

Phosphorus mirabilis: Illuminating the Past and Future of Phosphorus Stewardship

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Abstract

After its discovery in 1669, phosphorus (P) was named *Phosphorus mirabilis* (“the miraculous bearer of light”), arising from the chemoluminescence when white P is exposed to the atmosphere. The metaphoric association between P and light resonates through history: from the discovery of P at the start of the Enlightenment period to the vital role of P in photosynthetic capture of light in crop and food production through to new technologies, which seek to capitalize on the interactions between novel ultrathin P allotropes and light, including photocatalysis, solar energy production, and storage. In this introduction to the *Journal of Environmental Quality* special section “Celebrating the 350th Anniversary of Discovering Phosphorus—For Better or Worse,” which brings together 22 paper contributions, we shine a spotlight on the historical and emerging challenges and opportunities in research and understanding of the agricultural, environmental, and societal significance of this vital element. We highlight the role of P in water quality impairment and the variable successes of P mitigation measures. We reflect on the need to improve P use efficiency and on the kaleidoscope of challenges facing efficient use of P. We discuss the requirement to focus on place-based solutions for developing effective and lasting P management. Finally, we consider how cross-disciplinary collaborations in P stewardship offer a guiding light for the future, and we explore the glimmers of hope for reconnecting our broken P cycle and the bright new horizons needed to ensure future food, water, and bioresource security for growing global populations.

Core Ideas

- This special section comprises 22 papers celebrating the 350th anniversary of P discovery.
- Historical and emerging challenges and opportunities exist in P research and understanding.
- Authors address P use efficiency and a kaleidoscope of challenges for efficient P use.
- Focusing on place-based solutions is required for effective P management.
- Cross-disciplinary collaborations in P stewardship are needed for food and water security.

OUR CELEBRATION of the 350th anniversary of the discovery of *Phosphorus mirabilis* (“miraculous bearer of light”) provides a timely opportunity to reflect on our relationship with phosphorus (P), an element on which our very existence depends. Phosphorus was discovered by the German alchemist Hennig Brandt in 1669, in Hamburg, Germany (Sharpley et al., 2018). He was searching for the elusive Philosopher’s Stone, believed to transform base metals into gold. As Brandt gazed in awe at the eerie blue light emanating from his flask, he could not have imagined that this substance would be of far greater direct benefit than gold for sustaining human life.

The metaphor of P as bearer of light certainly resonates with the timing of its discovery in 1669, at the start of the Enlightenment (White, 2018). The Enlightenment, or Age of Reason, was a period of rigorous scientific, political, and philosophical discourse that characterized European society from the late 17th century to the ending of the Napoleonic Wars in 1815. It was a period of profound change in thought and reason, when centuries of custom and tradition gave way to exploration, individualism, tolerance, and scientific endeavor, which, along with developments in industry and politics, “witnessed the emergence of the modern world” (White, 2018).

The discovery of P clearly captured the imagination of English artists, poets, and scientists of the Enlightenment, including the artist Joseph Wright of Derby, whose iconic painting *The Alchymist, in Search of the Philosopher’s Stone, Discovers Phosphorus* (first exhibited in 1771) portrays this momentous scientific discovery for future generations (Fig. 1). Among the poets of the time, Erasmus Darwin (grandfather of Charles Darwin) waxed lyrical about “the pale Phosphor’s self-consuming flame” in his poem *The Economy of Vegetation* from *The Botanic Garden* (Darwin, 1791). During the Enlightenment, Antoine Lavoisier, known as the father of modern chemistry, used rigorous quantification and controlled experiments to demonstrate for the first time that the burning of P in air resulted in an increase in mass and that P was, in fact, an element (Lavoisier, 1789).

The greatest value of P to humankind, nonetheless, extended beyond its “chemoluminescence” (the emission of light when highly reactive elemental white P is exposed to the atmosphere),

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Abbreviations: 2D, two-dimensional; PUE, phosphorus use efficiency.



Fig. 1. Celebrating the 350th anniversary of the discovery of phosphorus: Helen Jarvie at the Derby Museum and Art Gallery, Derby, UK, pictured beside *The Alchemist, in Search of the Philosopher's Stone, Discovers Phosphorus*, by Joseph Wright (oil on canvas, exhibited 1771).

as depicted in Joseph Wright's painting. The true value of P is its role in harnessing light energy during the process of photosynthesis, for crop and food production. Phosphorus is vital in the photosynthetic capture of light energy by agricultural crops and conversion of carbon dioxide from the atmosphere to produce sugar phosphates, which are then used to build the myriad of organic compounds needed for crop growth and to produce food, fuel, and fiber (Bruulsema, 2017). Phosphorus fertilizers were a foundation of the Green Revolution, enabling modern crop yields that are the basis of all commercial food, fiber, and bioenergy production. Phosphorus fertilizers opened up vast tracts of land that otherwise would not be suited to agriculture, supporting population growth and facilitating the transition to modern, urbanized societies (Jarvie et al., 2015).

