Better Crops with plant food

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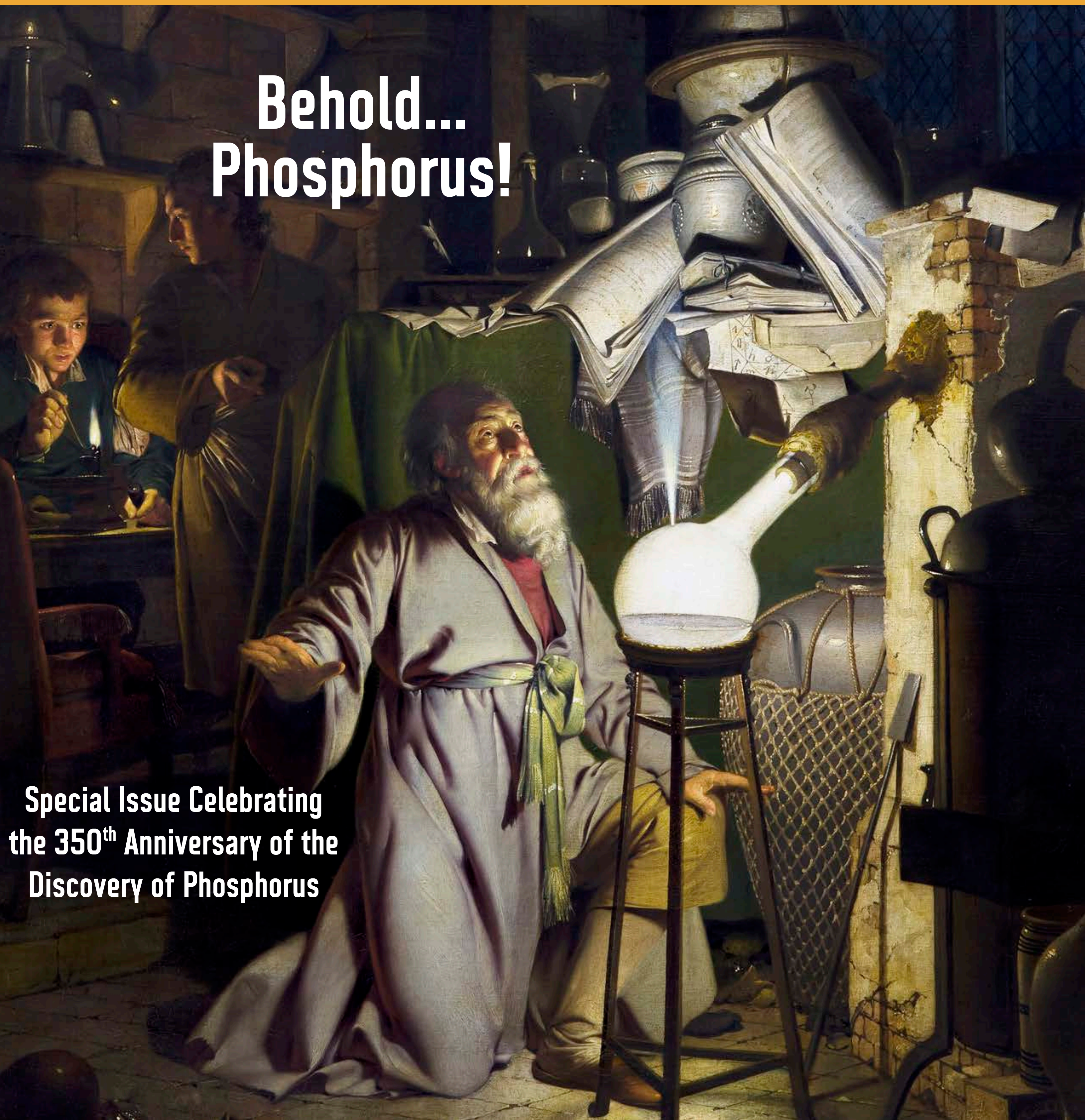

Behold... Phosphorus!

Special Issue Celebrating the 350th Anniversary of the Discovery of Phosphorus

Better Crops with plant food

Vol. CII (103) 2019, No. 1

Our cover: The Alchemist Discovering Phosphorus is a painting by Joseph Wright of Derby originally completed in 1771. Wikimedia Commons.

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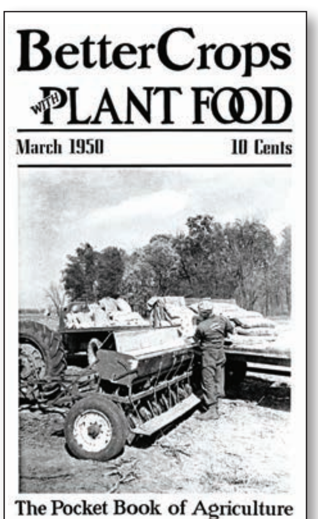

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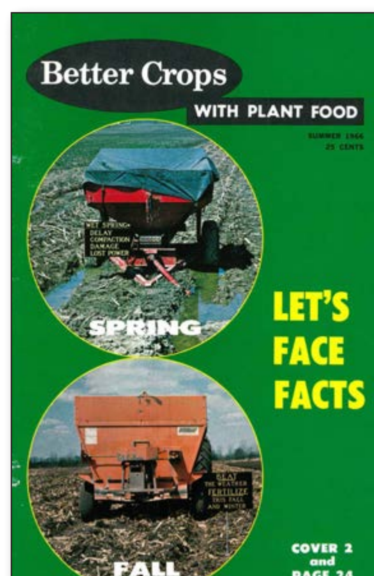
Publisher: American Potash Institute (1935 to 1970)

Editor's Note: Our Final Issue

The release of this special focus issue coincides with our last issue of *Better Crops with Plant Food*. This year (2019) marks the 92nd year for this publication. Actually, its origin dates back four more years to 1923, but officially in 1927 two parent magazines known as "*Better Crops*" and "*Plant Food*" merged to form the top of the masthead that you see today.

