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A framework for the evaluation of anthropogenic resources: the case study of phosphorus stocks in Austria

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A B S T R A C T

Due to a predicted shortage of raw materials, increasing attention is drawn to the utilization of anthropogenic resources through recycling and urban mining. However, in order to assess the availability of anthropogenic resources as potential raw materials, a consistent concept for categorizing anthropogenic materials into reserves, resources and other occurrences is needed. This study presents a framework for the evaluation of anthropogenic resources, derived from the standard procedure for resource and reserve identification, evaluation, and classification of the U.S. Geological Survey for natural stock resources. The framework was applied to a case study on phosphorus (P) stocks in Austria. Results indicate that only 10% of the anthropogenic P stocks in Austria (one million tons in total) are extractable at subeconomic levels with production costs 5–10 times above the market price for P fertilizer. 70% of P stocks are not technically extractable and 20% of such a low grade that recovery is not practically feasible. Based on the assessment, it is found that the extractable amount of P could have been much higher if P-rich materials were not mixed with low-grade materials during landfilling. Although the evaluation of anthropogenic P stocks in Austria was performed on a screening level, the application of the framework highlights that a consistent method for the evaluation of anthropogenic resources can provide a basis for enhanced utilization of anthropogenic resources. In future, further case studies are needed to demonstrate the application of the evaluation framework for various resources and in consideration of environmental, technological, and societal factors.

1. Introduction

The increase in resource consumption recorded during the last two centuries led to policy initiatives, such as the European Commissions' resource strategy and the United Nations Environment Programme (UNEP) International Resource Panel (EC, 2011; UNEP, 2013). Moreover, numerous concepts have been designed to overcome the predicted resource shortage, such as the propagation of increased material efficiency (Allwood et al., 2011), sufficiency instead of material-consuming economic growth (Princen, 2003), and waste recycling, urban mining and similar waste-related concepts (Cossu, 2013; Tchobanoglous and Kreith, 2002). Material efficiency and sufficiency address a reduced input of *natural resources* into the anthropogenic system, while the waste-related concepts focus on output materials from anthropogenic utilization, called *anthropogenic resources*.

In modern history, various meanings have been assigned to the term *resource*. Generally, *resources* are the means a subject uses to meet and feed its needs. Thereby, *natural resources* are transformed by the resources of capital and labor (Smith 1776). Before industrialization, in most of the then-agrarian societies, agricultural land and inputs were the most important *natural resources*. Industrialization shifted the focus to other *raw materials*, such as fossil fuels and minerals.

Until the 1940s, scientific and political discussions as well as actual practices in Europe and the U.S., considered not only *natural* but also *anthropogenic resources*, such as wastes. The latter, in particular, was observed from the perspective of limited technologies and access to markets of natural resources (Klinglmair and Fellner, 2010; Strasser, 1999). As soon as technology and a new stage of economic globalization began in the 1950s, the discussion about *anthropogenic resources* temporarily declined, until it recurred in the 1970s (Strasser, 1999). Then, research not only

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detected environmental pollution, a waste of materials, and a predicted shortage of raw materials (Boulding, 1966; Georgescu-Roegen, 1971; Meadows et al., 1972) but also found that for some materials, industrial production and consumption had built up significant anthropogenic material stocks which, for some materials (e.g., metals), may be on the same order of magnitude as natural stock reserves (see Fig. 1) (Kapur and Graedel, 2006; Klee and Graedel, 2004). Consequently, to date, approximately 30% of the copper consumed in Europe originates from secondary resources, and almost 70% of the US demand for iron and steel is met by scrap recycling (Rechberger and Graedel, 2002; US Geological Survey, 2009). These findings led to the consideration of the anthropogenic stock as an *urban mine* for *secondary raw materials* (Jacobs, 1969; Munro, 1984; Wittmer et al., 2003).

Notwithstanding the fact that information about the magnitude of stocks is a minimum requirement to evaluate the resource potential of the anthropogenic stock, a consistent concept to assess the availability of these stocks as potential raw materials is needed. In view of the lack of concept for evaluating anthropogenic resources, Johansson et al. (2013) note that existing "mining concepts fail to help us navigate reliably in the complex technosphere, since they are disorganized, […], and a clear categorization has not yet taken form". Therefore they suggest to categorize anthropogenic stocks first based on their location in the anthroposphere (in their words *technosphere*), and second due to the mining concept that can be applied in order to extract secondary raw materials from the different stocks. Though this approach is useful in terms of organizing anthropogenic resource deposits, it does not answer the question on which part of the anthropogenic stock can be further considered for the development of an urban mining project. Consequently, an anthropogenic stock resource evaluation framework is required, as it is unlikely that the entire stock as shown in Fig. 1 is potentially available for extraction (Klinglmair and Fellner, 2010; Schneider et al., 2011).