Beyond its primary contribution as a fertilizer, P has been used in a dazzling array of consumer products on which society has grown to depend (Sharpley et al., 2018). For example, P has provided "instant fire" in matches; it has made our whites brighter by enhancing the cleaning power of detergents; it has transformed our foods and drink, for example, adding tang to soft drinks and giving baked goods their light texture. However, there has long existed a darker side to our P use. The pervasive nature of P losses from agriculture and wastewater has cast a long shadow over our ambitions for ensuring clean water and improving the health and resilience of our aquatic ecosystems (Jarvie et al., 2013b; Flaten

et al., 2019). Some forms of P are poisonous; for example, white P caused the painful "phossy jaw" condition among workers in the production of lucifer matches. Phosphorus has also played a dark role as a military weapon through its use in bombs and incendiaries and in nerve agents and chemical warfare (Sharpley et al., 2018). Over time, there have been bouts of concern that our dependence on P makes us vulnerable to its eventual scarcity, requiring changes to its societal value and resource conservation that generally have not been heeded (Ulrich and Frossard, 2014).

In this special section of the *Journal of Environmental Quality*, we aim to illuminate our journey with P so far, by shining a spotlight on the historical and emerging challenges and opportunities in research and understanding of the agricultural, environmental, and societal significance of this vital element. This special section includes invited and volunteered papers presented at the cross-divisional symposium "Celebrating the 350th Anniversary of the Discovery of P: For Better or Worse" at the 2019 International Soils Meeting, 6–9 Jan. 2019, in San Diego, CA (<https://www.sacmeetings.org/>, <https://scisoc.confex.com/scisoc/2019sssa/meetingapp.cgi/Session/18572>) (Gregorich, 2019). The 22 papers making up this special section detail the history of P and its many uses, the role and management of P in modern agriculture, opportunities to improve this management in the future, and the socioeconomic challenges of forging broad societal alliances toward long-term global solutions for sustainable P and water quality management.

Highlighting the History of Phosphorus in Driving Research and Transforming Agriculture

The earliest documented cause-and-effect research on the use of P as a fertilizer in crop production was conducted at Rothamsted Research (previously known as Rothamsted Experimental Station and the Institute of Arable Crops Research), located in Harpenden, UK, founded in 1843, making it one of the oldest agricultural research institutions in the world (<https://www.rothamsted.ac.uk/about>). Johnston and Poulton (2019) demonstrate how 175 years of field experiments at Rothamsted provide a unique insight into the role of P in soil fertility and crop growth, as well as the build-up and drawdown of plant-available P. The "Park Grass Experiment" initiated in 1856, remains one of the longest continuously monitored soil fertility studies. Johnston and Poulton (2019) highlight how the collaboration between John Lawes (an entrepreneur, scientist, and founder of Rothamsted Experimental Station) and Joseph Gilbert (a chemist) during the last half of the 19th century forged an interdisciplinary alliance that has served as a model, both then and now, for how collaborative research can transform agricultural production systems.

Despite successful interdisciplinary research on the production, use, and management of P, new challenges have emerged that were once overlooked or minimized. Indeed, for P, the very systems that allowed humankind to overcome the fundamental inequalities in land resource distribution, using fertilizer and other inputs, have also resulted in a new type of inequality: the imbalance of P distribution across different agricultural sectors and between different regions (Jarvie et al., 2019). As an example, Reid et al. (2019) highlight the growing agronomic soil P

imbalances, with widening disparities between soil P deficiency and excesses, in agricultural production systems in Canada. Also, in China, there was a 50% increase in the rate of P applied in crop production between 2004 and 2014 (Zhang et al., 2019). Further, economic inequalities limit P fertilizer availability and use in Africa and some parts of Asia (MacDonald et al., 2011), and locally specialized production systems in the United States have created regional surpluses and deficiencies of P (Jarvie et al., 2015).