Over the years this quarterly has been known as "the pocket book of agriculture" and for "telling the whole truth …not selected truth." The success of *Better Crops* has been built on its reputation as a trusted source for practical, condensed, and noncommercial information that, looking back, documents the progression of best practice for nutri-



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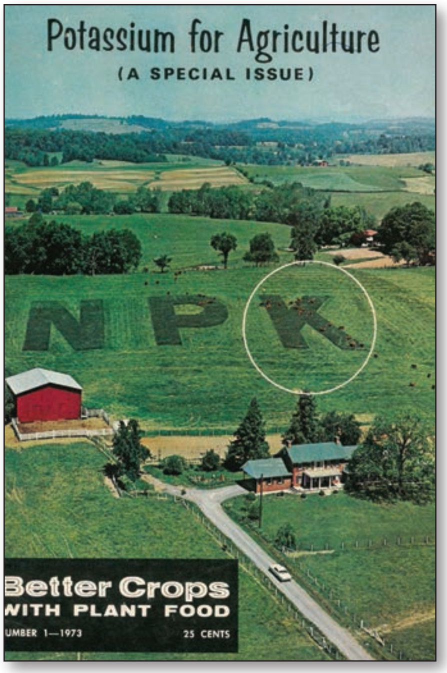

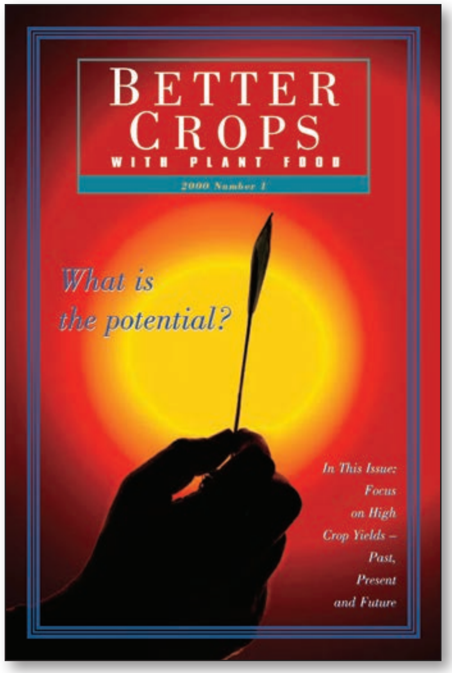

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2000 (February)
Publisher: Potash & Phosphate Institute/Potash & Phosphate Institute of Canada (1977 to 2006)

2016 (February)
Publisher: International Plant Nutrition Institute (2007 to 2019)

ents used in the production of food, feed and fiber.

We are grateful to both our network of contributors and our uniquely global readership of scientists, educators, marketers, students, and farmers. It's been a privilege to serve as editor of this extraordinary publication for the past eight years.

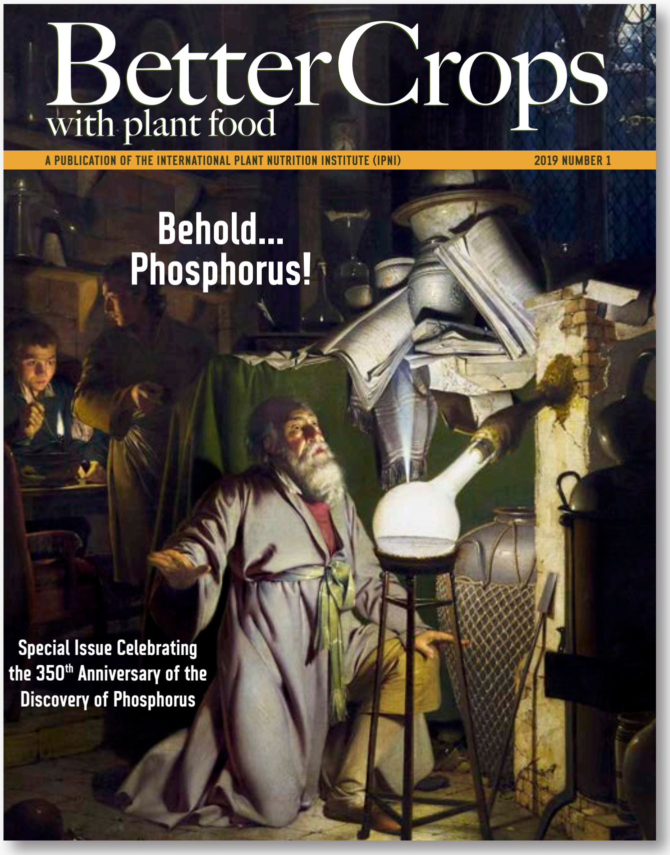
Please enjoy this special issue on phosphorus. It's an exceptional collection of articles and everyone knows it's always best to finish on a high note.

