

Celebrating the 350th Anniversary of Phosphorus Discovery: A Conundrum of Deficiency and Excess

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Abstract

2019 will be the 350th anniversary of the discovery of phosphorus (P) by the alchemist Henning Brandt. This perspective traces the historical threads that P has weaved through the fabric of our society and identifies challenges to improve P stewardship in the future and for our future. A century after Brandt's discovery, P was identified in bone ash, which became the primary source of P until guano and ultimately rock P was mined to provide the various mineral formulations used today. Owing to limited supplies, a strategic shift in resource management ethics—from exploiting to conserving P resources—is needed. In agriculture, remedial strategies should consider when conservation practices can transition from P sinks to sources; however, a broader, long-term strategy for P stewardship is needed. This must include Reducing P loss in food and other wastes, Recovering P from waste streams, Reusing P generated beneficial by-products, and Restructuring production systems. A key action to enact such changes will be collaboration across all sectors of society and the supply chain, from field to fork and beyond. As this will likely increase the cost of food, fiber, and feed production, it will require an innovative mix of public and private initiatives.

Core Ideas

- 2019, 350 years since phosphorus discovery, is a good time to envision our next 350 years.
- P weaves a complex web through the fabric of agricultural and societal management.
- We face a conundrum of coincident consequences of P deficiencies and excesses.
- Collaboration among the supply chain must engage in sustainable P stewardship.
- P stewardship 4Rs must be broadened to Reduce, Recover, Re-use, and Restructure.

A Glowing Start

PHOSPHORUS (P) was discovered by the alchemist Hennig Brandt in 1669, when he accidentally extracted it from a copious store of human urine (22 hog heads or 5500 L of urine) while searching for the illusive “philosopher’s stone,” believed to transform base metals into gold (Powers, 2017). Thus, P became the first element discovered with modern scientific techniques, partly because it is so reactive in elemental form that it never occurs free in nature. By the glow of this new substance, soon to be named “cold fire,” Brandt had found the P in pee! Ironically, we are still trying to find efficient and cost-effective methods to extract P from human and animal excreta. Which goes to show how little some things have changed over the last three and a half centuries.

Phosphorus is the sixth most abundant element in living organisms. It is an essential constituent of all life, from DNA and our genetic code, to the phospholipids of cell membranes, to the apatite of our bones, to ATP, the basic currency of all metabolic processes. Fertilizer P has provided the foundation for commercial food, fiber, and bioenergy production, supporting population growth and facilitating the transition to modern urbanized societies. However, events in the last 50 to 60 years have highlighted a conundrum of P deficiencies and excesses. During this time, publicized concerns about depletion of rock phosphate (the nonrenewable raw material for most P fertilizers) have arisen concurrently with growing concern about P use inefficiencies (e.g., losses from agriculture and wastewater) and the harm excess P can bring to the ecological balance of streams, rivers, lakes, estuaries, and seas worldwide.

Indeed, eutrophication of surface waters has resulted in proliferation of cyanobacteria, early life forms that have existed for more than 3.5 billion years, 10 million times older than our knowledge of P. These early life forms, which generated the oxygen atmosphere on which we depend, and which shaped the course of evolution and ecological change, are now responding to our increasingly inefficient use of P, triggering environmental degradation and harm. These environmental concerns, along with our longstanding efforts to extract P from waste, provide just

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Abbreviations: PAHs, polycyclic aromatic hydrocarbons; DOM, dissolved organic matter; DOC, dissolved organic carbon; SOM, solid organic matter.

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two examples of the persistent and pervasive historical threads that weave an intricate pattern of challenges and opportunities for our use and management of P.

The 350th “anniversary” of our relationship with P, therefore, presents an ideal vantage point from which to consider where we have been, where we are, and where we should take this relationship. It is also timely to reflect that Syers et al. (2011) estimated that rock P reserves would last for about another 350 years. In this contribution, we trace the historical threads that P weaves through the fabric of modern society. We take stock of the way we currently manage P in agriculture and consider research challenges that we should explore to improve P management in the future and for our future.

