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Physical, technical, and economic accessibility of resources and reserves need to be distinguished by grade: Application to the case of phosphorus

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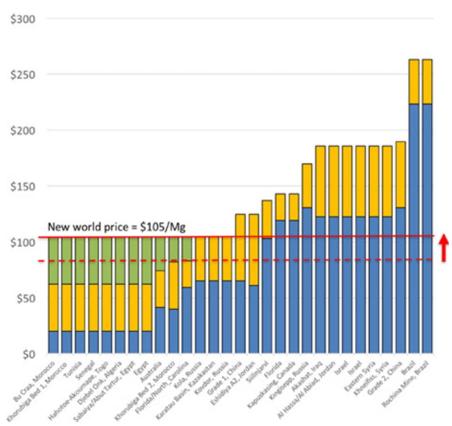
HIGHLIGHTS

- An input-output framework systematizes the physical, technical, and economic availability of resource stocks and flows
- Global phosphate ore resources are distinguished from produced phosphorus concentrate
- Global potential reserves with existing technologies are a fraction of known resources
- Four illustrative scenarios show how reserves can vary with technical and economic changes
- Improved data reporting and additional scenario analysis will enhance sustainable phosphorus knowledge

GRAPHICAL ABSTRACT



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ABSTRACT

The amount of phosphorus in the total environment is finite, yet recent estimates suggest that more than enough phosphate ore resources exist in the lithosphere to meet future increases in demand during the next century. Still, it remains unclear how the accessibility of this resource stock – which is heterogeneous in terms of grade and location – will change as currently accessible resources are utilized, as extraction and processing technologies develop, and as the relative economic costs vary. This study uses an economic framework, the World Trade Model with Rectangular Choice-of-Technology, to link estimates of known geological resources of various grades with the technically and economically accessible reserves. Using the most recent public data on phosphate ore stocks and mining and technological capacity, this study estimates that the ~400,000 teragrams (Tg) of known apatite ore (>1% P_2O_5 content) equate to ~110,000 Tg when converted to potential reserves (~30% P_2O_5) using existing technologies, with over half of these remaining potential reserves converted from resources with grades below 20% P_2O_5. Corresponding global reserves are estimated at ~70,000 Tg using the Rectangular Choice-of-Technology model, but since any reserve estimate is contingent on the state of the world economy, a set of five illustrative scenarios are constructed to show how this estimate can vary between ~67,000 and ~98,000 Tg with only a small number of changes to the economic and technical parameters and variables. Calculating accessibility using consistent definitions for resources and reserves while distinguishing between grades not only creates a clearer picture of remaining non-renewable resources, but creates a framework that can be used to explore future geopolitical scenarios about ore availability, extraction technologies, supply networks, and global commodity prices.

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1. Introduction

Estimates of identified phosphate ore reserves suggest that more than enough is accessible to meet future increases in demand during the next century (Brinck, 1977; Van Kauwenbergh, 2010). At the same time, the future availability of these stocks may be constrained by various factors, among which include the quality and location of phosphate ore, availability of extraction and processing technologies, and the stability global sourcing networks (Brinck, 1977; Cordell, 2013). The temporary yet substantial price increase of phosphate concentrate in 2008, as well as in 1975, is an example of how both physical and economic characteristics of phosphate ore producers can influence fertilizer prices and indirectly impact food prices and create food insecurity (Weber et al., 2014; Mew, 2016).

These seemingly conflicting assessments of plenty and scarcity result from different postulations regarding the potential extraction of phosphate rock resources. Conceptually, geologists distinguish resources and reserves, the former representing "a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible" and the later representing the amount that "could be economically extracted or produced at the time of determination" (U.S. Geological Survey, 2016). Phosphorus can hence be both economically scarce (low reserves) and/or physically scarce (low resources).

Geologists have determined that phosphorus is not physically scarce. Phosphorus is a relatively abundant element and makes up 0.1% of the Earth's lithosphere (Brinck, 1977; Carpenter and Bennett, 2011) and is actually present, albeit in relatively small amounts, in most rocks (McKelvey, 1973; Smil, 2000). This mass of this phosphorus is more than eight orders of magnitude larger than the amount extracted annually by the phosphate mining industry. With abundant resources and technological knowledge, all concentrations of phosphorus in the lithosphere could potentially become resources. Consider a phosphorus ore that is transformed into fertilizer and runs off into the ocean: the phosphorus does not disappear, and it could be harvested from the hydrosphere to be used once again.