May your crops always be better,

Gavin Sulewski, Editor

2018 (November)
Publisher: International Plant Nutrition Institute

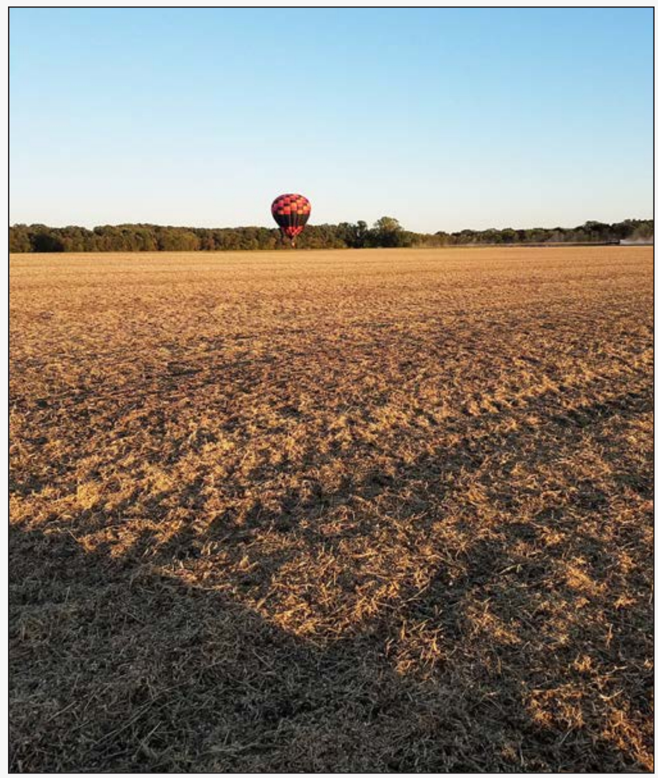
350 Years and Counting……



As 2019 marks the 350th anniversary of Hennig Brandt's discovery of phosphorus (P), sometimes referred to as "the Devil's element", it is a time to reflect back on the number of significant scientific advancements that have followed. As IPNI prepares to close its doors this June, we view this final special issue of *Better Crops* as a legacy of the research collaborations our organization has engaged in over the years to not only advance the field of crop nutrient management, but increase the adoption of practices across the globe through improved awareness.

World population is expected to increase by two billion people by 2050, elevating the urgency to advance the science of P management to more sustainably meet the global needs for food, fiber and feed while minimizing environmental impacts. The articles included in this P issue were chosen to strategically step through the fundamentals of P science, capturing highlights of the progress that agriculture, through the work of great researchers, has achieved over the decades.

To highlight the contribution of P to agricultural advancement, we begin this special issue of *Better Crops* with a historical perspective summarizing the impact of P on the global food supply. Balancing crop needs while minimizing ecological impacts is a conundrum facing the world, which will require a transformative solution based on new innovation. The breadth of the issue is described through articles focused on sources, cycling, uses, and spatial disproportionality. As science continues to advance to better quantify available soil P, we highlight topics around rhizosphere interactions, soil test approaches, and management strategies for increasing availability. We conclude this special issue with a projection on the future of P.



Patrick O'Connor

As we embark on our journey and move forward in the field of P science, during this time of climate and landscape change, our cropping systems must focus on adaptive management practices that engage sustainable solutions—ensuring that we integrate the use of our P sources with the principles of 4R Nutrient Stewardship and the adoption of conservation practices.

Cheers to the future of sustainable P management!

Heidi Peterson

Heidi Peterson
Phosphorus Program Director

Phosphorus: Past History and Contributions to the Global Food Supply

By Terry L. Roberts

In 1669, the German alchemist Hennig Brandt accidently discovered P while searching for the 'philosopher's stone', a legendary alchemical substance capable of transmuting lower value base metals into gold (Krafft, 1969). Brandt's experiments, involving the distillation of human urine with pieces of silver, produced a white, waxy substance that glowed in the dark. He named the substance 'cold fire', which was later changed to 'phosphorus', meaning light bearer.

In 1776, P was recognized as the 13th element in the history of the discovery of elements (Emsley, 2000). In its elemental form, white P is highly reactive and is not found in nature. Exposed to air, it is flammable, can spontaneously combust, and is poisonous in low doses. Because of its life-destroying properties when used in military applications (e.g., bombs, nerve gas), it became known as the 'devil's element.'

For a century, urine was the only source of P until it was found in bones by two Swedish scientists, Ghan and Scheele, in 1770 (Wisniak, 2005). In the years following, manufacturing processes were developed for commercial P production. Bone ash was reacted with sulfuric acid to produce calcium phosphate [$Ca(H_2PO_4)_2$]. In 1831, Heinrich Kohler patented a method for acidulating bones with sulfuric acid in Austria and in 1835, James Murray, an Irish medical doctor referred to 'superphosphate of lime" in lectures and was issued patents in Ireland, Scotland, and England covering the acidulation of bones in 1842. Later P was found to be a principal constituent of certain igneous and sedimentary rocks.

