Cycling and Anthropogenic Use of Phosphorus in the 21st Century: Geoscientific and Geosocial Foundations of Agriculture

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From 1900 to 2010, the global population grew by a factor of 4.2, and total material extraction per person increased by a factor of 2.6 (Haas et al., 2015). Annual mineral P consumption has increased by a factor of 10 since 1950 (Jasinski, 2018; Ruhlman and Tucker, 1952). Given that terrestrial high-grade phosphate mines are limited and that the U.S. Geological Survey (USGS) judges the recycling of P in the U.S., for example, as "none," an understanding of this essential mineral's availability and cycles may become a critical factor for a viable planet. The annual global mining of mineral P, yielding approximately 34 million t (Mt) P/yr, far exceeds the estimated natural annual P input by weathering of 20 Mt P/yr (Ruttenberg, 2003). As expressed by the term 'Anthropocene' (Crutzen, 2002), humankind has also become a geological factor. This is especially true for the nutrient cycle.

Where Do We Find Phosphorus?

Of the known P resources, 95% are sedimentary and 5% are igneous phosphate rock deposits (Jasinski, 2018). However, even sedimentary phosphorite originates ultimately from igneous phosphorite deposits. Earth formed approximately 4.5 billion years ago. Carbonatites and silica-deficient alkali intrusions from Earth's mantle are particularly rich in P, but P is ubiquitous since all igneous rocks (and other types) have minor amounts. In the 10 miles of Earth's crust, P is the 11th most abundant element, with a mass of 1,120 ppm, thereby accounting for 0.1% (Binder, 1999). The concentration of average phosphate rock mined in 2013 shows a P concentration of 8% (Steiner et al., 2015).

Geological Phosphorus Cycling

During the passage of geologic time, P has continued to reach Earth's surface as part of the erosional process of the continental crust. It is delivered to oceans via river water in both dissolved and particulate form (Filippelli, 2008; Pufahl and Groat, 2017).

Every ore formation requires an enrichment process. For P in the sedimentary environment, enrichment occurs via dissolved and reactive P in the marine biogenic cycle. In contrast, more than half of the P flux to oceans is in the form of non-reactive particulate-bound P (i.e., grains of insoluble phosphate minerals), and is sedimented as an accessory component on continental margins or in the deep sea. Both marine-biogenic and marine-detrital phosphate may be subducted under the continental crust. In this way,

it becomes part of the rock cycle from erosion via deposition and deep burial to melting, intrusion, and uplift to erosion again. The amount of time required for the cycle is difficult to estimate and varies widely, but it is on the order of 100 to 1,000 million years. The average age of rock in the continental crust is estimated to be 650 million years (Skinner et al., 2013), and the estimated presence of phosphate in sedimentary rocks is on the order of 100 million years (Schlesinger, 1991).

Similar to metal deposits, the formation of phosphate deposits is essentially a consequence of the rock cycle. Yet, for the formation of phosphate deposits in the sedimentary environment, the interaction between the hydrosphere and the biosphere is of particular importance. Here, the interactions of reactive P with the marine biosphere are an essential element for the formation of exploitable deposits.

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Biological productivity critically depends on P that is fixed in the near surface (photic) zone by phytoplankton during photosynthesis as a vital component of the photosystems and their cells. Once incorporated into organisms, P follows the organic matter loop, undergoing active recycling in the water column and at the sediment/water interface. As a consequence, there is a nutrient profile in the ocean for dissolved P with surface depletion and enrichment at depth. The largest economic phosphate deposits have accumulat-

SUMMARY
The global P cycle is considered from the perspective of geologic and historic timescales to help in the understanding of whether and when fundamental changes in agricultural practices for sustainable P may be needed.

Mining phosphate rock in Morocco.

ed on continental shelves and in epeiric seas, where P-rich deep-bottom waters have been returned to the surface via coastal upwelling (Pufahl and Groat, 2017). Sustained productivity, accumulation, and decay of sedimentary organic material in this environment fuel the precipitation of apatite. In "phosphorite factories" (Pufahl and Groat, 2017) under certain physicochemical conditions, phosphate-saturated pore waters develop. These effectively transport phosphate toward the sediment/water interface, leading—under favorable conditions—to enrichment as apatite grains and nodules. The products of the "phosphorite factories" can be hydraulically and biologically reworked to create high-grade deposits. Under optimal physicochemical, hydrological, biological, and sedimentological conditions that persist for a longer period of time, giant deposits can form, such as the Permian Phosphoria Formation, the Western Phosphate Fields in the U.S., or the Late Cretaceous/Eocene South Tethyan Phosphate Province in North Africa and the Middle East, the single-largest P accumulation on Earth.