Contrary to anthropogenic stock resources, *natural stock resources*, like fossil fuels, metals, and minerals, are in the first step usually evaluated and classified based on their actual and potential exploitability, using evaluation frameworks like the resource-reserve classification developed by the USGS (1980). The evaluation procedure therein which is based on mineralogical (occurrence, grade, size) and economical (market prices, technology) factors, as well as the subsequent classification, are widely accepted, and it is beneficial to adapt and apply concepts like this to anthropogenic stock resources rather than design new ones. However, the question arises which of these procedures can be applied to anthropogenic resources and how?

Hence, the overall-objective of this paper is to present a framework for the evaluation of *anthropogenic stock resources* based on existing *natural stock resource* evaluation procedures in order to classify anthropogenic stocks with respect to their potential exploitability based on mineralogical (occurrence, grade, size of deposit) and economic (market prices, technology) factors. By building on natural resource evaluation research it is also possible to directly compare the results of anthropogenic and natural stock resource evaluation.

In order to test the applicability and further develop an existing framework, a case study can be used. To do so, a resource of particular relevance for modern humanity is selected, namely phosphorus (P) (Elser, 2012). P is a potentially critical resource because of its relevance as a non-substitutable macronutrient, its limited natural reserves, and its non-circular use in the economy (Cordell et al., 2009; Elser and Bennett, 2011; Gilbert, 2009; Ott and Rechberger, 2012). This particular role of P induced increasing efforts to recover P from anthropogenic resources such as waste water and solid wastes (Hermann, 2009; Kalmykova and Karlfeldt Fedje, 2013; Tan and Lagerkvist, 2011). Furthermore, a recent literature review by Chowdhury et al. (2014) on the material flows of P suggests the existence of a significant built-up of anthropogenic P stocks. However, an evaluation of the resource potential of these stocks in terms of prospection, exploration, and its resource potential from a mineral economic point of view has not been carried out yet.

In order to test the applicability of the evaluation framework developed, it is applied to anthropogenic phosphorus stocks in Austria.

2. Definitions and concepts in natural and anthropogenic stock resource evaluation

The interdisciplinary use of the term *resource* in cultural, social, and environmental sciences requires a clear definition of the terms used in this work, which are presented in Section 2.1. Afterwards, some current concepts used to evaluate natural and anthropogenic stock resources are briefly described in Section 2.2.

2.1. Terminology as used in this research

2.1.1. Natural and anthropogenic resources

Natural resources are the physical material base located in the natural spheres (atmo-, bio-, hydro-, and lithosphere) intentionally transformed by *human cultural resources* (e.g., labor, technology, institutions, capital) to fulfill a specific function for human utilization (Ciriacy-Wantrup, 1944). This transformation leads to a translocation from the natural spheres to the man-made anthroposphere (Carol, 1956; Husar, 1994). As soon as a material enters

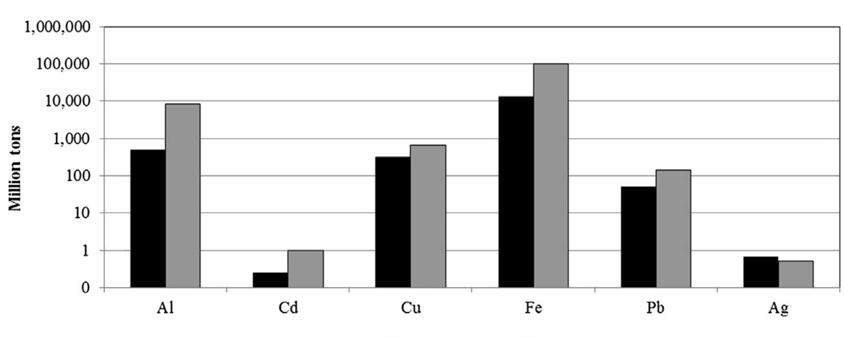

Fig. 1. Anthropogenic stock vs. reserve base including reference years (reference years for reserve base in brackets): Fe and Cd – 1985 (1996), Ag – 1991 (1996), Cu – 2000 (2000), Al – 2003 (2003) (Graedel, 2010; USGS, 1996, 2000, 2003).