Global distribution of material stocks: iron, copper and nickel

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Abstract. Economic growth has caused a rapid rise in the use of metals and minerals. In addition, the world's population is projected to rapidly increase, with increases concentrated in Asia and Africa. Asia has become the largest global user of natural resources, and established systems of production and consumption are tailored to the current high levels of natural resource use and the associated emissions. Closing the material cycle loop is a principal strategy to reduce natural resource consumption and associated emissions. Material flow analysis (MFA), widely used to assess the flow and stocks of materials within a system defined in time and space, is regarded as a core tool to assess the sustainability of material use. The objective of this study was to estimate material stocks of iron, copper, and nickel, for which the global demand has risen rapidly in recent years. Specifically, the goal was to examine transitions of the material stock of each substance from 1995 to 2010. The worldwide material stocks of iron, copper, and nickel drastically increased during this period, which coincided with an increase in demand for materials in Asia. The material stock of each substance in Asia increased almost threefold from 1995 to 2010. The material stock of iron, copper, and nickel in Asia accounted for 30%, 26%, and 20% of the world total in 1995, respectively, but these percentages increased to 42%, 37%, and 32% in 2010, respectively. There was also a drastic increase in the per-capita material stock of iron, copper, and nickel in Asia during the same period, but the per-capita material stock of each of these substances in Asia was not yet reached that of North America and Western Europe. The material stocks in Africa increased in line with the population growth in Africa from 1995 to 2010, so the per-capita material stock of each substance in Africa stayed about the same. The per-capita material stocks in Africa are also small compared with developed countries and regions. This situation shows the potential for a greatly increased demand as a result of expansions in production through accelerated industrialization as well as the increased demand for resources accompanying population and economic growth in Asia and Africa.

Keywords: material flow analysis (MFA) / supply chain / time series analysis / Asia / Africa / mineral resource

Résumé. Répartition mondiale des stocks de matières : fer, cuivre et nickel. La croissance économique a entraîné une augmentation rapide de l'utilisation des métaux et des minéraux. En outre, on prévoit une rapide augmentation de la population mondiale, l'augmentation étant concentrée en Asie et en Afrique. L'Asie est devenue le plus grand utilisateur mondial de ressources naturelles, et les systèmes établis de production et de consommation sont adaptés aux niveaux élevés actuels d'utilisation des ressources naturelles et aux émissions connexes. Fermer la boucle de cycle des matières est une stratégie principale pour réduire la consommation de ressources naturelles et les émissions connexes. Les comptes de flux de matières (CFM), largement utilisés pour

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évaluer le flux et les stocks de matières dans un système défini dans le temps et dans l'espace, sont considérés comme un outil de base pour évaluer la durabilité de l'utilisation des matières. L'objectif de cette étude était d'évaluer les stocks de fer, de cuivre et de nickel, pour lesquels la demande mondiale a augmenté rapidement ces dernières années. Plus précisément, l'objectif était d'examiner les transitions du stock de matières de chaque substance entre 1995 et 2010. Les stocks mondiaux de matières de fer, de cuivre et de nickel ont radicalement augmenté au cours de cette période, ce qui a coïncidé avec une augmentation de la demande de matières en Asie. Le stock de matières de chaque substance en Asie a presque triplé de 1995 à 2010. Le stock de matières de fer, de cuivre et de nickel en Asie représentait respectivement 30 %, 26 % et 20 % du total mondial en 1995, mais ces pourcentages ont augmenté à 42 %, 37 % et 32 % en 2010, respectivement. Au cours de la même période, le stock de fer, de cuivre et de nickel par habitant a considérablement augmenté en Asie, mais le stock de matières par habitant de chacune de ces substances en Asie n'a pas encore atteint celui de l'Amérique du Nord et de l'Europe de l'Ouest. Les stocks de matières en Afrique ont augmenté parallèlement à la croissance de la population en Afrique de 1995 à 2010, de sorte que le stock de matières par habitant de chaque substance en Afrique est resté à peu près le même. Les stocks de matières par habitant en Afrique sont également faibles par rapport aux pays et régions développés. Cette situation montre le potentiel d'une demande fortement accrue en raison des expansions de la production par une industrialisation accélérée ainsi que de la demande accrue de ressources accompagnant la croissance démographique et économique en Asie et en Afrique.

Mots clés: comptes de flux de matières (MFA) / chaîne d'approvisionnement / analyse de séries chronologiques / Asie / Afrique / ressources minérales

1 Introduction

Economic growth has accelerated the use of natural resources [1,2], which has potential environmental impacts at local and global scales. The United Nations projected that the world's population will reach 9.7 billion by 2050, with nearly 90% of the increase concentrated in Asia and Africa [3]. The Asia-Pacific region has become the largest global user of natural resources, and established systems of production and consumption are tailored to the current high levels of natural resource use with their associated emissions. In 2010, the region had a population of 3.6 billion, or 55% of the global population, and used 36 billion tonnes (53%) of global materials [4].

