Balancing the Global Distribution of Phosphorus With a View Toward Sustainability and Equity

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Abstract

Limitations in the geological reserves of phosphate rock, the source of fertilizer phosphorus, are not currently considered in agricultural practices or global trade, a very short-sighted approach considering that there is no “alternative fuel” for plant growth. Thus, it is important to understand the science of phosphorus-crop growth dynamics as a function of grain type, plant uptake, climate, and past fertilizer phosphorus application history. Recent work on modeling these factors on the global scale (Kvakić et al., 2018) provides the first scientific backdrop for developing an understanding of fertilizer phosphorus balances, and for informing forward-looking practices and policies that regulate toward long-term sustainability rather than short-term profit.

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Introduction

Feeding 7.3 billion humans equitably and adequately is challenging enough—feeding 10 billion humans in 2050 while our crops begin to experience substantial fertilizer limitations might simply be too much. Although much work is underway to either engineer the crop or engineer the system—the so-called "Wizard vs. Prophet" model describing crop scientist Norman Borlaug versus environmentalist William Vogt (Mann, 2018)—the reality is that the key linchpin to the entire food system relies on one element, and one element only, that is in vanishingly short supply. That element, phosphorus (P), is present in only minute quantities in rocks on Earth (0.09 wt%), and once P is liberated from minerals during weathering it is quickly sequestered in a number of more recalcitrant phases, limiting its day-to-day accessibility to plants and organisms. Sure, the fertilizers that fueled the "Green Revolution" contain nitrogen and potassium as well, but the former is plentiful from our atmosphere and the latter similarly plentiful in evaporite deposits. Unlike energy, which has many alternatives for production outside of the one (fossil fuel) that has dominated the globe over the past century, there is no Plan B for P (e.g., Filippelli, 2008). It is the ultimate speed limit to our global food systems (Cordell et al., 2009), and hence our global societal structure.

A paper published here by Kvakić et al. (2018) provides for the first time a roadmap toward understanding the global distribution of P fertilizer application plus a crop-specific uptake model tied to climate. This work follows closely on previous work by some of these authors on phosphorus model development (Ringeval et al., 2017) and a backdrop of global fertilizer P distribution studies (e.g., Bennett et al., 2001; Smil, 2000; MacDonald, et al., 2011) that have advanced the field to the point where science-based controls can be placed on human choices (crop cover and type, fertilizer applications) coupled to climate to yield a basis for forward-thinking strategies to balance global fertilizer use policies. This type of analysis thus plays a critical role in understanding where we are fertilizer-limited as a function of crop choice and climate, and where excess fertilizer P already resides on the landscape, awaiting either different agronomic engineering (à la Borlaug) or conservation (à la Vogt) solutions to providing a hungry planet with adequate nutrition while the phosphorus cupboards are becoming empty.

The limiting factor—phosphate rock reserves

The reserves of phosphate rock, the source material for fertilizer P, with the highest economic viability have already been exploited (Filippelli, 2011). The clean high quality guano phosphates from low-lying atolls in the central Pacific such as Banaba Island and Nauru have been completely exploited for decades now, although there is some discussion of re-mining the spoil piles given the high phosphate costs. Many of the more P-rich horizons from standard phosphate rocks have also been depleted, resulting in average P content of mined phosphate ore to decline from 15% P in 1970 to less than 13% P by 1996 (Smil, 2002). Furthermore, the distribution of viable phosphate rock reserves is not at all uniform, with one small region (Morocco and Western Sahara) containing 75% of global reserves (Cooper et al., 2011)—this has clear geopolitical implications with respect of trade partnerships and international relations.

The combination of recognized limitation and increased demand has resulted in higher prices (Fig. 1), which then has knock-on impacts on food costs. Some of the volatility in the phosphate market might also have been the result of the development and eventual dismantling of a limited number of "phosphate cartels" which controlled the mining and distribution of processed phosphate rock (Taylor and Moss, 2013), thus changing the competition landscape for this resource. Regardless of the market drivers, there is clearly market recognition of phosphate rock limitation, even though no real international discussions have taken place revolving around this issue. The declining quality of current reserves and the inherently low economic viability for, and high environmental consequences of, extraction from other potential phosphate rock resources signals a need for a careful examination of P usage. Clearly, economics engenders innovation, and we will see technologies and environmental controls in the next century that will open up some currently uneconomic phosphate rock resources to extraction. But we should be equally clear in realizing that there is no technological "out" for the P problem. There simply are limited resources on the earth's surface, and there is no biological replacement for elemental P.