Origins of Phosphorus Use in Production Agriculture

One century after Brandt discovered P, Gahn and Scheele identified P in bone ash in 1769, which quickly became the main source of P for the next century. In fact, reports suggest that bones from the battlefields of Waterloo in 1815 were collected and shipped to England for use as fertilizer, purportedly contributing to the phrase “England’s green and pleasant land” (from William Blake’s 1808 poem “Milton: A Poem in Two Books”). Following this, other battlefields yielded bones for “organic” P fertilizer.

Subsequently, bird and bat guano became “the” source of P until the refinement of rock phosphates, to produce various formulations of mineral P fertilizers, greatly expanded P use and availability and reduced the cost of P after World War II. This low cost is reflected in trends in US P fertilizer use, crop yields, and general farm productivity during the last 50 years (Fig. 1). Since 1960, global fertilizer P use has increased 350% (again that magical number 350), and food production has more than doubled (Khan et al., 2009). During the same time, the face of agriculture has changed from mixed crop and livestock systems to specialized crop and livestock systems that are often 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 to livestock, then fertilizer and manure to soils), building up P in soils well beyond levels needed for crop production. This uncoupling of P cycling has degraded ecosystem services, most notably by greater risk of P loss to water and associated eutrophication (Jarvie et al., 2015).

Devilishly Useful

To overstate the role of P in supporting modern society is difficult. Its history is inextricably linked to the industrial and now modern era and extends far beyond its primary use as an agricultural fertilizer to include a plethora of products on which society has grown to depend. For example, phosphoric acid is used in soft drinks to impart a tangy and crisp taste, as an additive to enhance the cleaning power of detergents (until it was banned in the United States, following P water-quality impairment of the Great Lakes in the 1960s and 1970s), and as a water conditioner to reduce the risk of lead poisoning in drinking water. Other P compounds contribute to a litany of common uses: food

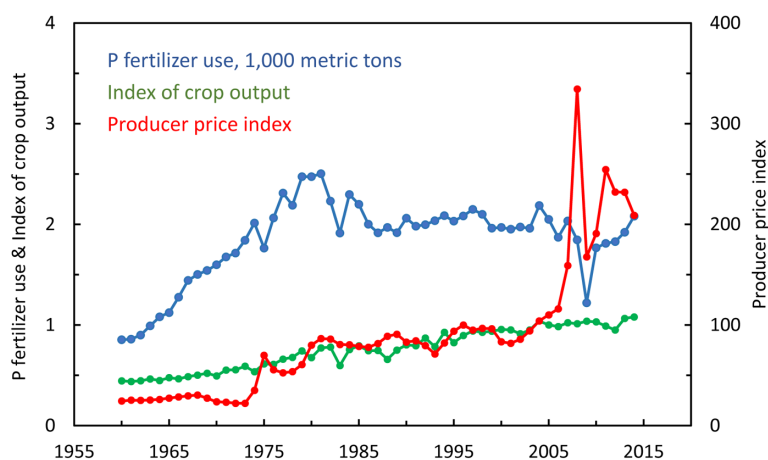


Fig. 1. Representation of the increase in fertilizer P use (as metric tons of P), crop productivity (as index of crop output), and farm productivity (as producer price index). Data from USDA, Economic Research Service using data from Tennessee Valley Authority, Association of American Plant Food Control Officials, and The Fertilizer Institute.

additives (e.g., diphosphate leavening agents to give baked goods a lighter texture); emulsifying agents, used for processed cheese and toothpaste; bisphosphonates in pharmaceuticals to treat bone wastage and certain types of bone cancer; and organophosphorus compounds in flame retardants, plasticizers, and pesticides (e.g., malathion and glyphosate).

Nonetheless, there has always been a darker side to our use of P. The use of white P in matches opened a new world of instant fire, even though it caused the extremely painful “Phossy Jaw” among factory workers, at least until laws were enacted and red P was discovered. If ingested, white P causes severe liver damage and a condition known as “Smoking Stool Syndrome.” One wife even tried to poison her husband by lacing his stew with white P, but the plot was thwarted when the hot stew gave off luminous steam (Emsley, 2000).

An increase in production capacity of white P allowed production to increase to the point where it could be used in weapons of war. For example, in World War I and II, white P was used in incendiaries, smoke screens, and tracer bullets and as a key component of napalm. Phosphorus is also used in chemical weapons, such as the nerve agents, sarin, tabun, and VX (i.e., weapons of mass destruction) and novichok (used in the poisoning incident of a former Russian agent in the UK, March 2018; British Broadcasting Corporation, 2018).

