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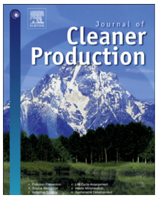

Tracking mercury emission flows in the global supply chains: A multi-regional input-output analysis

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ABSTRACT

Mercury emissions from nonferrous metal production have overtaken that from energy consumption as the leading contributor of global anthropogenic mercury emissions. Though Minamata Convention has put restrictions on import or export of mercury-added products, the inter-connected global economy that features an intensive correlated supply chain still has large impacts on mercury emissions. Therefore, this study aims to track global nonferrous metal related mercury emission flows among 186 individual economies for the year of 2010, by applying an empirically validated multi-regional input-output (MRIO) model. The total amount of direct mercury emissions is 974 tonnes, to which gold production contributed a dominant proportion. However, a spectacular 2/3 of mercury emissions from nonferrous metal production were traded internationally, primarily as exports from emerging economies such as mainland China and Colombia to wealthy economies including the USA and Germany through global supply chains. Understanding the redistribution of mercury emissions along the global supply chains can facilitate international efforts to reduce mercury emissions from nonferrous metal production.

1. Introduction

Atmospheric mercury, characterized as long range transportation and bioaccumulation in the environment, is a well-recognized global pollutant with high toxicity (US-EPA, 1997). Since the beginning of the industrial era, the concentration of mercury in air has increased by three times (Mason et al., 1994), which poses a serious threaten to living species all over the world. Due to the ubiquitous distribution and high toxicity to both human and environment, atmospheric mercury emissions have aroused global concern. Initiated in 2009, a global legally binding instrument on mercury was put on UNEP's agenda. After 4 years' arduous negotiations, delegations from different countries unanimously passed Minamata Convention aiming at global mercury mitigation. This event is a token that international community has reached an agreement to curb global atmospheric mercury pollution (Maxson, 2004).

Atmospheric mercury pollution is not only a hot topic in the political cycle, but also captures keen scientific attention. Studies on atmospheric mercury emissions from man-made sources have continued for over several decades. Back in the 1980s, Narigu and Pacyna compiled an inventory of global mercury emissions which

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amounted to 3560 tonnes in the year of 1983 (Nriagu and Pacyna, 1988). Following this work, Pacyna and his collaborators have conducted a series of studies to improve the global mercury emissions estimation and obtain more complete and accurate inventories (Pacyna and Pacyna, 2002; Pacyna et al., 2003, 2006). In recognition of the adverse effects, UNEP also convened hundreds of experts and scientists from different organizations to update global mercury emission information from anthropogenic sources (UNEP, 2008, 2013; UNEP, 2002). Moreover, a calculation tool which is now extended to direct mercury emissions estimation all over the world was invented by UNEP (UNEP, 2005).

Based on current knowledge, anthropogenic sources for mercury emissions mainly include fossil fuel combustion, nonferrous metal production, iron and steel production, waste incineration, cement production and some other industrial activities (Streets et al., 2011). According to the latest literature (UNEP, 2013), nonferrous metal production has replaced fossil fuel combustion as the top emitter, contributing about half of global total mercury emission inventory. Without doubt, nonferrous metal production has become the forefront of combating global atmospheric mercury pollution. Under this circumstance, it is vital to reduce nonferrous metal related mercury emissions to alleviate global atmospheric mercury pollution. However, the understanding of global nonferrous metal related mercury emissions is still far from sufficient, which hinders the efficient policy implementation.

Moreover, the currently prevailing method for estimating mercury emissions is production based, which considers direct emissions only. A huge blank remains in the field of mercury emission studies, which is the absence of indirect mercury emissions linked to the ever increasing international trade. There are hot arguments about whether the direct accounting method can effectively reduce emissions, as it neglects the indirect emissions embodied in imports and exports of a specific economy (Chen and Chen, 2012; Li et al., 2013; Liu et al., 2010; Peters and Hertwich, 2008b; Su and Ang, 2011). Embodied emissions can be defined as the total emissions induced to produce a good or service, considering both direct emissions within the production process and indirect emissions as feedback from the global economic system itself (Chen et al., 2013a). Regarding this, a more comprehensive accounting method, which can draw the holistic profile of embodied mercury emissions (direct plus indirect mercury emissions), is in great need to reflect the atmospheric mercury pollution from different angels and has significant implications for global mitigation actions.