About the same time, Justus von Liebig referenced mixing sulfuric acid with finely ground bones to make the bones more effective in supplying P to plants. In his 1840, and subsequent editions of *Organic Chemistry in Its Application to Agriculture and Physiology*, he recommended:

> *"… pour over the bones, in a state of fine powder, half their weight in sulfuric acid diluted with three or four parts water, and after they have digested for some time, to add one hundred parts of water, and sprinkle this mixture over the field before the plow … Experiments have shown that neither corn, nor kitchen-garden plants, suffer injurious effects in consequence, but that on the contrary they thrive with much more vigor" (Liebig, 1840).*

Leibig, in addition to suggesting that bones be treated with acid, greatly influenced the thinking on plant nutrition and fertilizers. His theories stimulated research by others.

John Bennett Lawes used bone dust on his estate near Harpenden, England to fertilize turnips in 1836-1838, but with little effect (Nelson, 1990). He then started a series of small-scale pot experiments in 1839 with bones and mineral phosphates acidulated with sulfuric and other acids, and in 1840-1841 moved his trials to the field, which led to the granting of his famous superphosphate patent in 1842. In 1846, Lawes purchased Murray's patent, to avoid any questions of priority that might arise and 1848 he amended his patent to remove all references to bone and bone products, confining it to 'apatite and phosphorite, and other substances containing phosphoric acid.'

The development of single superphosphate (SSP) by Lawes marked the beginning of world's phosphate fertilizer industry.

Lawes began manufacturing and selling superphosphate of lime in 1843 and that marked the beginning of the world's phosphate fertilizer industry. Within a decade, superphosphate was being produced by 14 firms in England and quickly spread to other parts of the world. (Russel and Williams, 1977). As bones became in short supply, producers in England switched to coprolites, a hard nodule found just above the clay layer in some nearby soils. Later apatite was imported from Norway and rock phosphate from France

SUMMARY
Since its early rudimentary forms, phosphate fertilizer has developed in step with our understanding of successful food production systems. Recognized as essential to life, the responsible use P in agriculture remains key to food security.

KEYWORDS:
phosphate; fertilizer history; broadbalk experiment; sustainable yields

ABBREVIATIONS AND NOTES:
P = phosphorus; N = nitrogen

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Site of the Broadbalk Experiment in Rothamsted, England, started by John Bennett Lawes in 1843.

and Belgium. Rock phosphate was discovered in the U.S. in 1867, and soon after in many other countries throughout the world.

Single superphosphate, with a relatively low P content (~20% P_2O_5), dominated P fertilizers for more than 100 years. Small amounts of concentrated superphosphate (44 to 48% P_2O_5), i.e. triple superphosphate (TSP) were produced in Germany in the early 1870s (Leikham and Achorn, 2005). However, as its production was dependent on phosphoric acid ... it wasn't until the 1950s that TSP became an important phosphate fertilizer with the development of the first phosphoric acid plant (Robinson, 1980). The introduction of TSP began the era of 'high analysis' phosphate fertilizers and established the phosphate industry near deposits of rock phosphate (Leikham and Achorn, 2005). Production of TSP peaked in the 1980s, but has since been replaced by ammonium phosphates. When synthetic ammonia became commercially available, its use to ammoniate superphosphate grew rapidly. Production of different grades of ammonium phosphate have been available since at the early 1910s, but it wasn't until the 1960s that ammonium phosphate production became commonplace.

Lawes experimenting with fertilizer materials led to his establishment of the Rothamsted Experimental Station on his estate in 1843 (Rothamsted Research, 2018). However, with no formal training in chemistry or other sciences he appointed Joseph Henry Gilbert, a chemist who had briefly studied under Liebig, as his scientific collaborator. Lawes and Gilbert worked together for nearly 60 years. They planted the first of the classical Rothamsted long-term experiments on the Broadbalk field in 1843 and during the next 13 years established nine long-term experiments. The objective was to measure the effects of inorganic fertilizers on crop yields. Inorganic fertilizers were compared to farmyard manure tested alone and in various combinations. Single superphosphate was tested in all of the studies. Growing the same crop on the same land, year after year was a feature of many of the studies.

Rothamsted has become home to the oldest, longest-running trials on fertilizer in the world. One of the most important early results from the experiments was that crops do not respond to N when there is too little plant-available P in the soil (Johnson and Poulton, 2018). We have learned much about plant-available P, P fixation, residual P, and the response of crops to P fertilization from these long-term trials.

Rothamsted's Broadbalk experiment has grown winter

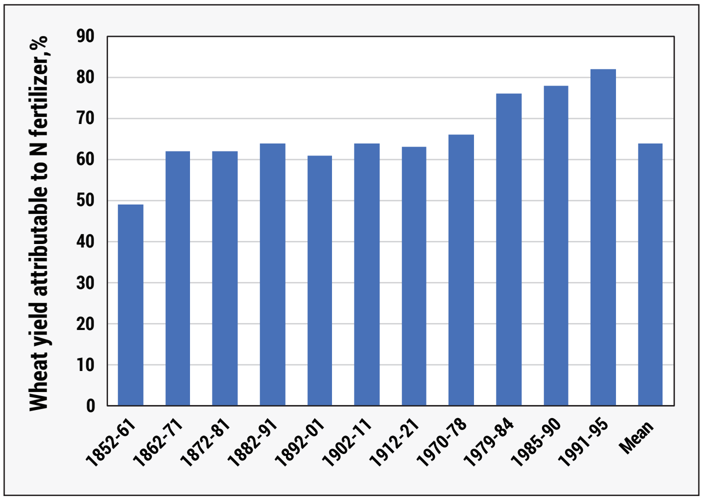

Figure 1. Winter wheat grain yield from NPK compared with P+K applied alone in the Broadbalk experiment at Rothamsted, England. Years between 1921 and 1969 are not shown because part of the experiment was fallowed for weed control (Adapted from Stewart et al., 2005).

wheat continuously since 1843. Application of N fertilizer, with P and K has been responsible for up to 82% of wheat yield compared to P and K applied alone, with an overall average of 64% (**Figure 1**). Between 1970 to 1995, with high-yielding varieties of winter wheat receiving 95 kg N/ha, omitting P decreased yields by an average of 44% (Stewart et al., 2005).

