



Towards better monitoring of technology critical elements in Europe: Coupling of natural and anthropogenic cycles



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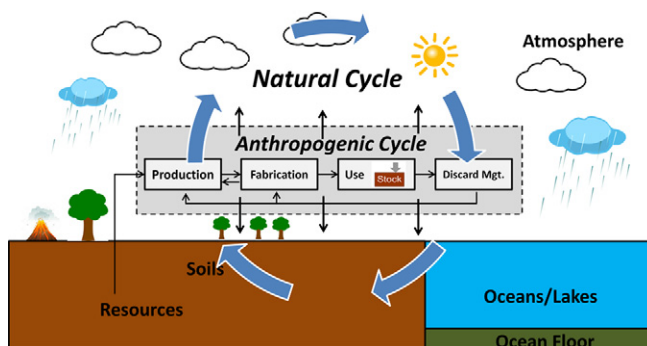
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HIGHLIGHTS

- EU raw material policies for enhanced monitoring of technology critical elements are discussed.
- Methodologies to define “technology critical elements (TCEs)” are described.
- Interconnections of anthropogenic and natural elemental cycles are highlighted.
- EU-28 anthropogenic element fluxes for TCEs are compared to global natural fluxes.

GRAPHICAL ABSTRACT



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ABSTRACT

The characterization of elemental cycles has a rich history in biogeochemistry. Well known examples include the global carbon cycle, or the cycles of the ‘grand nutrients’ nitrogen, phosphorus, and sulfur. More recently, efforts have increased to better understand the natural cycling of technology critical elements (TCEs), i.e. elements with a high supply risk and economic importance in the EU. On the other hand, tools such as material-flow analysis (MFA) can help to understand how substances and goods are transported and accumulated in man-made technological systems (‘anthroposphere’). However, to date both biogeochemical cycles and MFA studies suffer from narrow system boundaries, failing to fully illustrate relative anthropogenic and natural flow magnitude and the degree to which human activity has perturbed the natural cycling of elements. We discuss important interconnections between natural and anthropogenic cycles and relevant EU raw material dossiers. Increased integration of both cycles could help to better capture the transport and fate of elements in nature including their environmental/human health impacts, highlight potential future material stocks in the anthroposphere (in-use stocks) and in nature (e.g., in soils, tailings, or mining wastes), and estimate anticipated emissions of TCEs to nature in the future (based on dynamic stock modeling). A preliminary assessment of natural versus anthropogenic element fluxes indicates that anthropogenic fluxes induced by the EU-28 of palladium, platinum, and antimony (as a result of materials uses) might be greater than the respective global natural fluxes. Increased combination of MFA and natural cycle data at EU level could help to derive more complete material cycles and initiate a discussion between the research communities of biogeochemists and material flow analysts to more holistically address the issues of sustainable resource management.

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1. Introduction

Global population growth, wealthier lifestyles, technological change, and government policies have altered raw materials supply and demand patterns since the early twentieth century (Krausmann et al., 2009; Vidal-Legaz et al., 2016). In particular, the use of multiple materials in single applications to increase product functionality and the push towards low carbon technologies and resource efficiency have increased the demand for many of the technology critical elements (TCEs) that did not find widespread use just a few years ago (Greenfield and Graedel, 2013). Global trade networks of goods, in which materials move along the value chain of mining, processing, manufacture, use, disposal, collection, and waste management, have increased in complexity in recent years as multiple countries are involved in the life-cycles of products (De Benedictis and Tajoli, 2011; Fagiolo et al., 2009; Nemeth and Smith, 1985). Furthermore, future economic development and economic growth are expected to take place in areas such as renewable energy technologies, infrastructure for fuel efficient and clean energy vehicles, and low carbon public transportation (UNEP, 2011a), all of which heavily rely on metals (UNEP, 2013).

Against this context, the European Commission (EC) has launched a number of raw materials policies, of which two cornerstones are the EU Raw Materials Initiative (RMI) (EC, 2008) and the Circular Economy (CE) Action Plan (EC, 2015). The RMI aims at securing a sustainable supply of raw materials for Europe and was launched in 2008, and consolidated in 2011. It focuses on non-energy and non-agricultural materials and connects to EU external and internal policies, e.g., related to raw materials trade (EC, 2014a) and EU structural and investment funds (EC, 2014b). The RMI is an integrated strategy consisting of 3 pillars, which target sustainable supply of raw materials from outside and inside Europe, and aims to boost resource efficiency and recycling (Fig. 1). The initiative introduced and updated the list of critical raw materials (CRMs) for the EU in 2011, 2014, and 2017 (forthcoming) which identify materials characterized by a high supply risk and a high economic importance for Europe (Blengini et al., 2017c; EC, 2010, 2014c).

More recently, the CE action plan aims to stimulate Europe's transition towards a more circular economy (EC, 2015). Circular economy is defined as a state in which "the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized" (EC, 2015). The CE action plan is currently being implemented. In 2017, the Commission plans to present a

strategy for plastics, report on CRMs in the circular economy, an assessment of options for the improved interface between chemicals, products and waste legislation, a legislative proposal on water reuse, and a monitoring framework on circular economy (EC, 2017).