Current grain cropping systems demand high quantities of fertilizer P, which must be available for plant uptake at the right time and at a plant-favorable rate to maximize production. Agronomists and soil scientists continue to spend considerable effort to understand P concentration, geochemistry, and uptake kinetics so as to apply P at the right time, in the right form, and at the right rate so as to optimize P that goes into the crop instead versus being sequestered in soils or lost through infiltration or runoff (e.g., Richter et al., 2009). The practical application of this to farmers is to minimize fertilizer-P loss, which both costs money and also costs the environment via downstream eutrophication. The application of this knowledge is exemplified by precision agriculture techniques in the more developed countries. Precision agriculture and artificial fertilization have seemingly overcome most of the biogeochemical limitations on P available to crops, but a closer look reveals that P is up to its old tricks—building up in certain climate zones on fields that have been under cultivation for long periods of time, yet remaining unavailable under current cropping systems. Furthermore, vast regions have never received adequate fertilization and thus substantially under-produce from a lack of P. The application of fertilizer P is thus driven by local and regional economics and capacity, and not tuned for sustainability. This is exacerbated when considering global sustainability and limited supplies of P available for fertilizer production.

A portion of the applied P fertilizer will inevitably be sequestered by soil before plant uptake, and rain coming at inopportune times will continue to result in off-field P losses. Nevertheless, enough is now known about on-field P dynamics to begin extrapolating the net balance of fertilizer P inputs, retention, and off-field loss as a function of soil type, climate, and crop type, and indeed to attempt to do this at a global scale. These global P balance models have begun to show the stark realities of global fertilizer imbalances, as well as the limitations of our current grain production systems. This is particularly true given that large-scale grain production follows a pathway of grain to animal feed (and/or oil production) to human consumption, a calorically-inefficient system that is only become more widespread as Lower and Middle Income Countries transition to increasingly meat-heavy diets.

This brings science, and society, to an interesting intersection—coming to grips with the multiple pressures of feeding a growing and increasingly meat-hungry population under an ever-changing climate, depending on fertilizers and a global distribution patterns for both the fertilizer and the resultant food produced. This intersection is fraught enough with uncertainties without adding the very real issue of limitation in the availability and quality of phosphate that can be mined from rocks, and the economics and geopolitics that arise from a resource that is geologically based in only a few countries. The current modus operandi is to take this limited resources from its concentrated from, distribute it based on some set of proximal economic and ecological demands, process that originally concentrated source through grain crops, animals, and humans without much or any regard to recycling, and ultimately to return it to the environment in a very dilute form, where to make matters worse it causes continued issues with eutrophication and environmental degradation.

Using advanced modeling to predict global crop-specific limitation

A number of recent advances in our understanding of global P dynamics have significantly informed our understanding of the historical legacies of fertilizer application as well as the future agronomic needs of fertilizer P and a backdrop of global fertilizer P distribution studies (e.g., Bennett et al., 2001; Smil, 2000; MacDonald, et al., 2011; Ringeval et al., 2017; Kvakić et al., 2018). The most recent of these, Kvakić et al. (2018) provide a starting point for future decisions on P distribution. First, they separate the crop P demand for winter wheat, maize, and rice, all as a function of climate, P plant distribution, C:P ratios, and other factors. Next, they couple that to soil P supply, which is a function of extant soil P, fertilizer P input, and plant available P. Using these two factors, Kvakić et al. (2018) are able to calculate net P limitation on a global scale. They find that, as a global average, the current (or at least the year 2000 scenario that they used) soil P levels are adequate to sustain the theoretical crop yields, largely due to the history of global fertilizer P application. But the analysis also reveals significant spatial differences in the P limitation and the yield gap, with large legacy fertilizer P inputs needed to overcome P limitation in large parts of Central Asia, Africa, North and South America. By including current year fertilizer P inputs into the model, the yield gap is relieved except for western North America, southern South America, Africa, and Central Asia, owing to the P-poor nature of soils. This is particularly true for P-hungry maize, which is grown around the world, but based on these results grown very inefficiently with respect to P utilization in the low soil P supply areas of Central Asia and Africa.

