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The anthropogenic cycle of zinc: Status quo and perspectives

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ABSTRACT

Zinc is a key metal of industrial society that saw an unprecedented growth of its use between 2000 and 2010, largely driven by demand in China. Nonetheless, a contemporary understanding of multi-level stocks and flows of zinc is lacking. This paper presents the cycles of relevant countries, eight world regions, and the globe for 2010, relying on material flow analysis (MFA) for results that have the potential to inform policy makers and future research. We estimate the global zinc end-of-life recycling rate at 33%, which helps achieve a 27% of fabricated zinc coming from secondary sources. Most losses occur in waste management, most of it in the end use sectors construction and transportation. Increasing collection rates in these two sectors should be a priority for closing the zinc cycle. China dominates the global anthropogenic zinc cycle, and relies on primary zinc from Latin America and the Caribbean and Oceania to support its zinc demand. Government and industry in Europe and North America should anticipate shifts in exports of their zinc-containing scrap due to the growing availability of Chinese end-of-life zinc. Further research combining this study with scenario analysis could provide the knowledge base to answer questions related to this issue.

1. Introduction

Zinc is a key element of industrial society, besides being essential to any life form on Earth (Graedel et al., 2005; Kesler, 1994; Tolcin, 2012). It is remarkable due to its small reserve base (Gordon et al., 2006) in relation to the dissipative nature of its use when compared to other metals (Ciacci et al., 2015). In 2008, the world zinc reserve base was estimated at 480 Tg, a 12% increase from the 2000 estimate (USGS, 2000, 2009). In the same decade, the world witnessed the spectacular rise of the Chinese economy and a major financial crisis, both of which heavily affected metal flows. Global zinc mine production, metal production, and metal consumption increased by 6%, 13%, and 16% between 2009 and 2010, respectively (ILZSG, 2011; USGS, 2010). China is the largest zinc miner and metal producer with 31% and 41% of global amounts, respectively (USGS, 2010). China also significantly contributed to the metal use increase in 2010, i.e. 13% (ILZSG, 2013). Interestingly, amidst an ongoing debt and monetary crisis, Europe (including Russia) managed to increase its zinc use by 29% between 2009 and 2010 (ILZSG, 2013). As far as zinc is concerned, the demand-side crisis (Tolcin, 2010) is over largely thanks to growth in Asia (Tolcin, 2012). Instead, markets now fear a dwindling supply due to the closing of large mines and the difficulty to find new ones (Deaux and Matthew, 2015, April 8).

Jolly (1992) published the first study on flows of zinc with the USA as geographical scope. Yale's Stocks and Flows Project aims at quantifying global, regional, and national amounts of metal mined, refined, entering fabrication and manufacturing, entering use and stocked therein, discarded, and recycled, in order to support decision-making in government and industry. Earlier work on zinc resulted in a multi-level anthropogenic cycle of zinc for the years 1994 (Graedel et al., 2005) and 2000 (Graedel and Cao, 2010) as well as a historical analysis of zinc use in industrialized countries (Yang et al., in review). Other work focused on zinc's main application (galvanized steel) at a particular spatial level (global (Daigo et al., 2014), Japan (Nakajima et al., 2008; Tabayashi et al., 2009)) or on a country or region with an engineering emphasis on recycling technologies (Ma et al., 2011). However, zinc is also used as a key compound in various chemicals crucial to modern life, e.g., zinc oxides in tires. It is a widely used alloying element with brass and zinc die casts. No recent systematic picture of zinc mobilized by society exists; one that looks at all uses besides galvanized steel and encompasses different geographical scopes, from countries to the globe to provide a comprehensive knowledge base for zinc-related decision-making.

A big picture of zinc can also help better grasp many cross-metal issues. Zinc's fate is intertwined with that of a variety of other metals all along its life cycle. Its mines are the main source of

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other, scarcer metals such as indium and germanium prominent in environmental technologies (Licht et al., 2015; Stamp et al., 2012). Fluctuations in zinc supply directly affect the supply of these scarce metals (Graedel et al., 2015; Nassar et al., 2015). From fabrication all the way to waste management and recycling, it is combined to iron in galvanized steel and copper in brass alloys. As global secondary steel production is forecast to double by 2050 (Pauliuk et al., 2013), the supply of secondary zinc will largely depend on whether galvanized steel scrap is processed or not for zinc recovery. Such quantitative cross-metal understanding has the potential to enlighten current questions around criticality (Graedel et al., 2012), the circular economy (Bartl, 2015), recycling challenges (Reck and Graedel, 2012), urban mining (Brunner, 2011; Simoni et al., 2015), etc. And material flow analyses are always at the onset of answering these questions.

The goal of this paper is to characterize the anthropogenic zinc cycles in 2010 for the countries contributing most to its mobilization, eight world regions, and the planet. This will support government and industry in understanding the scale, linkages, and spatial distribution of anthropogenic zinc flows. For researchers, the present article strives to provide up-to-date and extensive information for future studies such as life cycle assessments or scenario analyses. Relying on this understanding and the earlier results from 1994 and 2000, we will present updated perspectives of the zinc cycles at different levels, compare key characteristics to these earlier data, and discuss implications for the future.

