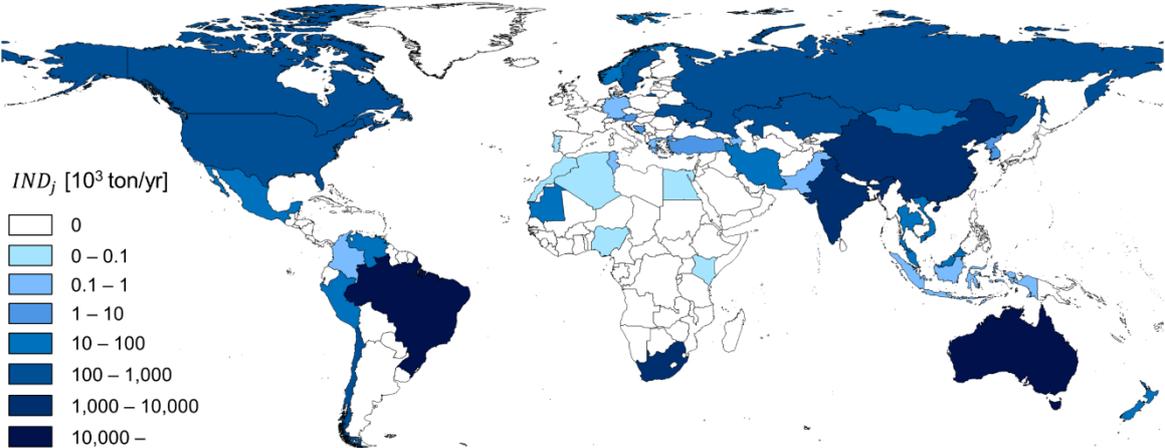
$$D_{IS} = \exp \left(\sum_j \frac{(SIND_{j,2011}^J - SIND_{j,2005}^J) / (\ln SIND_{j,2011}^J - \ln SIND_{j,2005}^J)}{(SMF_{2011}^J - SMF_{2005}^J) / (\ln SMF_{2011}^J - \ln SMF_{2005}^J)} \ln \left(\frac{IS_{j,2011}}{IS_{j,2005}} \right) \right) \quad (7)$$

$$D_P = \exp \left(\sum_j \frac{(SIND_{j,2011}^J - SIND_{j,2005}^J) / (\ln SIND_{j,2011}^J - \ln SIND_{j,2005}^J)}{(SMF_{2011}^J - SMF_{2005}^J) / (\ln SMF_{2011}^J - \ln SMF_{2005}^J)} \ln \left(\frac{P_{j,2011}}{P_{j,2005}} \right) \right) \quad (8)$$

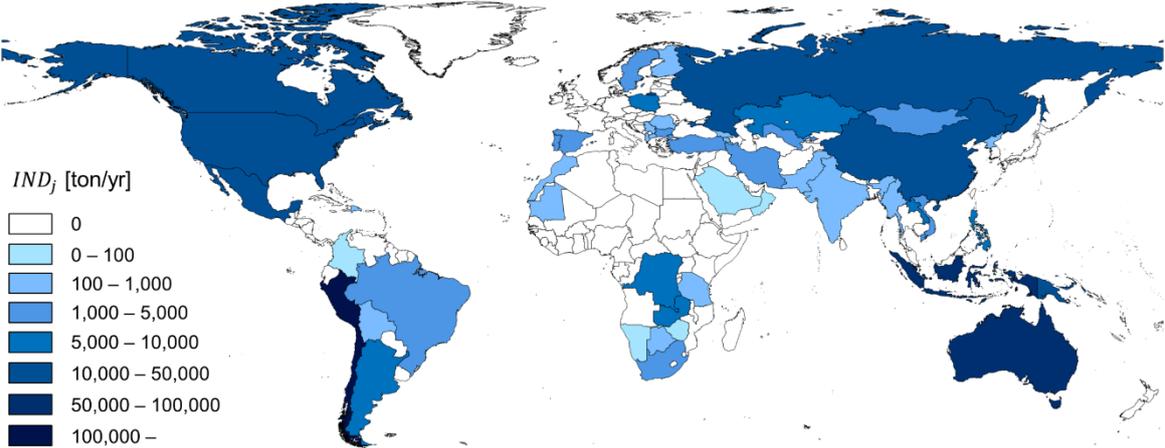
$$D_{IR} = \exp \left(\sum_j \frac{(SIND_{j,2011}^J - SIND_{j,2005}^J) / (\ln SIND_{j,2011}^J - \ln SIND_{j,2005}^J)}{(SMF_{2011}^J - SMF_{2005}^J) / (\ln SMF_{2011}^J - \ln SMF_{2005}^J)} \ln \left(\frac{IR_{j,2011}}{IR_{j,2005}} \right) \right) \quad (9)$$