Focusing on Phosphorus Mitigation for Addressing Water Quality and Use Impairment

The seminal work of Schindler (1977), highlighting the dependence of freshwater eutrophication on P inputs, has inspired a large body of research on factors influencing P runoff from various agricultural production systems and practices, as well as strategies to minimize P losses in runoff. Despite decades of activities aimed at mitigating P-related eutrophication, however, persistent challenges remain in translating P science into management strategies that are both palatable and workable to those charged with implementing them and effective in improving water quality (Jarvie et al., 2013b). Smith et al. (2019) point to the historical and contemporary factors affecting the efficacy of agricultural P mitigation for water quality, along a latitudinal transect of major North American watersheds, and the challenges in translating P science to agricultural P management. Kleinman et al. (2019) explore some of these translational challenges that have resulted in “uneven improvements” in water quality in the Chesapeake Bay watershed. Despite the application and coordination of policies to reduce P loadings to the Chesapeake Bay since 2010, Kleinman et al. (2019) show that soluble P is increasing in key tributaries where agriculture is a major source of P runoff, a phenomenon also observed in the Lake Erie watersheds (Jarvie et al., 2017).

A dark and widening gap that can limit the effectiveness of remedial measures derives from the exclusion of end users at various points of the process of developing and implementing P mitigation strategies. Osmond et al. (2019) explore that gap through their examination of factors affecting the efficacy and adoption of best management practices for improving water quality. They highlight the importance of watershed planning, farmer involvement in decision making, and educational outreach in successful mitigation programs.

Increasingly, P mitigation strategies require the integration of various models and decision support tools to illuminate best options in planning, practice and policy. Drohan et al. (2019) track the evolution of P decision support tools and systems, including the repeated role of “reactive legislation” in driving the need for new tools, as well as the growing possibilities for leveraging remote sensing, real-time monitoring, and “big data” analysis to advance P decision support. Withers et al. (2019) describe models that estimate soil test P changes in response to changes in P management and examine how managing soil loss and soil P fertility status could help draw down legacy soil test P to threshold values that are optimum for productivity and reduce eutrophication potential.

Reflecting on the Need to Improve Phosphorus Use Efficiency

While management efforts to minimize P runoff are of critical importance, the impacts of growing populations of increasing affluence necessitate a wider global focus on improving the utilization and use efficiency of P right across the food chain: from crop and livestock production to food production, consumption, and wastage to wastewater treatment and disposal.

The urgent need to improve P use efficiency (PUE) in agroecosystems is highlighted by Schneider et al. (2019) who argue that in many cases, crop yields can be maintained at lower soil test P levels and that greater efficiencies in P cycling at the field scale can be achieved through agroecosystem management. Such management would work to increase organic P mineralization, utilize plants and microorganisms, and exploit P recovery and recycling (Schneider et al., 2019). Along these lines, Zhang et al. (2019) demonstrate how PUE in China decreased in the decade between 2004 and 2014; they propose strategies to improve PUE, which include improving legacy P utilization, reducing fertilizer applications, and implementing soil P management strategies.

Given the complex and interdependent influences of climate, land management, and soil type, it is clear that improving PUE will be site specific to a large degree. The unique historical dataset for Rothamsted Research documents strong relationships between crop yield and Olsen soil test P that facilitate identification of “critical levels” of Olsen P for optimizing PUE (Johnston and Poulton, 2019). However, Hopkins and Hansen (2019) remind us that high-yield cropping systems require both high P supply and high P uptake; therefore, the “critical” soil test P levels may be too low for intensively managed scenarios. Improving PUE in these high-yield environments requires new technologies to enable high yields, including precision P placement and enhanced efficiency P fertilizer sources (Hopkins and Hansen, 2019). Das et al. (2019) use soil P modeling to assist in identifying strategies to improve PUE. They underscore the need for long-term field trials, field data, and multidisciplinary collaboration, while noting that climate change presents challenges to predicting P availability and nutrient cycling (Das et al., 2019).

Bruulsema et al. (2019) discuss opportunities to use P legacies in crop production to increase PUE and decrease water quality impairment. A significant improvement in PUE can, in fact, be accomplished through the development of a new generation of fertilizer products and application technologies, according to Weeks and Hettiarachchi (2019). This can increase plant P acquisition efficiency, which, along with wider responsible nutrient management practices, helps improve PUE.

From a wider societal standpoint, Jarvie et al. (2019) explore how the “new” bioeconomy in bio-based products could provide market stimulus and opportunities for greater P recovery and recycling, whereby P-rich organic wastes and by-products are more highly valorized. As agricultural production of novel biomaterials and bioenergy increases, it will be vital to ensure that society’s vision for a more circular economy to improve resource use efficiency goes beyond the carbon cycle to include P.