2. Materials and methods

Material flow analysis (MFA) is a method to quantify the stocks and flows of a material or element characterizing a system by applying mass balance (Ayres and Ayres, 2002). It entails setting system boundaries and defining processes within these boundaries through which materials or elements flow and possibly accumulate as stocks. Fig. 1 conceptually illustrates the anthropogenic cycle of zinc. The processes of an anthropogenic metal cycle are mining of ore, smelting and refining, fabrication of semi-fabricated products, manufacturing of end-use products, use in different end-use sectors (e.g., agriculture, infrastructure, transportation), and waste management and recycling. A scrap market supplies smelting and fabrication with secondary zinc from fabrication, manufacturing, and waste management and recycling. Large stocks are built up or depleted in the process of use. Exchanges between the anthropogenic and natural cycles take place in the form of mined material, dissipated material, and waste depositions. Exchanges also take place on markets among countries through imports and exports of zinc ores and concentrates, zinc slab, semi-fabricated products, end-use products, and scrap.

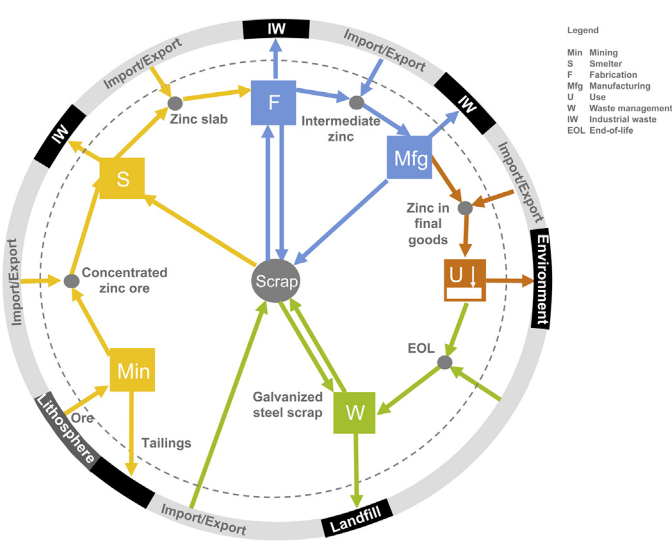

Fig. 1. Stocks and flows of the cycle of anthropogenic zinc.

Following earlier work, country cycles are aggregated into eight regional cycles, i.e., Africa, Asia, the Commonwealth of Independent States (CIS), Europe, Latin America and the Caribbean (LAC), the Middle East, North America, and Oceania, and to a global cycle.

2.1. Country selection

We cover 49 countries, country groups, and territories (called countries hereafter) that significantly contribute to the flows of mining, smelting of zinc, and/or its usage. Countries were selected so that at least 90% of each of these three flows, on a global level, was captured. Other countries are included as they are important for other metals, allowing for an update of existing cross-metal analyses (Graedel and Cao, 2010). A world map highlighting the 49 countries investigated in this study is provided in the Supporting Information (SI) as Fig. S 1, while a list of investigated countries is provided in Table S 8 of the SI.

2.2. Stocks and flows

Detailed explanations on the related models and data are provided in the SI. As recommended by Rechberger et al. (2014), we round the results to two significant digits. We approximated the uncertainty of each flow as the mean and standard deviation of a normal distribution. This approximation was based on the reported data, assumptions, and calculation procedures of the cycle model described above as well as on a personal communication with Eric van Genderen, International Zinc Association (2014). Error propagation and data reconciliation was calculated for the global cycle using the software STAN (Cencic and Rechberger, 2008). Table S 1 of the SI gives an overview of the model characteristics and the standard deviation of flows as a percentage of the mean. Fig. S 1 represents the generic cycle with these uncertainties. Further, a sensitivity analysis was performed on three key parameters to test the robustness of global results.

A detailed description of zinc's life cycle is provided by Gordon et al. (2003). Zinc's life cycle starts with zinc production, i.e., the mining of zinc ore, followed by a number of beneficiation processes and the smelting into zinc slab. At this life cycle stage, three commodities are actively traded, zinc ores, concentrates, and slab. A small fraction of zinc concentrates can be used directly by the chemical industry. Zinc slab can be produced from both primary sources and scrap.

Zinc slab is used to produce a number of intermediate zinc products, which we term first uses to distinguish them from the end-use sectors introduced in manufacturing. We distinguish among the following zinc first uses: galvanizing, zinc alloying, brass, zinc semi-fabricated products, chemicals, zinc dust, and miscellaneous.

Semi-fabricated products are further processed into six end-use sectors, i.e., construction, transportation, industrial and metal working machinery, electrical and electronic products, agriculture, and miscellaneous. Most end-use sectors include zinc applications that dissipate zinc into the environment during their use. Galvanized steel is used in construction, transportation, industrial and metal working machinery, and electrical and electronic products (galvanizing provides a zinc coating on steel that protects it from corroding at the expense of some of the weather-exposed zinc being oxidized over a product's lifetime). The end use agriculture (e.g., animal feed, fertilizer) is entirely dissipative, the zinc flow entering this category in 2010 leaves it entirely the same year. The transportation category contains zinc oxides applied in the vulcanization of rubber, another dissipative use.