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Global distribution of material consumption: Nickel, copper, and iron

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ABSTRACT

Economic growth and sometimes the use of green technologies have been associated with a rapid rise in the use of metals and minerals. In today's globalized economy, natural resource consumption influences environmental impacts far removed from the place of consumption. Knowledge about the flow of substances is fundamental to reducing natural resource consumption and controlling the material cycle. Economy-wide material flow analysis (MFA) is an excellent tool to quantify material balances in specific areas for resource and waste management. The goal of this study was to identify the worldwide material flow of nickel, copper, and iron in global trade among 231 countries and regions, and to examine the apparent consumption of the materials as a global systematic phenomenon. Here, apparent consumption means the mathematical sum of production plus imports minus exports, including products with high degrees of fabrication. The levels of apparent consumption of iron, copper, and nickel were 1.7 Pg, 20 Tg, and 2.1 Tg, respectively, in 2010, which represented increases by a factor of 2.1, 1.6, and 1.7, respectively, from 1995. These increases coincided with increasing demand for these materials in Asia. For example, the percentage of the apparent consumption of iron in Asia accounted for 41% of total worldwide consumption in 1995, but it rose to 64% in 2010. Similarly, the percentage of apparent consumption of copper and nickel in Asia reached 60% and 54%, respectively, in 2010.

1. Introduction

UNEP's International Resource Panel (UNEP IRP) has pointed out the importance of decoupling resource use and negative environmental impacts from economic activity (United Nations Environmental Programme, International Resource Panel (UNEP IRP), Decoupling Natural Resource Use and Environmental Impacts from Economic Growth 2011). Economic growth is associated with a rapid rise in the use of natural resources within the economy (van Vuuren et al., 1999; UNEP IRP, 2016), and sometimes greater implementation of green technologies has triggered a rapid rise in the use of metals and minerals (Kleijn et al., 2011; Vidal et al., 2013; Ali et al., 2017). The development of renewable energy sources and other high-technology applications (e.g., wind energy, solar energy, biomass, and fossil-fuel-based electricity with carbon capture and storage [CCS]) for a low-carbon society will require new infrastructure that will consume a different mix of minerals from current applications, including not only critical metals such as the rare earths, but also vast amounts of common metals such as nickel (Kleijn et al., 2011), copper (Kleijn et al., 2011; Vidal et al., 2013), and steel (Kleijn et al., 2011; Vidal et al., 2013). Because the successful achievement of the United Nations sustainable development goals and the implementation of the Paris Agreement will also require technologies that utilize vast quantities of a wide range of minerals, global resource governance will be required for sustainable development (Ali et al., 2017). The Asia-Pacific region has now become the world's largest user of natural resources, and established systems of production and consumption have been tailored to the current high levels of resource use and emissions. In addition, the Asia-Pacific region housed 3.6 billion people or 55% of the global population and used 36 billion tonnes of material or 53% of global material use in 2010 (UNEP, 2015).

Knowledge about the flow of substances is fundamental to reducing natural resource consumption and controlling the material cycle. Material flow analysis (MFA) is an excellent tool to quantify material and substance balances (e.g., Reck and Graedel, 2012; Reck et al., 2008; Johnson and Graedel, 2008; Nakajima et al., 2014, 2017) and material

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stocks (e.g. Gerst and Graedel, 2008; Daigo et al., 2010; Pauliuk et al., 2013) in specific areas, and it includes multi-regional analysis (e.g., Reck et al., 2008; Pauliuk et al., 2013). However, the absence of national statistics constrains the accurate detection of material flows and stocks, which can make it extremely difficult to understand the distribution of material consumption around the world.

Focusing on metal resources, global extraction of metal ores grew by more than 250% between 1970 and 2010, and the extraction of iron ore and copper ore accounted for more than half of the global extraction of metal ores (UNEP IRP 2016). Recently, global nickel production has shown significant growth, including near exponential growth since 1950, from about 0.01 Tg-Ni in 1900 to 1.6 Tg-Ni in 2007 (Mudd, 2010). Materials refined from these ores play a crucial role in modern society and are used in numerous types of infrastructure and technologies. In particular, nickel is a critical resource for low-carbon technologies, such as stainless steel pipes for CCS, nickel-based super alloys for ultra-supercritical power generation, and Li-ion or Ni-MH batteries for electric vehicles.

In this study, we focused on iron, copper, and nickel as a case study with which to discuss material consumption. Our aim was to identify the worldwide material flow of nickel, copper, and iron in global trade among 231 countries and regions and to examine the apparent consumption of the materials as a global systematic phenomenon. In this context, apparent consumption means the mathematical sum of production plus imports minus exports, which include products with high degrees of fabrication. The difference between apparent consumption and real consumption is that the latter definition also recognizes changes in stock levels.