A Kaleidoscope of Challenges Facing Efficient Use of Phosphorus

Effective P management must take into account local factors such as hydrology, soils, drainage, and type of production system. In addition to these factors, there are growing challenges of managing legacy soil and water P (Sharpley et al., 2013; Jarvie et al., 2013a), as influenced by climate change (Ockenden et al., 2017) and evolving environmental policies, which, together, can create a diversity of multiple pressures and trade-offs. This leads to a constantly shifting kaleidoscope of baselines and targets for P management (Jarvie et al., 2013b). Bieroza et al. (2019), Kleinman et al. (2019), Osmond et al. (2019), and Smith et al. (2019) all highlight the need to address legacy P stores and mitigate the increased P losses that are expected with climate change. They also champion the need to consider potential trade-offs involving P management practices, such as between particulate and soluble forms of P (Jarvie et al., 2017), as well as those practices that create “pollutant swapping” between P and nitrogen (N).

With regard to climate change, both Bieroza et al. (2019) and Kleinman et al. (2019) document increased mobilization of legacy P sources with increased frequency of prolonged drought or activation of latent sources during extreme storm events. The implications of interactions between legacy P and climate change, as long-term/historical factors affecting efficacy of agricultural P mitigation, are further explored by Smith et al. (2019).

As researchers and land managers struggle to develop scientifically sound and supported practices that address the challenges of legacy P on water-use impairment, a fuller understanding of the magnitude, extent, and timescales of P legacies is needed. For example, Neidhardt et al. (2019) discuss the role of transitional ecotones (e.g., buffer strips, stream banks, and stream beds) in legacy P storage and the transformations of P species between nonlabile and labile pools, with differing P bioavailability. Further, Glendell et al. (2019) show how combinations of multiple pressures (e.g., other pollutants, land use, and hydromorphological factors) can influence ecological response to changing P pressures; they recommend targeting P pressures alongside other multiple pressures.

Despite two decades of intensive monitoring and implementation of an ethos of nutrient and land conservation management in the Chesapeake Bay watershed, Kleinman et al. (2019) note increases in soluble P concentrations in some Chesapeake Bay watershed tributaries. They point to lingering concerns about legacy P in soils and reservoir sediments and the need to adapt P mitigation to address new and extreme events and hydrological regimes, brought on by climate change, which pose an acute risk to water quality (Kleinman et al., 2019).

Focusing on Place-Based Solutions: Think Globally, Act Locally

Our environmental, water, and P resource challenges are increasingly interconnected at a global scale; the movement of P as fertilizer, animal feed, food, and industrial commodities exemplifies the global interconnectivity of our nutrient, food, and bioresource production (Jarvie et al., 2015). However, there are disconnects between our understanding about better P resource management from regional and national scales and

the local social, environmental, and economic realities that determine farm-scale P management (Sharpley et al., 2016). This leads Smith et al. (2019) to highlight the challenges of applying science to agricultural management, and call into question “one-size-fits-all” approaches. Macrae et al. (2019), for example, examine the activation of surface runoff and tile flow as pathways of P transport and demonstrate that region-specific soil type and seasonality need to be considered when designing management strategies to decrease P loading via tile drains.

A unified promotion of the “4Rs” of nutrient stewardship (right source, right rate, right time, and right place, taking into account local site variations) by researchers, nongovernmental organizations, and agricultural supply chain stakeholders, has been a positive move forward to think globally, but act locally (Bruulsema et al., 2019; International Plant Nutrition Institute, 2014; International Fertilizer Association, 2009; Sharpley et al., 2016). Bruulsema et al. (2019) note that the initial goal of increasing the productivity and profitability of agricultural crop production via 4R-based P stewardship has been expanded to include the goals of minimizing P runoff, increasing recycling of P to reduce consumption, and improving soil health and agroecosystem biodiversity. Successful transitions in P management will require science–industry engagement, and Bruulsema et al. (2019) further describe how 4R nutrient stewardship addresses these multiple goals. However, the continued development of 4R practices depends on engagement between science and industry not only at the farm level but along the full agricultural value chain (Bruulsema et al., 2019).

Across diverse agroecosystems, Grant and Flaten (2019) describe how 4R management of P fertilizer use in the northern Great Plains—matching fertilizer rates to crop (small grains, oilseeds, and pulses) removal and banding fertilizer in or near the seed row at the time of seeding—provides the greatest P efficiency and long-term sustainability and environmental protection in this region. Ippolito et al. (2019) show how irrigation type influences soil P dynamics, noting a difference in soil P availability between sprinkler and furrow irrigation, with greater Olsen-extractable P in long-term furrow irrigation. In Australasian settings, Nash et al. (2019) detail the implications of varying hydrology on direct exports of P from fertilizer applications. They also describe how the use of information on local hydrology can help farmers identify principles for selecting fertilizers, to minimize risk of P loss, soon after application.

