Reframing Phosphorus Stewardship for Resilience in Food-Energy-Water Security

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Phosphorus (P) is closely linked to an increasingly fragile 'nexus' of food, energy, and water (FEW) security. While there are many other drivers that influence FEW security, P plays a unique and under-recognized role within the FEW nexus (Jarvie et al., 2015). We face a growing P 'paradox,' derived from simultaneous regional scarcity and abundance of P, which can be found across local to global scales. Irrespective of the actual mineral rock P reserves and projected timelines to deplete those resources, P is a finite resource that creates the challenge of overcoming scarcity of P to sustain terrestrial food and biofuel production, which threatens food and energy security. At the same time, we are faced with increasing occurrence and severity of water quality impairment from an abundance of P entering aquatic systems, which threatens water security.

The many factors defining the FEW nexus are recognized internationally by governments, global agencies (e.g. FAO, OECD, World Bank), and research organizations (e.g., National Science Foundation [NSF] and UK Research Councils), as a fundamental challenge to the stability of global economic and sustainable development (World Economic Forum, 2011). However, while other factors influence FEW security as well as P, the critical role of P on the stability of the FEW nexus has received little attention (Jarvie et al., 2015).

Here, we highlight a strategic research and environmental management need to reframe P stewardship for greater resilience in food, bioenergy, and water security. In Table 1, we identify key research opportunities and technology needs whereby sustainable P management, based on greater efficiencies in P use, can help address the P paradox, minimize tradeoffs, and catalyze synergies to improve resilience among components of the water, energy, and food security nexus. This requires a shift in thinking from separate water, energy, and food policies to a more holistic approach to P management.

P Scarcity Implications for Food and Energy Security

In relation to food security, both nitrogen (N) and P are required for sustainable food production. Unlike N, which is a renewable resource, P must be mined. Economically-extractable supplies of P are geographically limited, with North African countries holding about 80% of current global reserves (Jasinski, 2015). While recent analyses extend the time frame of current reserves to around 300 years using modern mining technologies (Scholz and Wellmer, 2013), rock P will be an important factor determining food security. For instance, P deficits occur on 30% of global cropland, dominantly in developing countries where they are inextricably linked to food security (MacDonald et al., 2011).

In the past 40 years, global fertilizer P use has increased 350%, and food production more than doubled (Khan et al., 2009). Over this time, the face of agriculture has changed from mixed crop and livestock systems to specialized, crop and livestock systems that are cost-efficient, yet geographically disparate (Sharpley and Jarvie, 2012). The main consequence of this uncoupling of production systems has been a one-way transfer of P (as feed, fertilizer, and manure) to localized grain and livestock production and human consumption. This increase in agricultural productivity has come at a cost to

other ecosystem services, such as a greater risk of P loss to water and associated eutrophication (Jarvie et al., 2015).

It is clear that greater efficiencies in P use and more effective coordination of P recycling and recovery is needed at global, regional, local, and even farm levels (Table 1). The value of P in manures and urban and industrial by-products needs full recognition and has to be appropriately accounted for in watershed planning strategies, which may require innovative integration of financial incentives and/or stricter regulations. At the same time, indirect or unintended consequences associated with conflicting strategies should be avoided. Research opportunities that may help transform some of these tradeoffs into synergies for improved FEW security include the development of innovative cost-effective technologies and practices for manure processing and production of higher value recycled products. Policies and initiatives that promote food and energy security, via agricultural intensification, must be better coordinated and financially linked with P recycling and implementation of conservation measures that address both P scarcity and abundance issues.

P Abundance Implications for Water Security

A multitude of tradeoffs for water quality and security have arisen as a result of drives to increase crop yields for food security and biofuel energy. As global P fluxes have expanded to meet food production demands, the availability of relatively cheap P fertilizers has resulted in hotspots of P utilization that are increasingly inefficient and spatially disparate. While a varying fraction of this applied P can be lost to receiving waters (<1 to 10%; Carpenter, 2008), amounts have not been of agronomic significance. Even so, this loss of P is known to accelerate freshwater eutrophication (Schindler et al., 2012). The disproportionate impact of agricultural P on water quality complicates efforts to manage P losses to the environment on the basis of efficient use alone.

Inefficiency, however, sets the stage for today's environmental concerns with P, placing a premium on recycling and reuse of P. It is estimated that less than 20% of P mined for fertilizer reaches the food products consumed and only around 10% of the P in human wastes is recycled back onto agricultural land (Neset and Cordell, 2012). As a result, the broken P biogeochemical cycle must be reconnected (Elser and Bennet, 2011).