Nitrogen provides the basis for animal and human protein and is essential for crops to achieve optimum yields. About half the world's population is supported by N fertilizer (Erisman et al., 2008), but N is not used efficiently or effectively without P. Examples of the positive interaction between N and P on wheat yield and nitrogen use efficiency (NUE) from Australia, Canada, United States, and the United Kingdom have been recently reviewed by Duncan et al. (2018). They reported on data from 11 studies showing grain yields ranging from 1,000 to 3,590 kg/ha without fertilizer, 1,100 to 4,015 when N was applied alone, and 2,610 to 6,270 kg/ha when N and P were applied together (**Figure 2**). The additional yield from the P ranged from 142 to 3,205 kg/ha. Applying P with N, increased NUE in 9 of the 11 studies, resulting in increases ranging from 2.1 to 31.2 kg additional grain/kg N applied compared to N applied alone. Phosphorus is a crucial for balanced plant nutrition.

Summary

Phosphorus is the basis for all life on earth. It is the sixth most abundant element in living organisms, is a necessary constituent of DNA and our genetic code and provides the energy for all metabolic processes. Phosphorus is essential to global food security. The production of food, feed, fiber, and energy supporting population growth would not be possible without P. However, P lost from agriculture can cause problems with water quality resulting in eutrophication, and the raw material for making P fertilizer, rock phosphate, is

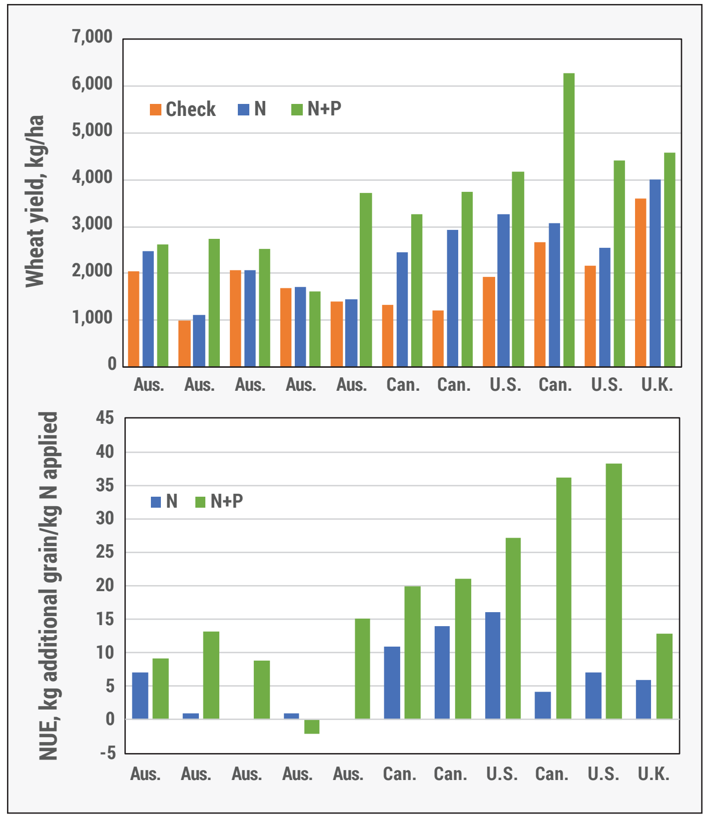

Figure 2. Summary of results from studies in Australia, Canada, U.S. and U.K. investigating the effect of N and N+P on wheat yield (top) and NUE (kg additional grain/kg N applied) (bottom) (Adapted from Duncan et al., 2018).

a non-renewable resource. While the world is in no danger of running out of rock phosphate in the foreseeable future, it behooves us to use this valuable resource as efficiently as possible (Scholz et al., 2014). Nutrient management within a 4R framework—application of the right source of plant nutrient, applied at the right rate, at the time, and in the right place—is the foundation of efficient P use. **BC**

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

By Roland W. Scholz and Friedrich-Wilhelm Wellmer

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.

> ***"In 'phosphorite factories' ... 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."***

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.

KEYWORDS:
phosphate rock; nutrient cycles; use nutrient efficiency; resource management

ABBREVIATIONS AND NOTES:
P = phosphorus; N = nitrogen

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L. Prochnow/IPNI

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). Standardized 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.

"…the (phosphate rock) reserve/production ratio may be viewed as an early warning indicator; yet it is about 266, which is one of the largest among all mineral commodities."

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 efficient 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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Measuring Crop-Available Phosphorus

By John Kovar and Heitor Cantarella

E. Francisco/IPNI (main); J. Kovar (nset)

Proper P management is important to minimize the risk of economic losses due to P deficiency or environmental degradation resulting from excessive P applications. The main image shows unfertilized soybean in the foreground of a P-deficient field. The inset image shows eutrophication due to excess P that was transferred to the water body.