It is worth noticing that input-output analysis is a useful tool that covers not only environmental emissions and resources use by producers, but also detailed information associated with intermediate transactions that are included in the whole supply chain (Chen and Chen, 2015; Song et al., 2015; Su and Ang, 2014, 2015; Wiedmann, 2009; Zhang et al., 2014). In this context, multi-regional input-output (MRIO) analysis is able to trace both direct and indirect ecological elements for different economies as well as analyzes the effect of trade on economies' ecological element use. Because of this merit, a considerable number of literature have employed MRIO to investigate the impact of trade on GHG emissions (Davis et al., 2011; Peters and Hertwich, 2008a), energy consumption (Chen and Chen, 2011; D. Cortés-Borda et al., 2015), water use (Chen and Chen, 2013; Feng and Hubacek), land use (Chen and Han, 2015), PM emissions (Meng et al., 2015; Yang et al., 2015, 2016) and even threats to species (Lenzen et al., 2012b) at global and national scales. Notably, although there exists MRIO based analysis for atmospheric mercury footprints of nations (Liang et al., 2015) as well as China's inter-provincial mercury emission flows (Liang et al., 2014), a specific investigation on re-allocation of mercury emission from non-ferrous metals is still lacking.

In light of the previous studies, this paper portrays global nonferrous metal related mercury emissions, i.e., embodied emissions of each economy and the international nonferrous metal related mercury emission trade, by adopting MRIO. The current study has two main goals: (1) shed light on global mercury emissions from comprehensive and systematic perspective by analyzing both the direct and indirect non-ferrous metal related mercury emissions; (2) provide insight for efficient policy design for global mercury emission reduction. This paper uses a high-resolution global multi-region input-output table in 2010 to trace mercury emissions flowing from the economy where they are produced to other economy where the final consumption happens.

2. Method and data sources

2.1. Method

MRIO analysis is founded on MRIO table, which covers international trade of intermediate products and final demand by household and governments. Assuming there are *M* economies and each economy has a certain number of sectors and the total number of sectors is *N*. Each sector can be considered as a basic unit of global economy. The embodied mercury emissions balance of Unit *i* can be expressed as:

$$me_i + \sum_{j=1}^{N} \varepsilon_j \times z_{j,i} = \varepsilon_i \times \left(\sum_{j=1}^{N} z_{i,j} + \sum_{r=1}^{M} d_{i,r} \right) \tag{1}$$

where me_i is direct mercury emissions from Unit *i*, ε_i and ε_j represent the embodied mercury intensities of Unit *i and j*, $z_{i,j}$ denotes intermediate inputs from Unit *i* to Unit *j*, $d_{i,r}$ stands for output from Unit *i* to final demand in economy *r*.

Introduce the following matrix notations:

$$\mathbf{E} = [\varepsilon_1, \varepsilon_2 \cdots \varepsilon_N],$$

$$\mathbf{ME} = [me_1, me_2 \cdots me_N],$$

$$\mathbf{X} = \begin{bmatrix} z_{1,1} & , & z_{1,2} & \cdots & z_{1,N} \\ z_{2,1} & , & z_{2,2} & \cdots & z_{2,N} \\ \vdots & & & \ddots & \vdots \\ z_{N,1} & , & z_{N,2} & \cdots & z_{N,N} \end{bmatrix},$$

and

$$\mathbf{Y} = \begin{bmatrix} \sum_{j=1}^{N} z_{1,j} + \sum_{r=1}^{M} d_{1,r} & , & 0 & , & \cdots & 0 \\ 0 & , & \sum_{j=1}^{N} z_{2,j} + \sum_{r=1}^{M} d_{2,r} & , & \cdots & 0 \\ \vdots & & & & \ddots & \vdots \\ 0 & , & \cdots & , & & \sum_{j=1}^{N} z_{i,j} + \sum_{r=1}^{M} d_{i,r} \end{bmatrix}$$

Then Equation (1) can be re-written as:

$$\mathbf{ME} + EX = EY \tag{2}$$

Given the condition that **(Y–X)** is reversible, **E** can be obtained from the following equation by re-ranging Equation (2):

$$\mathbf{E} = ME(\mathbf{Y} - \mathbf{X})^{-1} \tag{3}$$

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