Collectively, these results begin to paint a picture of how crop choice, historical fertilizer application, and climate and soil factors interact, and particularly how understanding different crop-P uptake dynamics can better inform what crops to grow where, and where fertilizer P augmentation will be most beneficial for increasing total grain production. With 7.3 billion and counting mouths to feed, this is an important consideration.

Unresolved Science

A number of intriguing and important questions remain about the science and the implementation of these phosphorus utilization models. Some of these relate directly to the soil biogeochemical dynamics of P, which are relatively complicated, and others relate to national and international trade policies and agreements that recognize our current inefficient, and unjust, P distribution and application processes and work to incentivize balancing P trade and application to push back to the time of P reserve depletion.

On the science side, the model-based examination of P fertilization needs developed in Kvakić et al. (2018) depends heavily on the basic P geochemical data, which the authors note is perhaps one of the more poorly-quantified inputs, plus a whole set of P cycling and plant utilization equations. Additional factors to consider include perhaps the most important variables that impact phosphorus-plant interactions—phosphatase and mycorrhizal fungi. Phosphatase is an enzyme produced by plants at great metabolic cost to bind plant-available phosphorus before it becomes lost through runoff or immobilization. Mycorrhizal fungi are a plant root symbiont that significantly enhances the effective root surface area for phosphorus binding. Some recent global studies of both of these factors indicate that, like with phosphorus-plant dynamics, both of these also vary according to climate, soil type, and other factors. Detailed on-field and experimental work on P sequestration has revealed the critical role that organic carbon, nitrogen, and iron mineral biogeochemistry play in modulating P sequestration and release kinetics (e.g., Keiluweit et al., 2012; 2015). A global analysis (Margalef et al., 2017) reveals a wide range in phosphatase activity, controlled largely by nitrogen (interestingly, not organic P content), with climate and soil type additional correlated variables. A global meta-analysis of mycorrhizal fungi data (Soudzilovskaia et al., 2015) also reveals climatic controls on fungi colonization, with soil chemistry (including carbon-to-nitrogen ratios) additionally influencing abundance. There seems to be no end to the variables that control soil P cycling and crop use efficiency, and many of them, like climate, are also changing. Regardless, the knowledge structure that has now extended to a global scale will continue to inform estimates of resource use efficiency and sustainability.

Pathways forward

Developing a more balanced and pseudo-sustainable global P cycle requires two distinct priorities: (1) Better science to inform better management in the short term, and (2) Implementing better management to adjust to scarcity in the long term. Better management is underpinned by the need for more science, particularly that that reaches across a discipline divide. This divide is between biogeochemists and agronomists who are developing detailed and realistic on-field and in-lab experiments of P behavior in soils, and global modelers who are utilizing relatively more simplistic models of P soil behavior integrated into ecosystem and climate models to characterize P resource and utilization deficits. I would argue for studies that test the Kvakić et al. (2018) model output using detailed regional studies to see how predictions hold up, and identify whether key measurable variables exist that may improve the quality of P soil behavioral data fed into the global model. But the “science informing better management” may be the easier of the two pathways..

Better management will require acknowledging two key principles—that the current “free market” for global P distribution and agriculture isn’t fair, and it doesn’t adequately account for resource scarcity (Foley et al., 2011; Cordell and White, 2011; de Ridder et al., 2012). A good example of the failure of the free market to balance global P distribution is China, which is largely sitting on its reasonably abundant P reserve and importing phosphate rock while protecting their own P reserve from export by the application of various protectionist tools (such as export tariffs and export quotas; de Ridder et al., 2012). And one needs look no further than the largely un-fertilized continent of Africa to see the unfairness in global P distribution and application for agriculture (Bennett et al., 2001).

Water is the “oil” of the 21st century. Will phosphorus become the “water” of the 22nd century? Based on current use and reserve quantity, it certainly seems so (Fig. 1). But this needn’t be the case. With a better understanding of soil P dynamics, we can better manage current fertilizer P applications, and with a better understanding of the global soil-plant-climate picture, we can better manage global P use efficiency. Furthermore, a host of P recycling and reclamation studies are currently underway to limit P wastage from our fields and our cities. But even together, these efforts will not permanently forestall a food production crisis at some point in the not-too-distant future. Whether that comes in the 22nd or the 25th century is solely dependent on us recognizing the pivotal role that P plays in global society, and treating it not as a limitless commodity but instead as the vital nutrient that it is.