Proper diagnosis of crop-available soil P is a critical first step to guide the use of P fertilizer in agriculture. Soil P tests provide an index of plant-available P, which is then used to determine the amount of supplemental P, if any, needed to prevent economic loss of crop value. Soil P tests also provide a means to monitor changes in available P over time, which is useful for making P management decisions that not only affect the crop, but also play a role in the protection of water quality (Fixen and Grove, 1990).

Within a growing season, plant tissue analysis can be used together with a soil test as a diagnostic tool to monitor the P nutrition of the crop. Plant analysis is said to be the "final judge of the success or failure of a fertility program" (Bryson and Mills, 2014). Research has shown that there is a consistent correlation between the P concentration in a specific part of the plant collected at a specific growth stage and the growth or yield of the plant. This relationship provides the basis for assessing P deficiency or sufficiency in the plant.

Testing soil to predict P availability generally consists of four steps: 1) collecting a representative sample; 2) analyzing the sample for plant-available P; 3) correlating the results of the analysis with known crop responses; and 4) calibrating and interpreting the results to make a fertilizer P recom-

SUMMARY

It is likely more critical than ever to have access to proven indicators of the plant availability of P given the awareness of the implications of its management in crop production and the surrounding environment. Methods of assessing P availability will vary regionally, but commonly achieve good correlation to plant response. Continued improvement in the delivery of P sources to crops is in turn encouraging research that is improving our understanding of how to assess the behavior of P in soil.

KEYWORDS:

plant-available P; labile P; soil testing; fertilizer recommendations

ABBREVIATIONS AND NOTES:

P = phosphorus

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mendation. Of the steps required for a soil P-testing program, the chemical analyses are usually the most accurate part. In this article, our main focus is soil analysis.

The chemistry of soil P is quite complex. Phosphorus in soil solution, the pool from which plant roots acquire P, is generally of low concentration and must be replenished by solid-phase P. This P is found in insoluble minerals, organic compounds, and chemical species that are not readily taken up by plants. A small fraction of the soil P is considered labile P, which is the solid-phase P that rapidly replenishes the solution P. The amount of labile P in a soil is one of several factors that determines plant-available soil P. Labile P and plant-available P are highly correlated, but not equivalent.

The amount of plant-available P is not a distinct value for a given soil. It varies with environmental conditions that affect both plant and soil processes. This presents a challenge for scientists who want to develop soil analysis methods that can quantify plant-available P. Fortunately, several useful P extraction procedures that correlate well with plant P uptake have been developed and continue to be refined.

The soil P analysis methods used by different laboratories tend to be quite empirical (i.e, based on past experience or observation). As the prevailing chemical species of P vary with soils, different methods that extract specific soil P fractions have been proposed for different situations.

The majority of soil samples are tested for available P by extraction with dilute solutions. More than a century ago, a 1% citric acid solution was used to extract P and other "available mineral plant food" from soils. Since that time, extracting solutions specifically targeting soil P availability have been developed. For example, the Bray P1 and Mehlich-1 methods are dilute acid extractants usually employed in more acidic soils, while the Olsen test (a bicarbonate solution) is more suitable for alkaline soils. Calcium lactate or calcium-acetate-lactate (CAL) extraction is popular in Europe, Australia, and elsewhere. The Mehlich-3 extractant was developed to be a multi-nutrient extractant that suits many soil testing laboratories due its cost effectiveness. Other tests, such as the ion-exchange resin and iron-oxide coated paper methods, work well with more diverse types of soils, but have not gained in popularity because of their perceived complexity. Ultimately, soil scientists should determine the most appropriate methods for each region or situation, based on local experimentation.

The results of plant-available soil P tests must be correlated with known crop responses (**Figure 1**) and calibrated in laboratory and field studies so that they can be interpreted and subsequently used to make P fertilizer recommendations. The better the correlation, the more accurate the soil P test.

Results of soil P tests are typically divided into classes, such as very low, low, medium, high, and very high. These

