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Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus?

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ABSTRACT

This paper elaborates in what way a dynamic perspective on reserves, resources and geopotential is necessary to provide robust estimates on resource availability. We introduce concepts of essentiality, criticality and economic scarcity and discuss for the case of phosphorus (P) how they are defined and may be measured. The case of P is considered in detail as P an essential element for global food security with a highly dissipative use and is geographically unevenly distributed across the globe. We distinguish and relate the complementarity between physical and economic scarcity and discuss limits and potential of static indicators such as static lifetime, Hubbert curve applications, and the Herfindahl–Hirschman-Index of P for predicting future availability of these resources. We reveal that these static indicators are – in general – not valid approaches to predict physical scarcity of resources. Geological data show that though the P reserves have not been systematically and completely assessed on a global scale, the static lifetime of P is high. When acknowledging socio-economic and technological dynamics, and available geological facts, statements predicting physical scarcity or a peak in P production within a few decades are unlikely to be accurate or valid. We elaborate that some simplified indicators such as static lifetime or the Hubbert curve based prediction of peaks may serve as screening indicators preceding early warning research, which may induce increased mining activities, technology innovation or other actions. However, in general, these simplified indicators are not valid approaches to predict physical scarcity of resources. Although one day there may be a supply-driven P production peak, demand-driven production plateaus and multiple peaks are probable in the near future. Given its geopotential, essentiality, and the learning curve of efficient fertilizer use, P is subject to demand-driven market dynamics. Thus, a symmetric decline and unavoidable shortage of P in the next decades are unlikely. This insight does not refute the need to close the anthropogenic P loop. Activities associated with P production and consumption use has a significant pollution potential in part because of the dissipative nature. The paper reveals the necessity to mitigate risks (such as economic scarcity, especially for poor farmers) of both short-term price peaks and longer lasting step-changes in price, e.g. due to knowledge gaps of technological adaptation in energy and water management or other reasons of insufficient supply-demand dynamics management. The complexity of this task necessitates a transdisciplinary approach.

1. Introduction

This paper deals with some fundamental questions of future availability, scarcity and a new term, *criticality*. The focus will be on phosphorus (P), *peak* P and the *lifetime of* P, with relation to the current discussion on scarcity and the history of resources management.

P, the 13th most abundant element of the Earth's crust on the periodic table, is a very reactive and dissipative element (Binder, 1999). It is an interesting case as it is non-substitutable for virtually all living organisms. Thus there is no substitute within food production. *Rock phosphate* (RP) *deposits* from which P is extracted are non-renewable on a human time scale. But – naturally – P *atoms* are not disappearing but are transferred from the rock formation to other compartments making them theoretically accessible, however perhaps at unacceptable costs necessitating critical sacrifices (Brobst, 1979; Skinner, 1979).

When referring to mineral economics this paper reveals that simplified concepts such as *static life* time or a prediction of a (maximum possible production) *peak* P based on *Hubbert curve* (Cordell et al., 2009; Déry and Anderson, 2007) are not appropriate for predicting the future availability of P. Arguments for this have

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been recently provided by Mew (2011) and Vaccari and Strigul (2011). This paper substantiates this view from two perspectives. First by taking a historic resource economics perspective (see Tilton, 2003) while introducing a dynamic view on the multiple geological, socio-economic and technological dynamics that are involved in resource exploitation. Second, we refer to standard geological knowledge and data (Hein, 2004a)

1.1. The emergence of criticality studies and phosphorus

Despite of concerns on limits of supply in the 1970s, in the 1980s and 1990s, the prevalent opinion in industry and among many economists was that raw materials would always be readily available on world markets. This tide turned at the beginning of the 21st century when *commodity prices reached levels never seen before* (see Humphreys, 2010) resulting from an increasing demand by heavily populated developing nations. China consumed 8.2% of the worldwide steel in 1990, but today consumes nearly 45% and is now the leading consumer for every major commodity with the exception of crude oil and natural gas (Brown, 2005).

The price increases starting in 2002 made industry, politicians and governments aware of the vulnerabilities of raw material supply and *supply shortage*, especially from foreign sources. *Criticality studies* were commissioned by governments even at the state level (see VBW, 2009), the EU, and the Organisation for Economic Co-operation and Development (OECD). Only two of these studies list P as a critical element (see also Erdmann and Graedel, 2011). One German study (IWD, 2010) considers P as the 6th most critical element after yttrium, neodymium, cobalt, scandium and tungsten, and more critical than e.g. niobium, the platinum group elements, germanium, or indium. The aspect of criticality here is P's role as a nutrient. The second study considering phosphorous as critical is the one from the US Department of Energy "Critical Materials Strategy" (US Department of Energy, 2010). Here not P's major use as a fertilizer but as an important element to increase lighting efficiency and thereby saving energy is mentioned. Today on a global level; only 8% of P is consumed in industrial applications, about 82% in fertilizers and 18% in non-fertilizers, of which feed phosphates make 7%, 3% chemical derivatives from elemental phosphorus P_4 and 8% chemical, pharmaceutical, industrial, etc. uses (Prud'homme, 2010).