While these challenges are global in extent, drivers vary regionally, according to differing soil P availability and use, land and water management, and priorities in food and biofuel production (Haygarth et al., 2014). For example, in China, rapid economic and population growth have resulted in dramatic shifts in agricultural food and biofuel production (Lu et al., 2015), with a resultant increase in P loss to water (Wang et al., 2011). In Europe, which has no significant indigenous rock P reserves, P use and management strategies are in place to balance agricultural P inputs with output in produce and to increase P recycling (Withers et al., 2015). In contrast, food and biofuel production across Africa is severely limited by soil P deficiency, despite globally rich rock P reserves (Jasinski, 2015). Here, P additions rarely meet plant needs, such that crop yields are 25% of global averages, and clearly increasing soil fertility is a primary requisite to food security across this continent (Van der Velde et al., 2014).

Table 1 highlights how improved soil and land management, along with as P recovery and recycling, will be needed to increase P use efficiency and secure synergies across water, energy, and food security sectors. Precision conservation and nutrient management programs will be needed to address P sources (e.g., rate, method, and timing of applied P) and transport controls (e.g., conservation tillage, contour ploughing, and riparian buffers) to achieve the required improvements in water quality and security. Moreover, protecting and enhancing soil structure and fertility and minimizing P losses will be fundamental to increasing the resilience of provisioning and regulating ecosystem services that support food and biofuel crop production and sustain water quality.

Experience reveals that there needs to be a minimum level of conservation that avoids risky practices in vulnerable landscapes. In extreme cases of highly vulnerable landscapes, certain production systems may be inherently unsustainable, regardless of the suite of conservation practices used or conservation measures adopted. Opportunities exist for new sensor technologies to improve monitoring as well as management of soil, water and fertilizers. Better application and integration of these technologies would improve assessment of watershed strategies and facilitate targeting conservation measurements. Ongoing development of nutrient criteria for waters of the U.S. should address what is achievable and affordable, given that pristine "reference" conditions may not be achievable in some watersheds with intensive agricultural production. Concurrent with this, cost-benefit analyses of nutrient reduction strategies are necessary to determine what is achievable, affordable, and even desired by the majority of watershed stakeholders.

References

Carpenter, S.R. 2008. Phosphorus control is critical to mitigating eutrophication. Proc. Nat. Acad. Sci. 106(32):11030-11040.

Elser, J.J., and E. Bennett. 2011. A broken biogeochemical cycle. Nature 478:29-31.

Haygarth, P.M., H.P. Jarvie, S.M. Powers, A.N. Sharpley, J.. Elser, J. Shen, H.M. Peterson, N.-I. Chan, N.J.K. Howden, T. Burt, F. Worrall, F. Zhang, and X. Liu. 2014. Sustainable phosphorus management and the need for a long-term perspective: The legacy hypothesis. Environ. Sci. Technol. 48:8417-8419.

Jarvie, H.P., A. Sharpley, D. Flaten, P.J.A. Kleinman, A. Jenkins, and T. Simmons. 2015. The pivotal role of phosphorus in a resilient water-energy-food security nexus. J. Environ. Qual. 44:1308-1326.

Jasinksi, S. 2015. Phosphate Rock In: Mineral Commodity Summaries U.S. Department of the Interior and U.S. Geological Survey http://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf.

Khan, S., M.A. Khan, M.A. Hanjra, and J. Mu. 2009. Pathways to reduce the environmental footprints of water and energy inputs in food production. Food Policy 34:141-149.

Lu, Y., A. Jenkins, R.C. Ferrier, M. Bailey, I.J. Gordon, S. Song, J. Huang, S. Jia, F. Zhang, X. Liu, Z. Feng, and Z. Zhang. 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1:e1400039.

MacDonald, G.K., E.M. Bennett, P.A. Potter, and N. Ramankutty. 2011. Agronomic phosphorus imbalances across the world's croplands. Proc. Nat. Acad. Sci. 108:3086-3091.

Neset, T.S.S., and D. Cordell. 2012. Global phosphorus scarcity: Identifying synergies for a sustainable future. J. Sci. Food Agric. 92:2-6.

Schindler, D.W., R.E. Hecky, D.L. Findlay, M.P. Stainton, B.R. Parker, M.J. Paterson, K.G. Beaty, M. Lyng, and S.E.M. Kasian. 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. Proc. Nat. Acad. of Sci. 106:11254-11258.