Additional results

(1) Iron



(2) Copper



(3) Nickel

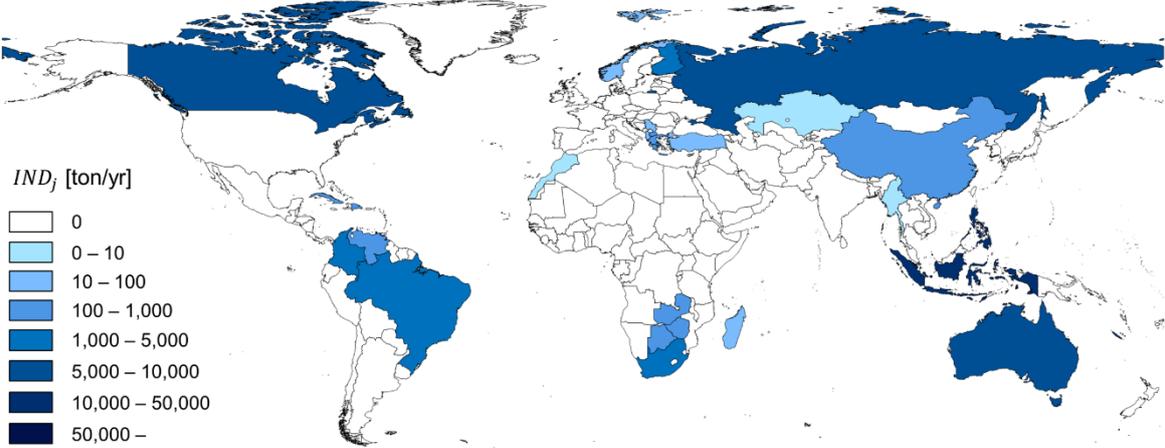
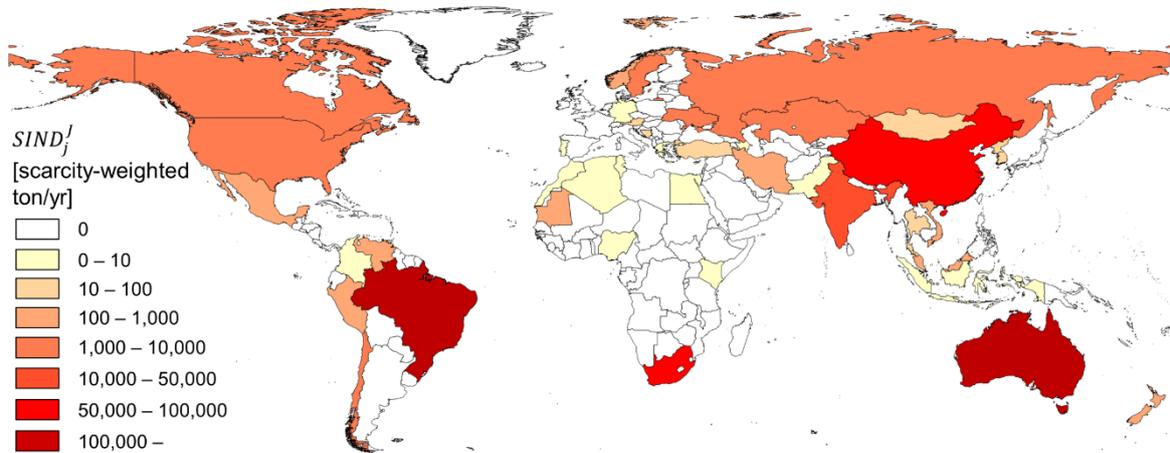
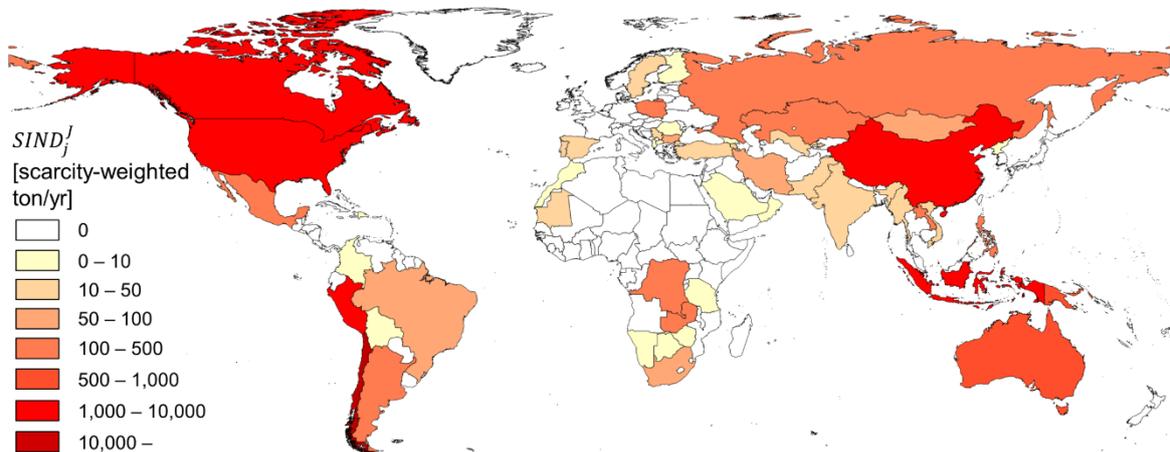