References

Bennett, E.M., S.R. Carpenter, & N.F. Caraco, N.F. (2001). Human impact on erodible phosphorus and eutrophication: a global perspective. *Bioscience* 51, 227–234.

Cooper, J., R. Lombardi, D. Boardman, & C. Carliell-Marquet (2011). The future distribution and production of global phosphate rock reserves. *Resources, Conservation and Recycling*, 57, 78-86. doi: 10.1016/j.resconrec.2011.09.009.

Cordell, D., & S. White (2011) Peak phosphorus: Clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability* 3(10), 2027–2049. doi:10.3390/su3102027.

Cordell, D., J.-O. Drangert & S. White (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19(2), 292-305. doi: 10.1016/j.gloenvcha.2008.10.009.

De Ridder, M., J. Polchar & S. Lingemann (2012). Risks and Opportunities in the Global Phosphate Rock Market. The Hague Centre for Strategic Studies (HCSS), Rapport No. 17|12|12. ISBN/EAN: 978-94-91040-69-6. 96 pp.

Foley, J.A., N. Ramankutty N, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D, Tilman & D.P.M. Zaks (2011). Solutions for a cultivated planet. *Nature* 478:337–342.

Food and Agricultural Organization, UN (2017). World Food Situation. Accessed at http://www.fao.org/worldfoodsituation/csdb/en/ on March 5, 2018.

Filippelli, G.M. (2011). Phosphate rock formation and marine phosphorus geochemistry: The deep time perspective. *Chemosphere*, 84(6), 759-66.. doi:10.1016/j.chemosphere.2011.02.019.

Filippelli, G.M. (2008). The global phosphorus cycle: Past, present and Future. *Elements*, 4(2), 89-95.

Keiluweit, M., J.J. Bougoure, L.H. Zeglin, D.D. Myrold, P.K. Weber, J. Pett-Ridge, M. Kleber & P.S. Nico (2012). Nano-scale investigation of the association of microbial nitrogen residues with iron (hydr) oxides in a forest soil O-horizon. *Geochimica et Cosmochimica Acta,* 95:213–226.

Keiluweit, M., J.J. Bougoure, P.S. Nico, P. Weber, J. Pett-Ridge & M. Kleber (2015). Mineral protection of soil carbon counteracted by root exudates. *Nature Climate Change,* 5: 588-595.

Kvakić, M., S. Pellerin, P. Ciais, D.L. Achat, L. Augusto, P. Denoroy, J.S. Gerber, D. Goll, A. Mollier, N.D. Mueller, X. Wang & B. Ringeval (2018). Quantifying the limitation to world cereal production due to soil phosphorus status. *Global Biogeochemical Cycles*. doi: 10.1002/2017GB005754

Mann, C.C., 2018. The Wizard and the Prophet: Two remarkable scientists and their dueling visions to shape tomorrow's world. Alfred A. Knopf, New York. 640 pp.

Margalef, O., J. Sardans, M. Fernández-Martinez, R. Molowny-Horas, J.A. Jannsens, P. Ciais, D. Goll, A. Richter, M. Obersteiner, D. Arsenio & J. Peñuelas (2017). Global patterns of phosphatase activity in natural soils. Scientific Reports, 7(1), 1337. doi: 10.1038/s41598-017-01418-8

Richter, D. Jr. & M.L. Mobley (2009). Monitoring the Earth's critical zone. *Science* 326:1067–1068. doi:10.1126/science.1179117

Ringeval, B., L. Augusto, H. Monod, D. van Apeldoorn, L. Bouwman, X. Wang, D.L. Achet, L. P. Chini, K. Van Oost, B. Guenet, R. Wang, B. Decharme, T. Nesme & S. Pelerin (2017). Phosphorus in agricultural soils: drivers of its distribution at the global scale. *Global Change Biology*, 23(8), 3418-2432. doi: 10.111/gbc.13618.

Smil, V. (2000). Phosphorus in the environment: Natural flows and human interferences. *Annual Reviews Energy Environment*, 25, 53–88.