Scholz, R.W., and F.W. Wellmer. 2013. Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus? Global Environ. Change-Human Policy Dimensions 23:11-27.

Sharpley, A.N., and H.P. Jarvie. 2012. Agricultural management, water quality and ecology: Putting practice into policy. p. 87-116. *In* A. Eaglesham (ed.), National Agricultural Biotechnology Council Conference Proceedings 24. Boyce Thompson Institute, Ithaca, NY. Library of Congress # 2012954078. Available at http://nabc.cals.cornell.edu/Publications/Reports/nabc_24/24_2_3_Jarvie.pdf.

Van der Velde, M., C. Folberth, J. Balkovic, P. Ciais, S. Fritz, I.A. Janssens, M. Obersteiner, L. See, R. Skalsky, W. Xiong, and J. Penuelas. 2014. African crop yield reductions due to increasingly unbalanced nitrogen and phosphorus consumption. Glob. Change Biol. 20:1278–1288.

Wang, F., J.T. Sims, L. Ma, W. Ma, Z. Dou, and F. Zhang. 2011. The phosphorus footprint of China's food chain: Implications for food security, natural resource management, and environmental quality. J. Environ. Qual. 40:1081–1089.

Withers, P.J.A., K.C. van Dijk, T.S.S. Neset, T. Nesme, O. Oenema, G.H. Rubaek, O.F. Schoumans, B. Smit, and S. Pellerin. 2015. Stewardship to tackle global phosphorus inefficiency: The case of Europe. Ambio 44:193–206.

World Economic Forum. 2011. Water security: The water-food-energy-climate nexus. Island Press. Available at http://www3.weforum.org/docs/WEF_WI_WaterSecurity_WaterFoodEnergyClimateNexus_2011.pdf.

Table 1. Examples of the roles, research opportunities, and technology needs regarding P in a resilient water-energy-food security nexus.

Nexus connection	The role of P	Research opportunities	Technology needs
Water and **Food**	Use of P fertilizers has increased food grain, fiber, and livestock production and food security. P loss from agricultural production systems has contributed to more widespread eutrophication.	• Revisit dated Land Grant soil fertility recommendations. • Identify critical source areas and management practices for P loss. • Identify and quantify legacy sources of P within watersheds. • Unified framework to target precision conservation. • Innovative methods to recycle P at farm, watershed, and global scales that reduce reliance on mined P fertilizers.	• Innovative agricultural Conservation Practices (CPs) that help protect and enhance soil structure and fertility, minimize P loss, and increase water-use efficiency, while limiting consequences of unintended and conflicting outcomes. • Cost-effective technology to recover and recycle P from manure, and wastewater (e.g., through enhanced value products) will help close the P cycle and reducing reliance on imported inorganic P fertilizers.
Water and **Energy**	Use of P fertilizers has enabled the specialization and intensification of agricultural production, as well as growth of biofuels industry (based on grain ethanol and biodiesel), increasing energy and water demand.	• Quantify the impact of expanding agricultural production into marginal areas on soil erosion and P loss, with longer-term tradeoffs for soil C, and ecosystem services which support food production and clean water. • Revisit soil fertility recommendations for cellulosic feedstock. • Determine resilience of farming systems to reduced water availability and potential impacts on fertilizer use.	• Ensure landscape suitability and sustainability for biofuel grain so that right biofuel crops are grown in the right place to maximize yields, whilst minimizing soil erosion and P loss. • Enhance landscape diversity to support a greater range of biofuel crops, e.g., perennial cellulosic biofuel crops can help decrease P loading to surface waters and increase soil C in less productive areas.
Food and **Energy**	P inputs to food and biofuel energy production cannot be substituted by any other chemical element.	• Economic and strategic forecasting of consequences of competing biofuel and food crops for land and water resources. • Global analysis of impacts of increasing food prices with tradeoffs for food security in countries reliant on food imports. • Quantify production and environmental impacts of increased commodity prices that incentivize farmers to increase production and yields at the expense of conservation measures.	• Strategic analysis of co-locating CAFOs near biofuel processing plants to utilize waste products of biofuel production (e.g., distiller's grain) as animal feed that increases P-use efficiency, minimizing P losses. • Cost-effective technology to generate energy from P-containing waste streams, as part of a sustainable P-recycling strategy.