Yet whether phosphorus is economically scarce – meaning that the known phosphorus is too difficult to obtain in a concentrated and useable form – is much more difficult to determine since it depends on both the physical characteristics of each "deposit" and the accessible technologies and economic resources for extracting and processing certain types of ores (McKelvey, 1974; Scholz et al., 2013). For instance, although occurring in almost every type of rock, concentrations of P are on average only 0.07% to 0.18% in sandstone, shale, and carbonates and 0.01% to 0.07% in igneous and metamorphic rocks (McKelvey, 1973; Slansky, 1986). Compare this to the 14% P occurring in high-grade phosphate ores or even the 4% in currently mined lower-grades (Van Kauwenbergh, 2010). Such low grade "occurrences", as they are termed by the USGS (2016), make up the majority of P (<99%) in the lithosphere (Smil, 2000) and are not considered resources.

As relatively accessible deposits are consumed and become physically depleted over time, there is nothing assuring new technologies exploiting less accessible resources will not be drastically more expensive. Even if an ore exists in high concentration, it may exist in places or formations that are hard to access or contain potentially harmful levels of contaminants such as cadmium and uranium that must also be removed (Vaccari, 2009; Scholz and Wellmer, 2013). The input costs required for extraction and processing (energy, labor, capital, water) as well as the existing variables and parameters in the global economy (infrastructure development, transport costs, taxes, access to processing facilities, interest rates and exchange rates) all impact the ability to produce a concentrated amount of usable phosphorus, and these factors can vary widely from deposit to deposit, region to region (Fantel et al., 1985; Steen, 1998; Van Vuuren et al., 2010; Weber et al., 2014; Mew, 2016). Hence, the economic role of technologies becomes a defining factor of overcoming the depletion of currently accessible resources and utilizing less accessible concentrations (Scholz and Wellmer, 2016).

The scarcity of relatively high quality, accessible phosphate ores could potentially disrupt the global economy and exacerbate such problems as food insecurity in vulnerable regions (U.S. General Accounting Office, 1979; Fantel et al., 1985). For instance, before the extraction of phosphate ore from mineral apatite expanded in the late 19th century, the industry began utilizing guano deposits from places like Peru, which had a relatively high soluble N and P content (~11% P_2O_5) compared to alternatives at the time (Mathew, 1970). Unfortunately, these deposits were limited and, as they became scarcer due to exploding global demand, prices rose, stimulating the geographical and technological discoveries that allowed the exploitation of higher grade apatite ores and guano deposits (Scholz and Wellmer, 2013; Ulrich and Frossard, 2014). Yet decades later, some of these high-grade resources also became depleted, such as the guano deposits in Nauru (~39% P_2O_5), collapsing regional economies that depended upon the resource rents (McDaniel and Gowdy, 2000).

Historically, these technological developments stimulated by past price increases have cost-effectively avoided economic scarcity of phosphorus at the global scale. Periods of concern about scarcity have been followed by periods of discovery of new ore types and technologies for accessing and using them, leading to a counter-intuitive expansion of global P reserves over the past century (Ulrich and Frossard, 2014). In fact, newly accessible resources replacing depleted reserves may even be at higher grades, as was the case globally for phosphate ore mined between 1983 and the present (Steiner et al., 2015), showing that economic accessibility of ore is not necessarily correlated with grade. Such trends are consistent with conventional economic and mining theory on non-renewable resources (Hotelling, 1931; Lasky, 1945), which show that resource constraints are short-term due to price incentives and technological innovation that expand reserves and resources, the long-term trend of technological capacity overcoming short-term scarcity.

These two countervailing forces of resource accessibility and technological development must be clearly represented in order to explicitly and transparently estimate the amount of phosphate reserves from data on known resources at different grades. Yet, as pointed out by others, data sources often use different vocabulary and criteria for distinguishing reserves from resources, and often the key economic variables and parameters that distinguish reserves from resources are not made explicit (Emigh, 1973; Van Kauwenbergh, 2010; Ulrich and Frossard, 2014; Edixhoven et al., 2014; Mew, 2015; Scholz and Wellmer, 2016). In particular, the assumed costs and technologies used to distinguish reserves from other categories such as the reserve base and additional resources are often arbitrary and unclear, particularly when defining categories such as currently, marginally, and subeconomic (U.S. Geological Survey, 2016).

The purpose of this paper is to present an economic framework that distinguishes economic reserves from physical resources using an explicit representation of both resources by grade and technologies for extracting them. The method proposed here uses a global economic model of the world economy, the World Trade Model (Duchin, 2005; Duchin and Levine, 2011), to further clarify the differences between such concepts by linking different grades of phosphate resources with potential technologies for converting them into processed ore. These relationships are then used to derive comparable estimates of lithospheric resources and reserves for different regions and grades, with five illustrative scenarios showing how these estimates can vary greatly given a small number of parameter changes. This approach provides a framework for improved data reporting and consistency, leading to further improvements in future phosphate reserves and price estimations. For instance, data provided in this fashion can be used to test scenarios that estimate phosphorus availability given any number of future pathways, illustrating how much it may cost in the future to extract the