EU policies such as the RMI and CE action plan rely on information and data on material flows and stocks within the EU economy and their level of circularity within Europe (*anthropogenic cycles of the elements*) (EC, 2012). Material flow analysis (MFA) approaches (Brunner and Rechberger, 2004, 2016; Müller et al., 2014) have been used widely over the past decade to characterize the anthropogenic life cycles of both substances and goods (Chen and Graedel, 2012). MFA aims at examining the anthropogenic stocks and flows of materials at each stage of their life cycle in order to gain a more complete understanding of their status above ground. Material flows and stocks can be illustrated using Sankey diagrams (Schmidt, 2008) if the number of transformation processes is small, or network visualizations (Nuss et al., 2016) for datasets involving a larger number of transformations steps and material flows between them. Understanding the whole system of material flows can help to quantify potential primary and secondary source strengths, manage metal use more wisely, and protect the environment (Brunner and Rechberger, 2004, 2016). The EC has recently published MFAs for the EU-28 (28 member states which comprise the European Union (EU)) for 28 materials (referred to as Material System Analysis (MSA) studies in the report by (BIO by Deloitte, 2015)) and a EU MFA data platform is currently in development in the Raw Materials Information System hosted at the EC Joint Research Centre (Manfredi et al., 2017).

The anthropogenic cycles of elements are embedded into their larger natural biogeochemical cycles (*natural cycles of the elements*) (Schlesinger, 2005) which describe, e.g., the exchanges of the anthroposphere (often also referred to as the "technosphere") with the environment and subsequent transport, fate, and accumulation of elements in nature. Natural cycles include natural element flows, e.g., due to riverine flux to oceans, eolian dust, seaspray, net primary productivity (NPP), extraterrestrial matter, volcanoes, and soil erosion (Sen and Peucker-Ehrenbrink, 2012). The characterization of elemental cycles has a rich history in biogeochemistry. Famous examples include the global carbon cycle, or the cycles of the 'grand nutrients' nitrogen, phosphorus, and sulfur. Knowledge of natural cycles has evolved over many decades as new sinks and sources have been discovered and missing flows between reservoirs have been quantified. For example, the current COST action TD1407 "Network on technology-critical elements (TCEs): From Environmental Processes to Human Health Threats" funded under the EU Framework Programme Horizon 2020 attempts to expand the knowledge-base on the natural cycling of technology-critical elements (TCEs) (i.e., platinum group elements (PGEs), rare earth elements (REEs), Nb, Ta, Ga, Ge, In, Tl, Te) (Cobelo-García et al., 2015). It also aims to create a network of scientists working and interested on TCEs with the aim of defining the current state of knowledge and gaps, proposing priority research lines/activities, and acting as a platform for new collaborations and joint research projects.

However, to date both biogeochemical cycles and MFA studies suffer from narrow system boundaries, failing to fully illustrate the interlinkages between natural and anthropogenic cycles, relative anthropogenic and natural flow magnitude (Rauch and Graedel, 2007; Rauch and Pacyna, 2009; White and Hemond, 2012), and the degree to which human activity has perturbed the natural cycling of elements (Klee and Graedel, 2004; Rauch and Pacyna, 2009; Sen and Peucker-Ehrenbrink, 2012). For example, while MFA studies indicate the amounts of an element released from the anthroposphere into the environment (flows crossing the system boundary), the subsequent transport and fate, and possible accumulation in the environment are often poorly studied. Given that increasing amounts of TCEs are today transported and accumulated in man-made technological systems, knowledge about anticipated future exchanges is also of importance accounting for material end-use patterns in modern technologies and

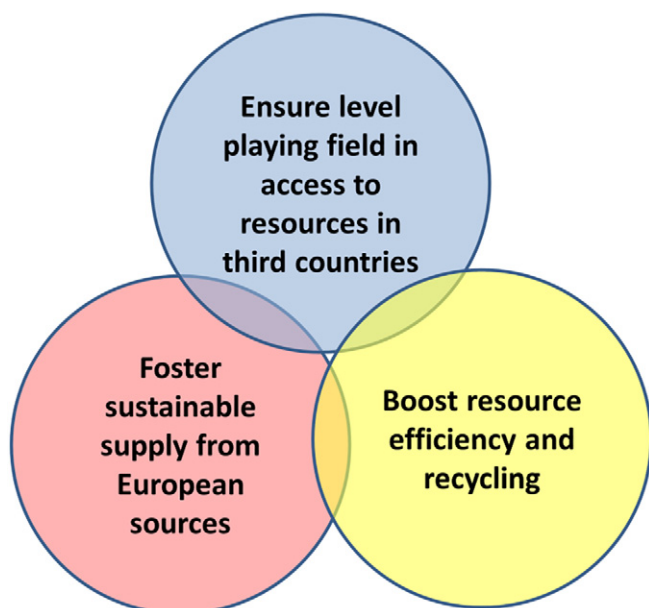


Fig. 1. The three pillars of the EU Raw Materials Initiative (RMI).

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