Figure S1. Induced mine production (IND) of Japan for Fe, Cu, and Ni in 2011, Related to Figure 1.

(1) Iron



(2) Copper



(3) Nickel

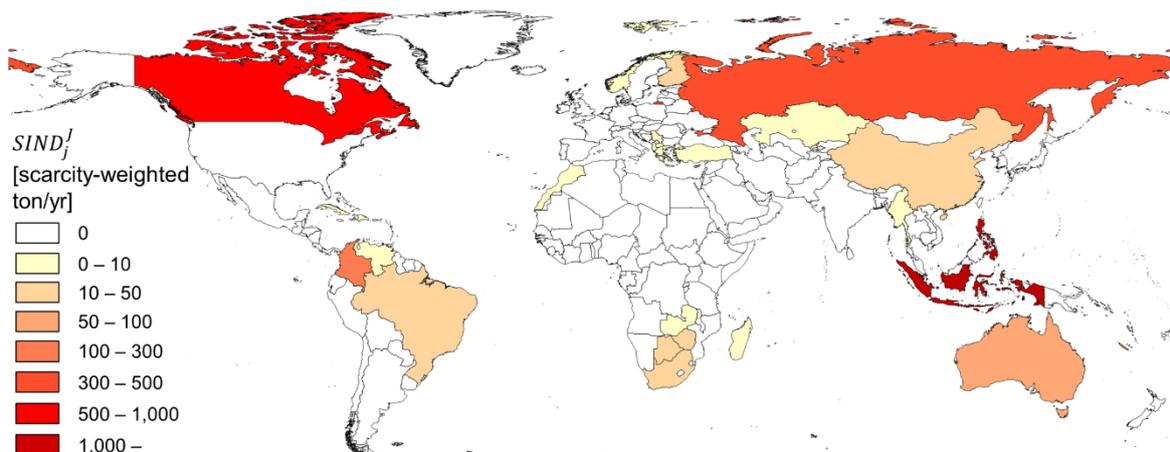
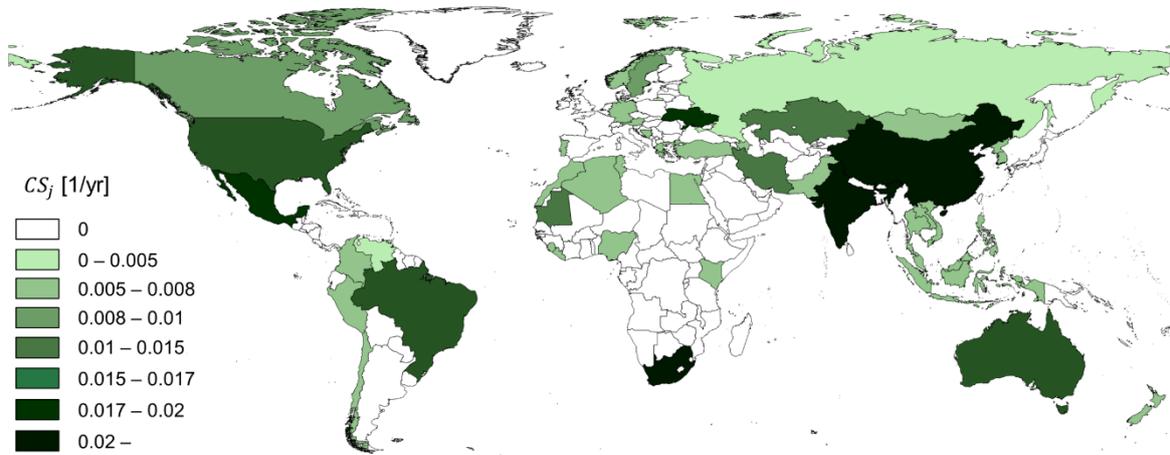
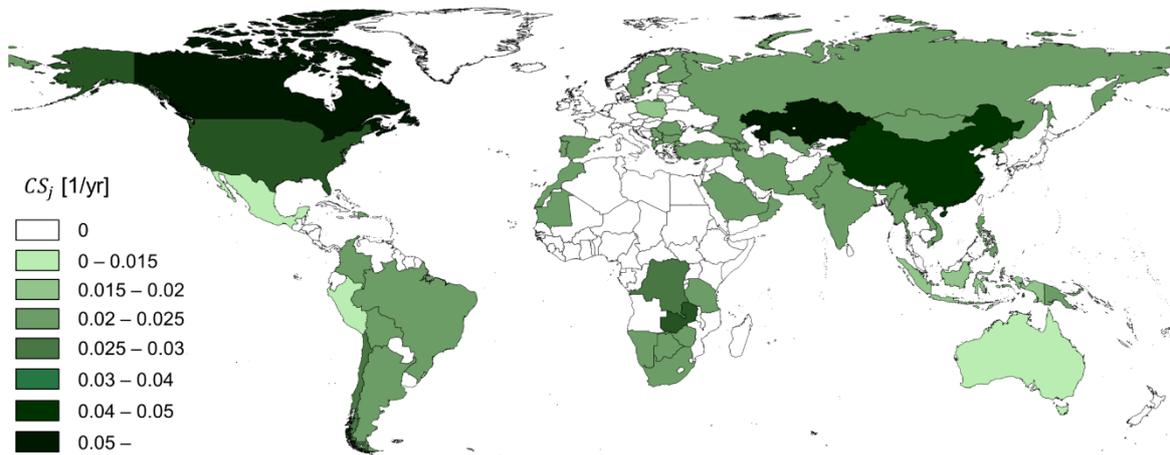