2. Materials and methods

Nansai et al. (2014) established an MFA approach that created a complete global MFA system boundary, and Nakajima et al. (2014, 2017) estimated the global flow of nickel and iron associated with trade in 2005 with this global MFA method. In this study, we recompiled a dataset, $t_{pq}^{(k,i)}$, which indicates the amount of substance i moving from country p to q contained in the trade of commodity k. To ensure a global system boundary, we considered 231 countries and regions for p and q (see Table S1 in the Supplementary Materials). To define commodity k, we selected all commodities assumed to contain the element from among approximately 6000 commodities as defined by the HS (Harmonized Commodity Description and Coding System) code. The system has 6-digit classification numbers, and we aggregated selected ones into 543 commodity groups (4-digit: 196 commodities; 6-digit: 347 commodities) for iron, 288 commodity groups (4-digit: 196 commodities; 6-digit: 92 commodities) for copper, and 303 commodity groups (4-digit: 205 commodities; 6-digit: 98 commodities) for nickel (see Table S2 in the Supplemental Materials for a complete commodity list). For the estimation, we extracted trade volumes ($v_{pq}^{(k)}$) for each commodity group in monetary or physical units for 231 countries and regions, using the BACI database (Base pour l'Analyse du Commerce International; CEPII, 2017), which is an improvement relative to the UN Comtrade database (as discussed below in section 4.3). To consider the ratio of products with target substance i in the trade volume of each good k obtained from the BACI database, we set a cut-off value $r_p^{(k,i)}$ in the range from 0 to 1; we then multiplied trade volume by this cut-off value to improve the accuracy of our estimates of the flow of goods with target substance i. The estimates were converted to a flow of the target substance embedded in trade by multiplying the values by the substance content rate $s_p^{(k,i)}$of each of the goods from various sources (e.g. Tuck, 2015; Brininstool, 2015; Kuck, 2012; see Table S2) or by using an estimation model for material composition of products (Nakamura et al., 2007; Ohno et al., 2014). Specifically, we calculated the $t_{pq}^{(k,i)}$ through transactions of good k via trade as:

$$t_{pq}^{(k,i)} = v_{pq}^{(k)} \times r_p^{(k,i)} \times s_p^{(k,i)} \qquad \text{Eq. (1)}$$

Then we calculated $C_p^{(i)}$, the apparent consumption of substance i in country p, as follows:

$$C_p^{(i)} = M_p^{(ore,i)} + M_p^{(2nd,i)} + \sum_k \sum_q (\bar{t}_{qp}^{(k,i)} - \bar{t}_{pq}^{(k,i)}) \qquad \text{Eq. (2)}$$

Here, $\bar{t}_{pq}^{(k,i)}$ and $\bar{t}_{qp}^{(k,i)}$ denote calibrated substance flows from the initial estimates ($t_{pq}^{(k,i)}$, $t_{qp}^{(k,i)}$) with quadratic programing to ensure $C_p^{(i)} \gg > 0$ for all p. $M_p^{(ore,i)}$ is the amount of substance i embedded in mine production in country p, and $M_p^{(2nd,i)}$ is the amount of substance i embedded in secondary resources recovered from urban mines in country p.

Data for the amount of substance i embedded in mine production originated from the United States Geological Survey (USGS) Minerals Yearbooks (iron, Tuck 2015; copper, Brininstool, 2015; nickel, Kuck 2012; Table S3 in the Supplementary Materials), and the amount of substance i embedded in secondary production was estimated from statistics (iron, World Steel Association 2015; copper, Brininstool 2015; nickel, WBMS 2015 and Daigo et al., 2010; see Table S3). The amount of iron extracted globally from natural ore was equivalent to 1.3 Pg-Fe, and 66% of the iron ore was mined in China (26%), Brazil (21%), and Australia (19%). The amount of copper extracted globally from natural ore was equivalent to 17 Tg-Cu, and 47% of the copper ore was mined in Chile (33%), Peru (7.5%), and China (7.2%). The amount of nickel extracted globally from natural ore was equivalent to 1.7 Tg-Ni, and 42% of the copper ore was mined in Russia (16%), Indonesia (14%), and the Philippines (12%).

3. Results

3.1. Global flows

A total of 1.5 Pg-Fe moved through the global market in 2010 (Table S4 in the Supplementary Materials). Transactions between major iron ore producers (China, Australia, Brazil, and India) and major steel producers (China, the United States, Japan, and Korea) predominated, with the 10 largest flows accounting for 34% of the entire flow of iron among the 231 countries and regions, and the 50 largest flows accounting for 50% of the total (Fig. 1). The percentage of imports of the world's iron resources accounted for by the BRICS nations (Brazil, Russia, India, China, and South Africa) and the Next Eleven (N-11: South Korea, the Philippines, Pakistan, Iran, Republic of Indonesia, Egypt, Turkey, Nigeria, Bangladesh, Vietnam, and Mexico) is noteworthy because the BRICS countries excluding China accounted for only 1.9% of imports of the world's iron resources. The percentage of imports of the world's iron resources by the N-11 and BRICS countries excluding China was no more than 14% in 2010.

Worldwide copper and nickel flows followed a similar pattern; that is, they were concentrated in specific countries and regions far removed from the place of consumption (see Figs. S1 and S2 and Table S4 in the Supplementary Materials). A total of 40 Tg-Cu was transacted on the global market, with the 10 largest flows accounting for 16% of the entire flow, and the 50 largest flows accounting for 39% in 2010. The BRICS countries excluding China accounted for 2.5% of imports of the world's copper resources. The percentage of imports of the world's copper resources by the N-11 and BRICS countries excluding China was less than 11% in 2010. In the case of nickel, 3.3 Tg-Ni was transacted on the global market, with the 10 largest flows accounting for 21% of the entire flow and the 50 largest flows accounting for 45% in 2010. The BRICS countries excluding China accounted for 2.6% of imports, and the percentage of imports of the world's nickel resources by the N-11 and BRICS countries excluding China was no more than 8.3% in 2010.

3.2. Apparent consumptions

The top 25 countries and regions identified as having the largest apparent consumption of iron are shown in Fig. 2 (see additional details