Closing the loop of material cycles is a principal strategy to reduce natural resource consumption and the associated environmental impacts. Policymakers have recognized the importance of circular economy strategies [5], with closed material cycles and the economic stimulation accompanying resource renewal activities attracting attention. Material flow analysis (MFA) is widely used to assess the flows and stocks of materials within systems defined in time and space. It is considered a core tool to assess the sustainability of material use (e.g., Reck and Graedel 2012 [6]; Reck et al. 2008 [7]; Pauliuk et al. 2013 [8]; Nansai et al. 2014 [9]; Wiedmann et al. 2013 [10]; Nakajima et al. 2014, 2017 [11,12]). However, the absence of national statistics constrains the detection of material flows and stocks, making it extremely difficult to understand the distribution of material consumption around the world and clarify the drivers of accelerated material consumption.

The objective of this study was to estimate material stocks of iron, copper, and nickel, the global demand for which has risen rapidly in recent years, by using the global MFA approach established by Nansai et al. [9]. The global extraction of metal ores grew by more than 250% between 1970 and 2010, and the extraction of iron ore and copper ore account for more than half of the global extraction of metal

ores [2]. Moreover, global nickel production has shown nearly exponential growth since 1950 [13]. Materials refined from these ores play a crucial role in modern society, with uses in numerous types of infrastructure and technology. This study therefore clarified global transitions in the material stock of each of these substances from 1995 to 2010.

2 Methods and data

Nansai et al. [9] established an approach to create a complete global MFA system boundary, which Nakajima et al. [11,12] used to estimate the flow of iron and nickel associated with global trade in 2005. We recompiled the dataset and estimated the material stock (S) of substance i in country p at the end of year t as follows:

$$S_{p,t}^{(i)} = S_{p,t-1}^{(i)} + \Delta S_{p,t}^{(i)} \quad (1)$$

where $\Delta S_{p,t}^{(i)}$ shows the net addition to the stock of substance i in country p in year t . The net addition was calculated by multiplying the apparent consumption of substance i in country p ($C_{p,t}^{(i)}$) by the accumulated ratio of substance i in country p ($\alpha_{p,t}^{(i)}$); that is, $\Delta S_{p,t}^{(i)} = C_{p,t}^{(i)} \times \alpha_{p,t}^{(i)}$. For this study, we calculated $C_{p,t}^{(i)}$ as follows:

$$C_{p,t}^{(i)} = M_{p,t}^{(\text{ore},i)} + M_{p,t}^{(2nd,i)} + \sum_k \sum_q (f_{qp}^{(k,i)} - f_{pq}^{(k,i)}) \quad (2)$$

where $M_{p,t}^{(\text{ore},i)}$ is the amount of substance i embedded in mine production in country p , $M_{p,t}^{(2nd,i)}$ is the amount of substance i embedded in secondary resources recovered from urban mines in country p , $f_{qp}^{(k,i)}$ is the amount of substance i

Fig. 1. Distribution of the 25 countries and regions with the largest material stock of iron in 1995, 2000, 2005, and 2010.

Fig 1. Répartition des 25 pays et régions possédant le stock de fer le plus important en 1995, 2000, 2005 et 2010.

embedded in imports of commodity k from country q to p , and $f_{pq}^{(k,i)}$ is amount of substance i embedded in exports of commodity k from country p to q . Because of data limitations in trade statistics (Base pour l'Analyse du Commerce International (BACI) [14]; UN Comtrade database) for the calculation of $C_{p,t}^{(i)}$, we calculated $S_{p,1994}^{(i)}$ from the World Bureau of Metal Statistics (WBMS) [15].

To ensure a global system boundary, we considered 231 countries and regions around the world for p and q . To define commodity k , we selected all commodities assumed to contain the element among the approximately 6000 commodities defined by the Harmonized Commodity Description and Coding System (HS) code with 6-digit classification numbers and aggregated the 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. We extracted the trade volume

for each commodity group in monetary or physical units for 231 countries and regions, using BACI [14]. The amount of substance i embedded in mine production originated from USGS mineral yearbooks (e.g., iron: Tuck 2015 [16]; copper: Brininstool 2015 [17]; nickel: Kuck 2012 [18]), and the amount of substance i embedded in secondary production was estimated from statistics (e.g., iron: World Steel Association 2015 [19]; copper, Brininstool 2015 [17]; nickel, WBMS [15] and Daigo et al. 2010 [20]). We also obtained $\alpha_{p,t}^{(i)}$ from previous MFA studies (iron: Wang et al. 2007 [21]; copper: Graedel et al. 2004 [22]; nickel: Reck et al. 2008 [7]), but the accumulated ratio ($\alpha_{p,t}^{(i)}$) was assumed to be constant regardless of the year because of data limitations.