1.2. Essentiality, criticality and scarcity

If the need for a specific natural resource is analyzed in detail, it must be concluded that it is not the specific metal or raw material that is most important, but the *function* provided by an intrinsic property of the material or commodity (Wellmer, 2008). Taking copper as an example, the electrical conductivity is the intrinsic *function* that makes copper industrially most useful. However, from an efficacy perspective, other commodities can perform the same functions just as well, often in conjunction with fundamentally different technologies. For finding solutions to fulfil functions there are three resource domains available: the resources of the *geosphere* (i.e. primary raw materials), *technosphere* (e.g. secondary raw materials), and *socio-epistemic* sphere (Scholz, 2011). The latter is *human creativity and inventiveness* (McKelvey, 1972). Non-energy raw materials are not consumed but only transferred from the geosphere to the techno- and ecosphere wherein they may ultimately dissipate. Fertilizer elements however, as shown for phosphorous by Dumas et al. (2011), have the advantage that via the plant growth route they can be concentrated again from a dissipated state once a certain threshold level in soils is exceeded.

1.2.1. Essentiality

Essential elements of a process or system are not substitutable. *Bio-essential elements* which are indispensably involved in any organism metabolism or enzyme activation are essential elements for food production and thus for life. Essential nutritional elements are: nitrogen (N), P, and potassium (K), and the micronutrient elements calcium, sodium, magnesium, sulphur, boron, chlorine, iron, manganese, zinc, copper, molybdenum, nickel, cobalt, and selenium. There are also *beneficial* elements that support plant biomass growth but are not really necessary for life (Arnon and Stout, 1939).

Micronutrients are present everywhere though in varying amounts: as trace elements in soils and rocks, or abundant in seawater, like magnesium and boron. On the contrary, the major nutritional elements P, N and K have to be concentrated by nature or technical processes. Therefore, their future availability has to be critically examined. For N and K future availability is not a real problem because the atmosphere is an inexhaustible source of N and K which is about 20 times as much available as P. P, however, is a different case as there is no ample abundance and it has a highly dissipative nature due to soil erosion, run-off, manure and waste water discharges

1.2.2. Criticality

Criticality defines the supply risks for elements whose shortage may endanger the functioning of technology, infrastructure, or the basis for a productive society. The supply risk may be related to "the political-economic stability of the producing countries, the level of concentration of production, the potential for substitution and the recycling rate" and the endangered supply by environmental means "taken by countries with weak environmental performance" (European Union (EU), 2010, p. 5). In a 2008 study, for example, the US National Research Council (National Research Council (NRC), 2008) established a two-dimensional criticality matrix between *supply risk* and *impact of supply restrictions* and defined a "critical zone" within the matrix. As the indicators are static, the assessment typically provides a snapshot of the criticality of a certain material at one point in time. The limited value of these indicators is seen by comparing recent studies with those from thirty years ago. In the 1970s, most studies (e.g. BGR et al., 1977) listed chromium as the most critical raw material. Today the EU does not list chromium as a critical metal at all (European Union (EU), 2010) and of six criticality studies examined by Erdmann and Graedel (2011) only two included chromium.

The distinction between essentiality and criticality is evident with energy. Energy is *essential* for any working organism and the functioning of the society. The lack of primary energy resources, such as uranium may be considered *critical* from the perspective of managing society. However energy carriers are substitutable. Via electricity all functions of energy, heat, motion, light and power can be fulfilled by every energy source. Far more critical are other metallic and non-metallic elements for the production of energy, e.g. super alloys for high temperature resistant turbine blades or indium for the production of solar cells. This is why the US Department of Energy composed a strategy for coping with critical elements including indium and lithium (US Department of Energy, 2010).

1.2.3. Scarcity

There are different notions of scarcity of natural resources. Skinner (1979) provides a purely physical definition: an element is *geochemically scarce*, if the average abundance in the Earth's crust lies below 0.01 weight-percent (i.e. about the abundance of copper). This definition is an "objective" measurement, *independent* from its functionality and societal demand, and is thus unsuitable for the economic use of elements. *Rare earth elements*