Soudzilovskaia, N.A., J.C. Douma, A.A. Akhmetzhanova, P.M. Bodegom, W.K. Cornwell, E.J. Moens, K.K. Treseder, M. Tibbett, Y.-P. Wang & J.H.C. Cornelissen (2015). Global patterns of plant root colonization intensity by mycorrhizal fungi explained by climate and soil chemistry. Global Ecology and Biogeography, 24, 371-382. doi: 10.1111/geb.12272.

Taylor, C.R. & D.L. Moss (2013). 'The Fertilizer Oligopoly: The case for global antitrust enforcement", Washington DC: The American Antitrust Institution.

United Nations (2017). World Population Prospects, 2017. Accessed at https://esa.un.org/unpd/wpp/ on March 5, 2018.

United States Geological Survey (2018). Phosphate Rocks Statistics and Information. Accessed at https://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2018-phosp.pdf on March 5, 2018.

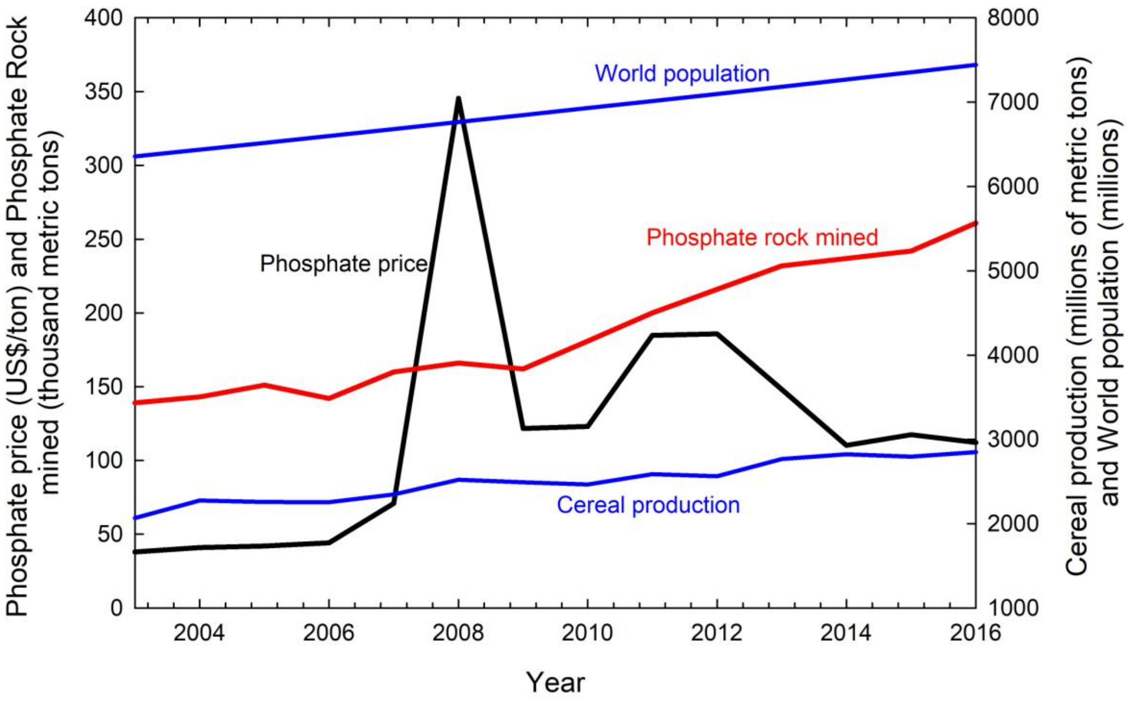

Fig. 1. Increase in world population (UN, 2017), annual phosphate rock mining (USGS, 2018), annual cereal production (FAO, 2017), and price of phosphate (USGS, 2018) from 2003-2016. The world population increase is being supported by increased food production and greater global demand for phosphate rock fertilizer, which in turn has resulted in an increase in the price of phosphate, although the latter is also strongly influenced by global trade patterns of market volatility. Note that the total amount of phosphate reserves are 68,000 thousand metric tons (USGS, 2018), indicating that reserves will be 50% depleted under the current annual rate of extraction by about the year 2150. This of course assumes that we have accurately characterized reserves and can project forward demand—there is wide scatter in various published estimates of the 50% depletion timeframe (e.g., Smil, 2000; Filippelli 2008; Cordell and White, 2011) and like the Hibbert “peak oil” curve, should be viewed with caution.