3 Results

The 25 countries and regions identified as having the largest material stock of iron are shown in Figure 1. The

Fig. 2. Distribution of the 25 countries and regions with the largest material stock of copper in 1995, 2000, 2005, and 2010.

Fig 2. Répartition des 25 pays et régions possédant le stock de cuivre le plus important en 1995, 2000, 2005 et 2010.

total material stock of iron doubled from 1995 to 2010 and was estimated at 24×10^9 t-Fe in 2010. The three countries or regions with the largest material stock accounted for 41% of the world total in 2010 (PR China: 20%; USA: 13%; and Japan: 7.9%), the top 10 accounted for 63%, and the top 25 accounted for 83%. The material stock of iron in Asia and Africa was 11×10^9 t-Fe (Asia: 10×10^9 t-Fe; Africa: 0.81×10^9 t-Fe) in 2010, which accounted for 46% (Asia: 42%; Africa: 3%) of the world total.

The top 25 countries and regions identified as having the largest material stock of copper are shown in Figure 2. The total material stock of copper was estimated at 37×10^7 t-Cu in 2010, which increased by a factor of 1.9 from 1995 to 2010. The three countries with the largest material stock accounted for 40% of the world total in 2010 (PR China: 19%; USA: 15%; and Germany: 5.5%), the top 10 accounted for 64%, and the top 25 accounted for 83%. The material stock of copper in Asia and Africa was 15×10^7 t-Cu (Asia: 14×10^7 t-Cu, Africa: 1.2×10^7 t-Cu) in 2010, or 40% (Asia: 37%; Africa: 3%) of the world total.

The top 25 countries and regions identified as having the largest material stock of nickel are shown in Figure 3.

The total material stock of nickel was estimated at 29×10^6 t-Ni in 2010, which increased by a factor of 2.2 from 1995 to 2010. The three countries and regions with the largest material stock accounted for 38% of the world total in 2010 (PR China: 18%; USA: 11%; and Japan: 8.1%), the top 10 accounted for 63%, and the top 25 accounted for 86%. The material stock of nickel in Asia and Africa was 9.9×10^6 t-Ni (Asia: 9.3×10^6 t-Ni; Africa: 0.64×10^6 t-Ni) in 2010, which was 34% (Asia: 32%; Africa: 2%) of the world total.

4 Discussion

The worldwide material stock of iron, copper, and nickel drastically increased from 1995 to 2010, coinciding with increases in demand for materials in PR China and other Asian countries (Fig. 4). The material stock of each substance in Asia increased almost threefold from 1995 to 2010. The material stock of iron, copper, and nickel in Asia accounted for 30%, 26%, and 20% of the global total in 1995, respectively, and those percentages reached 42%,

Fig. 3. Distribution of the 25 countries and regions with the largest material stock of nickel in 1995, 2000, 2005, and 2010.

Fig 3. Répartition des 25 pays et régions possédant le stock de nickel le plus important en 1995, 2000, 2005 et 2010.

37%, and 32% in 2010. These results also reveal a dramatic threefold increase in the per-capita material stock of iron, copper, and nickel in Asia from 1995 to 2010. In particular, economic activities in PR China accelerated the rapid rise in material stocks of these substances in Asia. Material stocks in Africa increased in line with the population growth in Africa from 1995 to 2010, so the per-capita material stock of each substance in Africa stayed about the same (Fig. 5).

The world population is projected to increase, with much of that growth concentrated in Asia and Africa. Asia has already become the largest world user of iron, copper, and nickel, but the per-capita material stock of each of these substances in Asia has not yet reached that of North America and Western Europe. The per-capita material stocks in Africa are also small compared with

developed countries and regions. This situation shows the potential for a greatly increased demand as a result of expansions in production through accelerated industrialization as well as the increased demand for resources accompanying population and economic growth in Asia and Africa. From the perspective of natural resource conservation, emerging countries in Asia and Africa should introduce and strengthen their recycling systems of each substance to close the material cycle loop.

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Fig. 4. Distribution of population and material stocks in 1995 and 2010: (a) iron, (b) copper, and (c) nickel.

Fig 4. Répartition des stocks de population et de matières en 1995 et 2010: (a) fer (b) cuivre et (c) nickel.

Fig. 5. Recent trend of material stocks from 1995 to 2010: (a) iron, (b) copper, and (c) nickel.

Fig 5. Tendence récente des stocks de matières de 1995 à 2010: (a) fer (b) cuivre et (c) nickel.

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