From these less salubrious uses, P has earned a dark moniker, “the Devil’s Element.”

The Conundrum

Which brings us to the present. Phosphorus is essential to our development and well-being, yet our efforts to engineer systems that redistribute the world’s P stores have created unintended outcomes that we are only beginning to recognize. The element is an essential component of an increasingly fragile nexus of food, energy, and water security (Jarvie et al., 2015; Fig. 2). Although there are many other drivers that influence food–energy–water security, P plays a unique and under-recognized role within the food–energy–water nexus (Jarvie et al., 2015). We face a conundrum, derived from simultaneous deficiencies and excesses of P across local, regional, and national scales. Irrespective of the

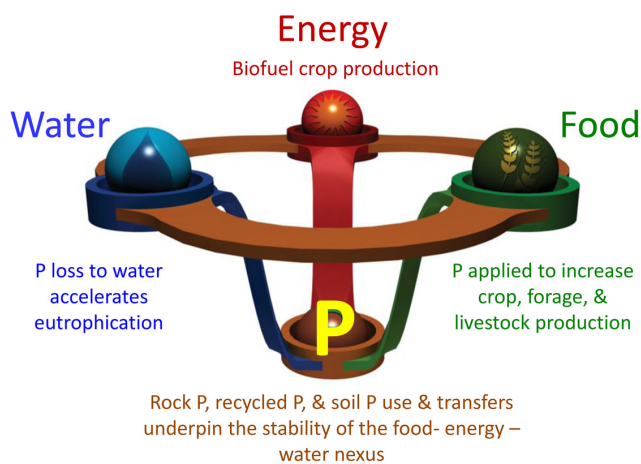


Fig. 2. Conceptual representation of the critical roles of P in the food-energy-water nexus.

projected timelines to deplete finite rock P reserves, there remain major challenges in overcoming P deficiencies to sustain 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 excess P entering aquatic systems and with the accumulation of large legacy P stores within the landscape and water bodies, which threaten water security over a wide range of timescales (Sharpley et al., 2013).

Some of the major challenges to addressing the P deficiency-excess conundrum center on forging societal solutions, efficiently using and recycling P, and promoting sustainable P management.

How do we forge societal solutions?

Phosphorus is a nonrenewable resource that must be recognized more broadly as such to forge solutions spanning agricultural, rural, and metropolitan sectors. This requires development and adoption of sustainable P conservation strategies coordinated across all sectors of the supply chain from producer to consumer, as well as to the postconsumer issues of wastewater treatment. Such strategies would Reduce P loss in food and other wastes, Recover P from waste streams, Reuse P-generated beneficial by-products, and Restructure production systems and sectors. These are the 4Rs for P management that will enable us to utilize P for the next 350 years, borrowing from and complementing the 4R nutrient management strategies promoted by the International Plant Nutrition Institute (2014) and the sustainable 5R strategy proposed by Withers et al. (2015).

A key component to enacting our 4R sustainable conservation strategies and facilitating change is collaboration across all sectors of society. In an effort to facilitate adoption of such strategies, several companies and nongovernmental organizations (see, e.g., <https://www.landolakessustain.com/> and <https://www.tysonustainability.com/>) are collaborating across the supply chain to sustainably manage nutrients (including P) from “field to fork” (Shilling, 2016; Tyson Foods, 2017).

Improved soil and land management, along with P recovery and recycling, is critical to increase P use efficiency and secure synergies across food-energy-water security sectors. Adoption of precision conservation and nutrient management programs to address P sources (e.g., rate, method, and timing of applied P) and transport drivers (e.g., water management, conservation

tillage, contour plowing, and riparian buffers) have the potential to achieve the required improvements in water quality and security. However, their adoption often comes with an increased cost to society of food, feed, and fiber production.

Increased P use efficiency is critical to mitigate environmental concerns with P; however, the lack of a premium on the recovery and reuse of P represents a challenge. It is estimated that less than 20% of P mined for fertilizer reaches the food products consumed and that only 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. As a first step, greater efficiency and coordination of P reduction, recovery, reuse, and restructuring are needed at global, regional, local, and even farm levels. Achieving this will require an innovative mix of public and private initiatives.