Glimmers of Hope and Bright New Horizons: Phosphorus Stewardship as a Guiding Light for the Future

The last five years have seen a strategically important convergence in research effort between P biogeochemistry and water quality and P resource sustainability and security across a wide range of agroecosystems and rural and urban environments to the global scale. A lasting legacy (of knowledge, not of P, in this case) of this collection of papers in this special section of JEQ is how diverse research areas, views, geography, and land management—perhaps most fundamentally—identify connections and commonalities toward the overall goal of improving P stewardship and, in particular, our societal P use efficiency. Moving forward, our research efforts will need to focus on the importance of

connecting a diverse range of scientific and stakeholder perspectives for addressing the P sustainability issues in the comprehensive manner that we know is required. This collection of papers is a step toward engaging a strategy of teamwork that will also need to extend beyond the scientific community and engage our wider stakeholder communities.

Of course, there are challenges ahead, particularly where the evolution of production systems has not optimized the efficiency of fertilizer P delivery. A lack of consistency among fertilizer recommendations, which in many cases rely on dated field trials, has clouded our ability to provide accurate and reliable advice to farmers on optimal crop P requirements. We face a conundrum arising from the simultaneous deficiencies and excesses of P across local, regional, and national scales, which have led to impairment of water quality, limiting water use and reducing both water and P security (Sharpley et al., 2018).

Addressing these challenges will require collaboration across all sectors of society to increase our P use efficiency. Clearly, this will require broader societal recognition that P is a nonrenewable resource and an essential component of an increasingly fragile nexus of water, bioresource, and food security (Jarvie et al., 2015). Wider collaboration will be needed to integrate soil, land, and water management; to manage the drawdown of our soil, landscape, and water-body P legacies; to capitalize on opportunities to recover and recycle P; to reconnect our broken P cycle; and to catalyze wider societal P governance across the entire food system, from farm to fork, to wastewater treatment and disposal.

As we celebrate the 350th anniversary of the discovery of *Phosphorus mirabilis*, there are clear glimmers of hope in tackling some of these grand challenges. For example, Margenot et al. (2019) examine the potential for regional P recycling in the US Midwest and emphasize that differences in P speciation in recovered products from different waste streams have important implications for crop P uptake and P losses and also influence the fate of N in recovered P products. It will, therefore, be important to match P recovered from different waste streams to appropriate agricultural systems and end users (Bruulsema et al., 2019; Margenot et al., 2019; Smith et al., 2019).

The enthusiasm of governments across the world to develop bioeconomies offers new opportunities to rethink our P stewardship. Moreover, recent technological breakthroughs in P materials science over the last five years, with the discovery of new “two-dimensional” (2D) P allotropes (i.e., 2D black and blue P) (Jarvie et al., 2019), opens up new potential to expand the future role of P within the bioeconomy. These novel applications have new and contemporary resonance for *Phosphorus mirabilis* because they capitalize on the interactions between novel ultrathin P allotropes and light. Jarvie et al. (2019) highlight the developments in use of these 2D P allotropes, including in solar energy production and storage; as a photocatalyst for use in artificial photosynthesis and renewable energy conversion; in medical applications, as a photosensitizer in photodynamic therapy and in photo-responsive drug delivery; and in biosensors, based on the fluorescent and colorimetric detection of a variety of bioanalytes.

As we look to the future, it is clear that we can no longer consider agricultural P losses, water quality, and eutrophication in isolation. Solutions to address the challenges we face with accelerating global environmental change require vibrant and

multifaceted cross-disciplinary collaborative research: bringing together new understanding of how our agricultural, rural and urban systems will respond to climate change, and the wider impacts on global, regional, and local water and nutrient cycles. This will also necessitate closer integration of water quality science and P recovery technology, materials science, and engineering with the socioeconomic and institutional understanding of water and P management and governance.

These cross-disciplinary approaches to P stewardship provide a vital guiding light for developing integrated and adaptive approaches to land and water management to tackle the challenges, opportunities, and trade-offs that will undoubtedly arise between water resources management, urban development, and food and bioresource production. A fundamental requirement is the involvement and engagement of local communities and stakeholder groups in co-designing effective and lasting P stewardship solutions that consider local social, environmental, and economic conditions and address both environmental and human health and well-being concerns. This underscores the greatest challenge ahead for our long-term stewardship of *Phosphorus mirabilis*: moving from today's glimmers of hope toward the bright new horizons needed to ensure future food, water, and bioresource security for growing global populations—under increasing pressures from climate change—but without compromising the quality, ecological status, and health of our water resources.

Conflict of Interest

The authors declare no conflict of interest.

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