Figure S2. Scarcity-weighted induced mine production (S-IND) of Japan for Fe, Cu, and Ni in 2011, Related to Figure 1.

(1) Iron



(2) Copper



(3) Nickel

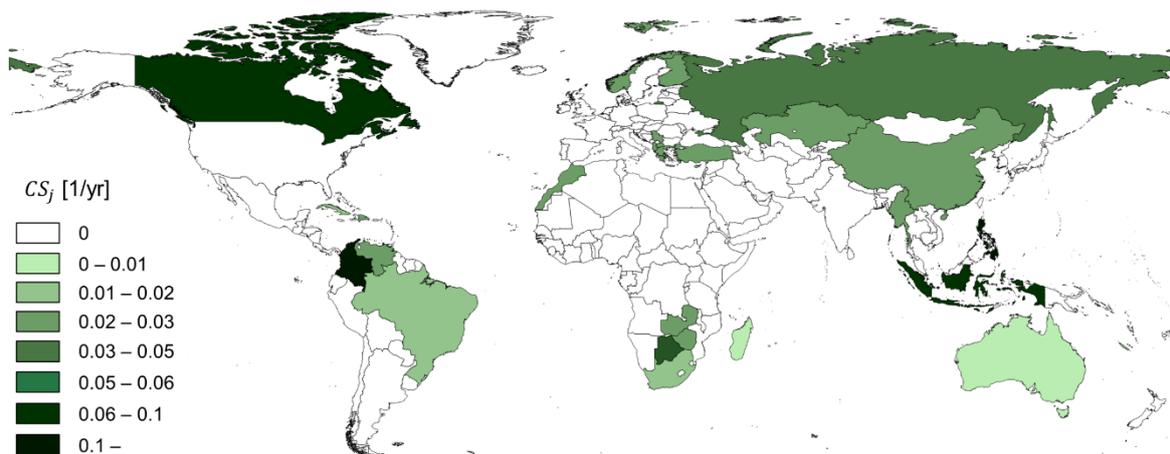


Figure S3. Country-specific scarcity (CS) for Fe, Cu, and Ni in 2011, Related to Figure 3.