How do we more efficiently use and recycle P within our food, energy, and water production systems?

While these challenges are global in extent, drivers vary regionally and even locally, as influenced by soil P availability and use, land and water management, and priorities in food and biofuel production. For example, in Europe, which has few reserves of rock P, except for Finland (i.e., total reserves of 2360 million tons; Ahokas, 2015), 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 that region’s rich rock P reserves (Jasinski, 2015; Syers et al., 2011). Here, P additions rarely meet plant needs, such that crop yields are 25% of global averages; clearly, increasing soil fertility is a primary requisite for food security across Africa (van der Velde et al., 2014).

Throughout the world, there is an increasing awareness of the need to validate and unify disparate fertilizer P recommendations based on soil test P measurements. These recommendations often lack transparency, and soil test P calibration-crop response trials have not been updated for several decades due to lack of funding for laborious field trials (Smith et al., 2018). Improving fertilizer and manure P recommendations will also directly benefit the reliability of P loss risk-assessment tools to minimize edge-of-field P runoff (Kleinman et al., 2017).

How do we promote sustainable agricultural P management when the cost of P loss is so little?

We face an intractable challenge that the losses of P responsible for water-quality impairment represent only a very small proportion of P applied to land. For example, the recent re-eutrophication of Lake Erie has been linked to increases in soluble P losses, which represent less than 5% of the annual fertilizer P applied within the watersheds (Jarvie et al., 2017). Without subsidies or incentives for implementing conservation practices, farmers have no economic motivation to address these P losses.

The Lake Erie example also raises important challenges for sustainable management, whereby conservation practices implemented to address a particular water-quality problem can have unintended consequences and initiate unexpected impairment (Smith et al., 2018). In the case of Lake Erie watersheds, reduced land tillage dramatically decreased erosion and particulate P loss.

However, surface application of P fertilizer without incorporation has led to increased losses of highly bioavailable soluble P fractions (Jarvie et al., 2017).

A greater understanding of the legacies of prior management on remobilization of P stored in land, river, and lake systems is needed to ensure the long-term benefits of conservation management. Thus, remedial strategies must consider current and future situations where P sinks may become sources, with only slight changes in watershed management and hydrologic response. In terms of system management, water-quality response will be a function of the rate-limiting or slowest-responding sectors of the system. Indeed, there have been many cases worldwide where concerted efforts to reduce P losses have not resulted in the expected ecological improvements within receiving water bodies. This lack of response is linked to lags in legacy P delivery, P reductions failing to reach the challenging P concentration thresholds to limit algal growth, and a wide range of confounding physical and biological factors (Jarvie et al., 2013; Meals et al., 2010; Sharpley et al., 2013).

Opportunities exist for new sensor technologies to improve monitoring and management of soil, water, and fertilizers (e.g., Elkin, 2014). Better application and integration of these technologies would improve assessment of watershed strategies and facilitate targeting conservation measurements to connect cause (land use and management change) and response (biological productivity change in receiving waters).

Experience reveals that a minimum level of conservation is necessary to avoid 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. Even so, a broader shift in resource ethics from one of maintaining the status quo to conserving P resources is required.

Summary

As we enter the 350th anniversary of Brandt's discovery of P, it is clear that use of global P reserves has yielded grand societal achievements in human health and nutrition. However, the historical threads of P use and management during the last 350 years have woven complex patterns of P deficiency and excess into the fabric of society. All of us can use this anniversary as a challenge to encourage public awareness and action to move society away from short-term exploitation toward long-term stewardship of P. A concerted effort is needed to improve societal P stewardship, reduce regional disparities in P availability, and avoid unraveling the successes achieved in the last 350 years.

Finally, we should use this anniversary to support an alternative definition of *legacy P*. It is an opportunity to share our collective knowledge and experience of P with policymakers, farmers, students, and the public, with the goal of enhancing P stewardship. In a tribute to the 4R mantra, we hope this perspective will help achieve that goal by Reminding readers of the importance of P, Reaffirming the value of existing efforts to improve sustainability of P use, Recruiting new people, ideas, and views to this cause, and Recommending priorities for these investments.

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