Such biogenic phosphate-enrichment cycles are much shorter than the rock cycle. The mean residence time of phosphate in the ocean pool is on the order of ~15,000 years (Filippelli, 2002), and the total residence time for phosphate in the sea is estimated to be between 4,000 and 80,000 years, depending on input as dissolved or particulate P (Froelich et al., 1982). As a result, there are very young deposits and occurrences even in the Holocene, such as those in Australia, offshore in Baja California Peninsula, Mexico; North Carolina in the U.S.; and offshore in East Africa. The youngest reported occurrence lies offshore of Baja California, Mexico, with an age between 10,000 and 20,000 years (Chernoff and Orris, 2002). Thus, the geologic scale meets the historic scale.

No (Physical) Short- and Medium-term Supply Security Risks

According to the USGS (Jasinski, 2018), the most authoritative database, there are reserves of 70 billion metric tons (Bt) of marketable phosphate rock (PR-M) with a P concentration 13.1% P (30% P_2O_5) and resources of 300 Bt PR-Ore. Global production in 2017 was 34 Mt P/yr (with more than 90% going toward food production). Standard-

ized against production of phosphate rock (263 Mt PR-M; Geissler et al., 2018), the reserve/production ratio may be viewed as an early warning indicator (Scholz and Wellmer, 2013); yet it is about 266, which is one of the largest among all mineral commodities.

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These reserve data have been questioned at various times because of Morocco's high amounts of reserves of (50 Bt), which comprise 71% of the total reserves. These reserve data have also been interactively and scientifically discussed (e.g., Edixhoven et al., 2014; Scholz and Wellmer, 2016). Mew, an independent consultant and one of the world's most knowledgeable phosphate rock experts, endorsed the high reserve figures (Mew, 2015).

Phosphorus is a low-cost commodity; each world citizen consumes 30 kg PR-M/yr at a cost of 3 to 6 US$. The global GDP per capita amounted to more than US$10,715 in 2017 (The World Bank, 2018). Thus, a global price increase for phosphate rock—though certainly highly critical for some developing countries—would not endanger the global food supply. Yet, as the amount of mined phosphate rock increases (non-linearly) with lower ore grades, a rise in price would increase reserves significantly. This is in line with the findings of Pufahl and Groat (2017). In their fundamental investigation, they state: *"Collectively, the discovery of new phosphorite deposits and development of more efficient processing of phosphate ores plus new technologies to effectively recycle P will allow Earth's burgeoning population to feed itself."*

No Cycles and No Circular Economy in Anthropogenic P Cycles Thus Far

Historically, nutrient management has shown a broad range of technologies, ranging from slash and burn to balanced forms of nutrient management. The 1911 book *Farmers of Forty Centuries: Organic Farming in China, Korea and Japan* by anthropologist F.H. King describes in detail the steps taken to manage local and regional nutrient cycles. Fertilizer management can be traced back at least 3,000 years (Wilkinson, 1982), and manure has been "religiously saved and applied to the fields" when being "dried and pulverized" (King, 1911/2004, p.8). But agriculture took on a new quality with Sir John Bennet Lawes' patenting of superphosphate by solubilizing the P in bones using sulfuric acid in 1842 and the Haber–Bosch industrial N fixation process patented in 1908 (Bosch, 1908). Fertilizers became physically (practically) available in unlimited amounts. Technology further enabled large-scale farming and economically effi-

cient large-scale animal production. Agricultural production became spatially separated from places of residence, and as a result, sewage and food waste were incinerated or deposited in landfills, rupturing the nutrient-related P cycle.