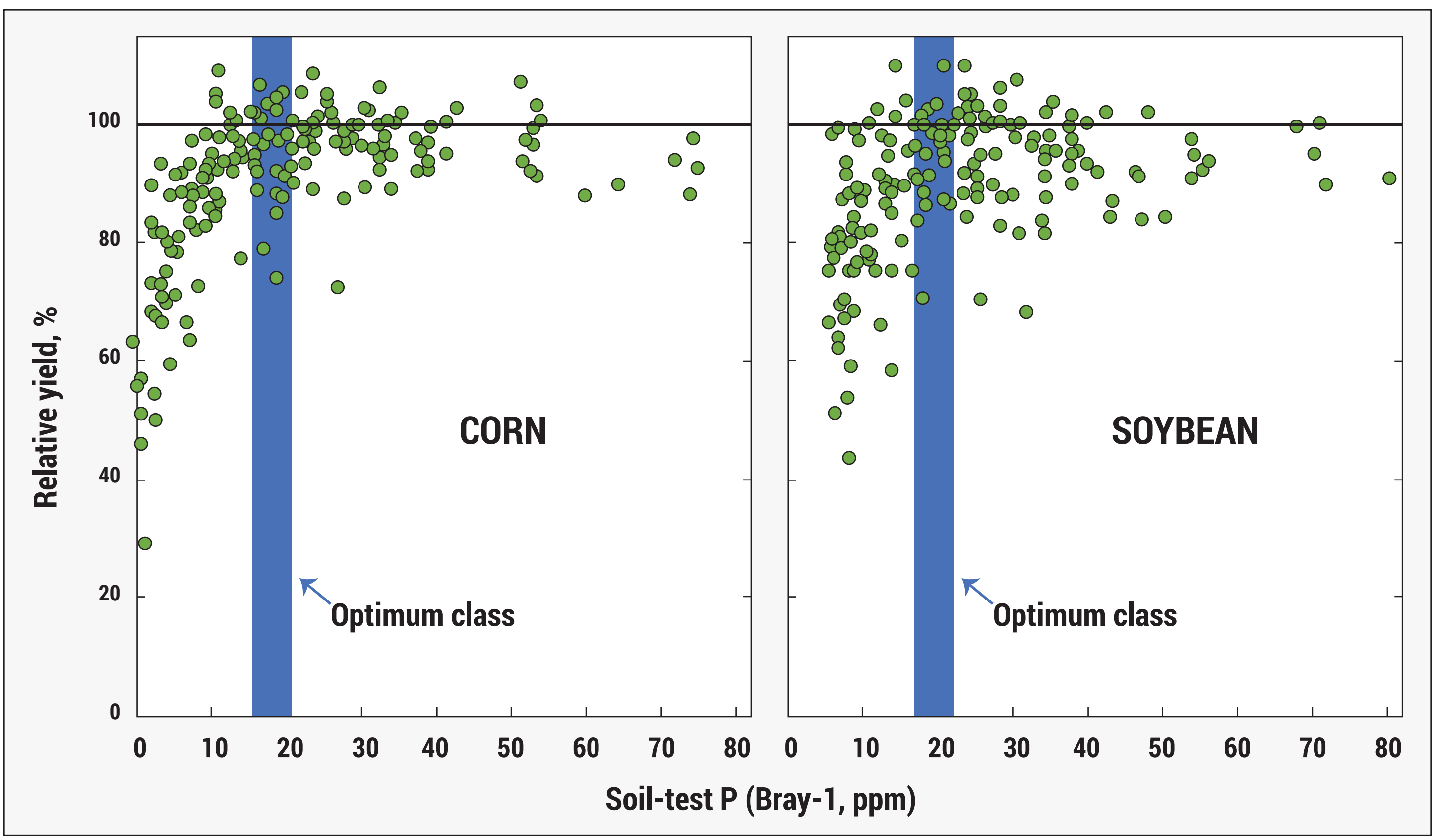

Figure 1. Relationship between soil-test P and relative yield of corn and soybean across several years of experiments at Iowa locations. Only maintenance P fertilizer is recommended if soil test P is in the optimum class (Modified from Mallarino, 1999). The blue bar indicates the range of P sufficiency.

TAKE IT TO THE FIELD

Soil analysis optimizes P fertilization for (1) crop yield and economic return, and (2) avoidance of unnecessary expenses and environmental risks in situations where additional P is not necessary.

There are different soil tests for P, but the interpretation of their results can be straightforward, and relatively simple: very low, low, medium, high and very high. End-users, such as farmers, consultants, and extension personnel, will intuitively know what the results mean.

classes are self-explanatory: soils testing low or very low require high inputs of P fertilizer to produce an optimum yield, whereas soils testing high or very high need little or no supplemental P. The amount of P fertilizer to apply also depends on the crop and the expected yields. Applying a fixed amount of P without determining available P with a soil test can result in crop yields below potential or unnecessary fertilizer application, negatively impacting the economic return.

Brazil has an interesting example of how selecting an adequate soil P method helped farmers to have a better diagnostic of available P. The prevailing soils in Brazil are oxisols that are highly acidic, P-fixing, and low in plant-available P. Yet acid extractant solutions containing hydrochloric and sulfuric acid may still underestimate plant-available P in many of these soils. This leads farmers to apply more P than necessary, especially in areas that have been previously fertilized.

Figure 2 (top) shows the relationship between relative yield of cotton and soil P as determined by an acid extractant versus ion-exchange resin in 27 fields. The acid extractant failed to differentiate between responsive and nonresponsive sites with soils having less than 10 mg P/dm^3, which theoretically should be low in P. When the ion-exchange resin method was used, it became clear that many of those soils that were classified as P deficient in the previous analysis had adequate available P, and the correlation between plant response and soil analysis was much better (**Figure 2**, bottom).

As can be expected, plant uptake provides a better indicator of available P in the soil. Much of the success of ion-exchange resin methods is based on the extracting procedure ability to mimic the action of roots capturing P from the soil solution (**Figure 3**). Based on this research and other studies, this method has been adopted by many laboratories.