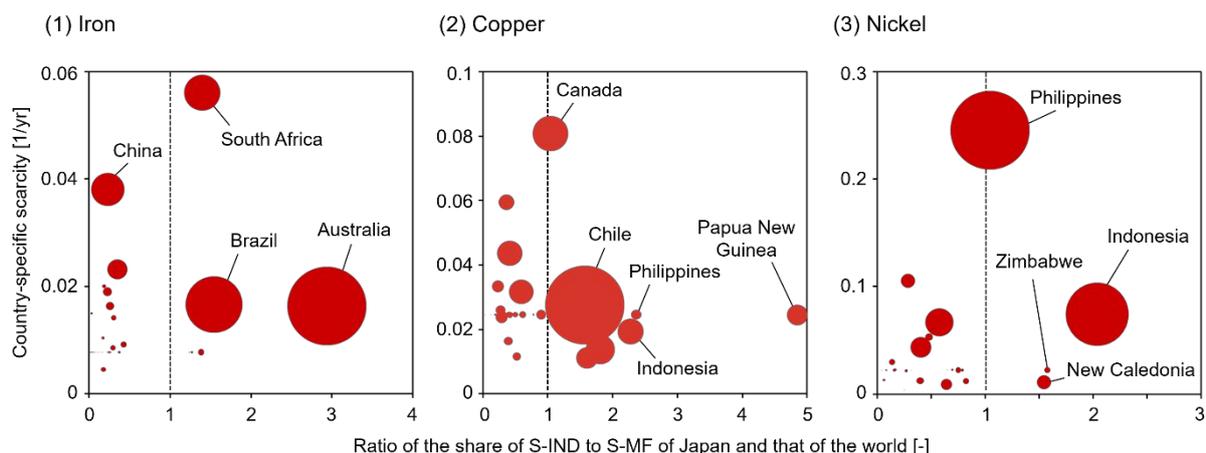


Figure S4. Bubble charts showing the relative significance of Japanese responsibility for metal scarcity in mining capacity and country-specific scarcity in 2011, Related to Figure 3. The size of the circles represents the scarcity-weighted induced mine production (S-IND) of Japan for each producing country.

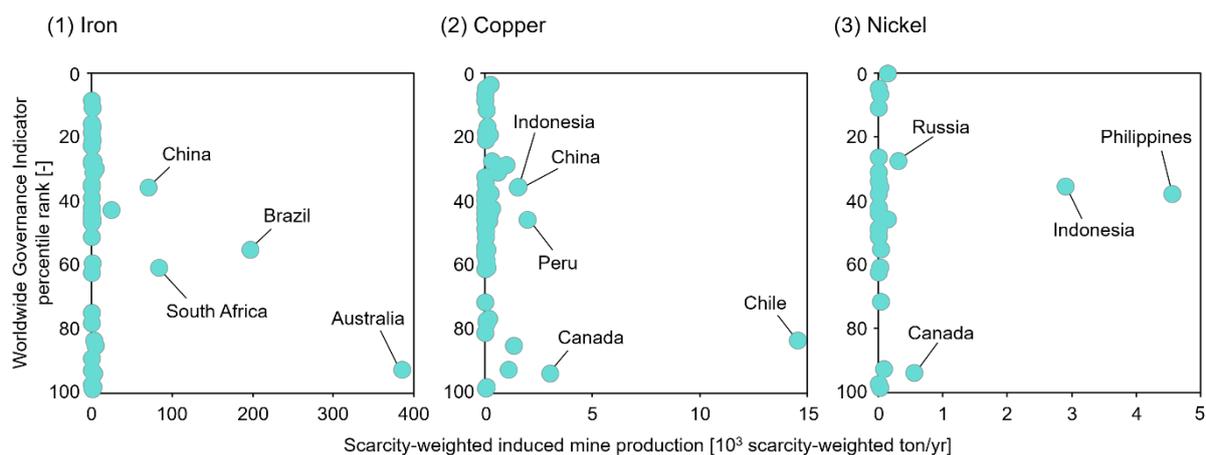


Figure S5. Relationship between the scarcity-weighted induced mine production (S-IND) and political risk in 2011, Related to Figure 1. The horizontal axis represents the scarcity-weighted induced mine production (S-IND) of Japan; the vertical axis represents the World Governance Indicators (WGI) value (Kaufmann et al., 2010). The WGI is published by the World Bank and is comprised of six aspects: voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. In this figure, the average value of the percentile ranks for these six aspects (0–100) is used. A higher WGI value indicates a lower political risk in a country. New Caledonia is excluded from the charts because WGI values have not been calculated for New Caledonia.

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