The current global P cycle is characterized by large *losses* and a very low *total-use efficiency*, but obtaining a reliable view of these is not that easy. When we focus on agricultural uses only, we have to acknowledge that, globally, half the nutrients come from mineral fertilizers (Erisman et al., 2008; Stewart et al., 2005). Thus, roughly about half of P in food is supposed to come from weathered P and the other half from mineral fertilizers. If we figure out the total nutrient efficiency as the ratio of the intake of P (globally across all people around 1.0 g P/d, see Olza et al., 2017; Scholz et al., 2014) to the amount of phosphate rock moved by economic activity, there are huge losses along the value chain. If we consider that 30 to 50% of the PR moved from the mines is lost from the current value chain, the annual production (consumption) of 260 Mt PR-M originates from a magnitude of 520 to 880 Mt PR-M/yr that is economically moved (Steiner et al., 2015). This provides a *total nutrient use efficiency* (P-NUE) along the supply chain for mineral P (if we take 90% of the PR dedicated for food use) of 2 to 4%. Note that this estimate of a magnitude below 5% does not incorporate naturally available weathered P. The estimate of total P efficiency is remarkably low and calls for serious thinking about the reasons (for a detailed discussion see Scholz and Wellmer, 2015b).

One of the reasons for the low *total P use efficiency* is stock-building in the soil. The agricultural P-NUE can be defined by the ratio of the quantity of P removed in harvested product divided by the organic and mineral P-fertilizer input. The global perennial, long-term P-NUE is estimated to be 44% (Sattari et al., 2012). Thus, more than half of the input of P fertilizer is lost from the agro-nutrient chain, and future global agriculture has to target a P-NUE far above 50%. Stock-building in soil, as well as erosion, runoff (in particular in extreme locations and related to weather events), leaching (in some sandy soils), and presumably insufficient manure management are major factors of these losses. Phosphorus becomes a pollutant if large amounts are (anthropogenically) distributed to aquatic environmental systems. Yet the estimate of anthropogenic input to freshwater systems alone is highly uncertain and varies, actually, by a factor of ten, roughly in the range of 2 to 20 Mt P/yr (see Mekonnen and Hoekstra, 2018; Penuelas et al., 2013), whereas higher estimates seem to show higher plausibility. In addition, inefficient economic overfertilization of 30 kg P/ha and more in some countries contributes to the large losses and low efficiency and calls for proper economic instruments (Scholz and Geissler, 2018).

The exceptional global *total nutrient efficiency* for mineral fertilizer of below 5% can be improved by recycling, as less phosphate rock must be mined. This suggests that increasing P recycling at all stages of the supply chain and improving use efficiency are musts. Here, as well, following the rules of good agriculture as described by two 4R conceptual frameworks (i.e., reduction, reuse, recycling, and recovery; right source, right rate, right time, right place) and developing missing strategies for soil test-based fertilization in the developing world also may help (Njoroge et al., 2015). However, we must also put more effective recycling of P from food waste, animal carcasses, sewage, and other organic wastes (Ohtake and Tsuneda, 2019; Scholz and Wellmer, 2015a, 2015b) at the top of the agenda for resource management if we want to maintain a long-term economic P supply (Ohtake and Tsuneda, 2019; Scholz and Wellmer, 2015a, 2015b).

Conclusions

Long-term P supply security requires an understanding of both the characteristics and dynamics of geologic and anthropogenic P cycles. Given the knowledge about the dynamics of igneous and sedimentary rock phosphate reserves and resources and given undisturbed markets, there will be no P-supply shortage in the near- and mid-term future (i.e., in the order of 1,000 years). This also holds true for future demands on decadmiation and deradionuclidation (as phosphate rock is a low-cost commodity that demonstrates elasticity with respect to quantity and quality).

The total phosphate (nutrient) efficiency is below 5% and thus exceptionally low. The anthropogenic recycling-based P nutrient cycle has been broken by urbanization, large-scale industrialized agriculture, and the absence of new recycling schemes for organic waste. New anthropogenic P (re)cycling schemes have to be created in order to reduce losses and to secure a mineral P supply in the long-term future (i.e., in the order of 5,000 years). The global losses of P in agricultural production are still very large. Even considering the high use efficiency for perennial crops, the average global P-NUE is low and can—given the rules of good agriculture—be improved. Likewise, effective and efficient recycling schemes after fork are missing in most parts of the world. There is evidence that, for many problems, not only continuous gradual change but also fundamental technology innovation is required.

If our aims are long-term supply security and intergenerational justice, these issues must be at the forefront of resource management strategies. **BC**

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