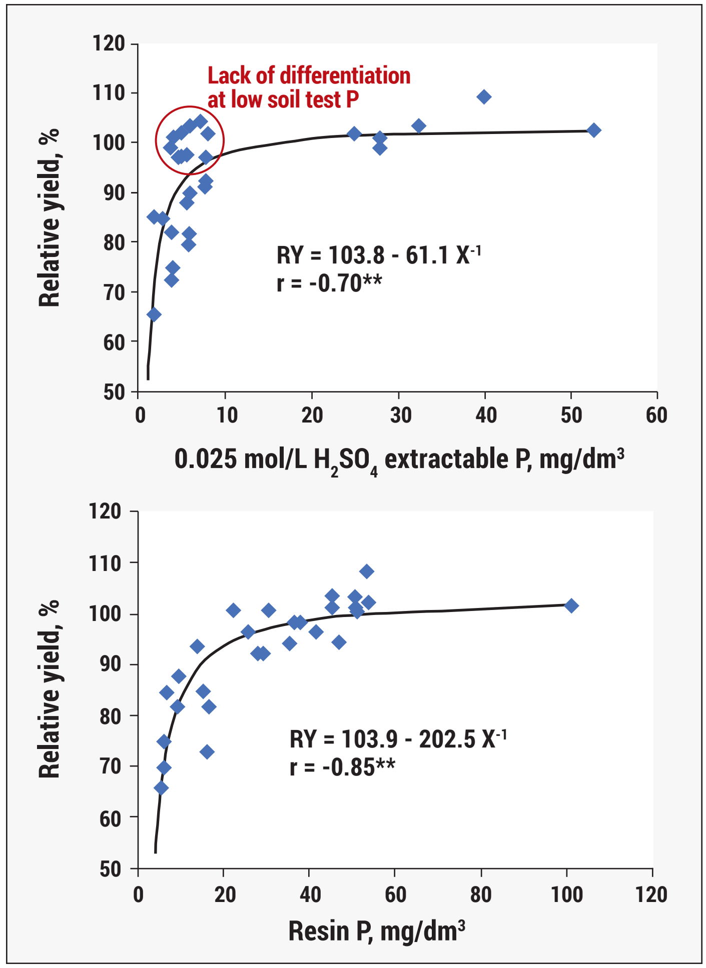

Figure 2. A nutrient extractant that matches soil characteristics is important for the determination of plant-available P. The acid extractant (top) performs poorly in acidic tropical soils, whereas ion-exchange resin extraction (bottom) provides a better diagnostic of available P for predicting relative yield (RY) (Modified from Raij et al., 1986).

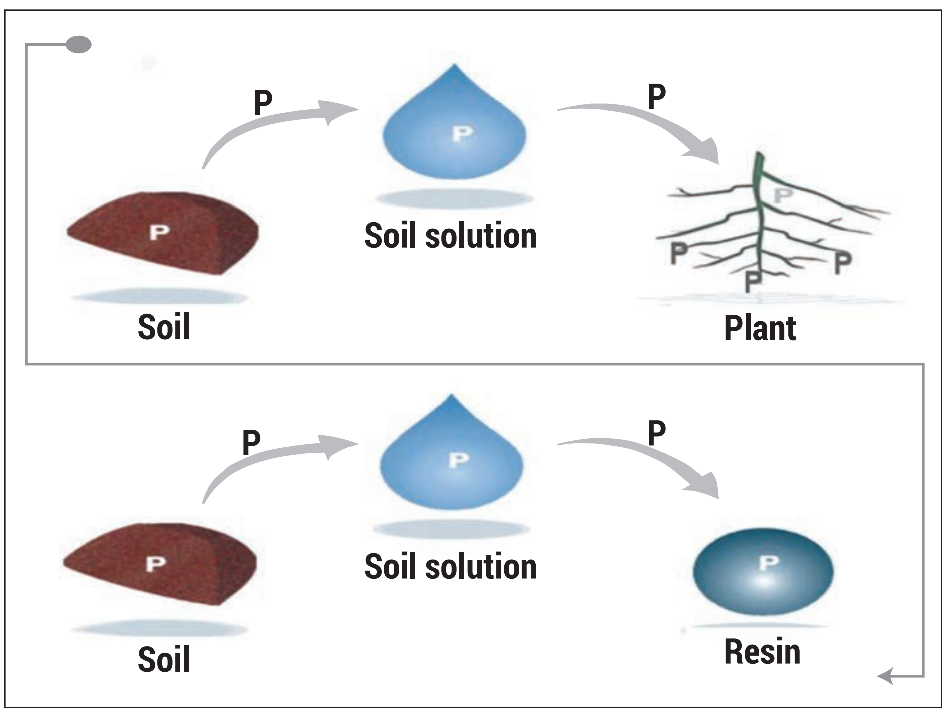

Figure 3. Schematic of P soil extraction with ion-exchange resin and how it mimics plant uptake of soil P (Raij et al., 2001).

Today, more than 100 soil testing laboratories in Brazil routinely use this procedure.

The sensitivity of the soil test to effectively detect low P is especially important in regions of the globe where P deficiency is common. In Brazil, approximately 80% of soils in the most important grain-producing region were originally P deficient. In regions where excess soil P may be a problem due to overfertilization or high manure inputs, soil testing is also an aid to manage crop nutrition and reduce environmental loss. In this situation, the choice of soil test method is less restrictive because most of them are able to indicate high concentrations of plant-available P. In any case, there is no good reason to avoid soil testing.

Closing Thoughts

The demands placed on soil P tests and their interpretations continue to increase. In recent years, we have acquired greater knowledge of the soil P cycle, soil P supply to roots, and the mechanisms of P uptake by plants, as well as the role P plays in our environment. Technological advances in fertilizer application (e.g., variable rate application equipment, applicator guidance systems) have surpassed the ability of most current soil P testing programs to provide recommendations. Therefore, research on improved soil P testing methods and more sophisticated interpretation of the results must continue. **BC**

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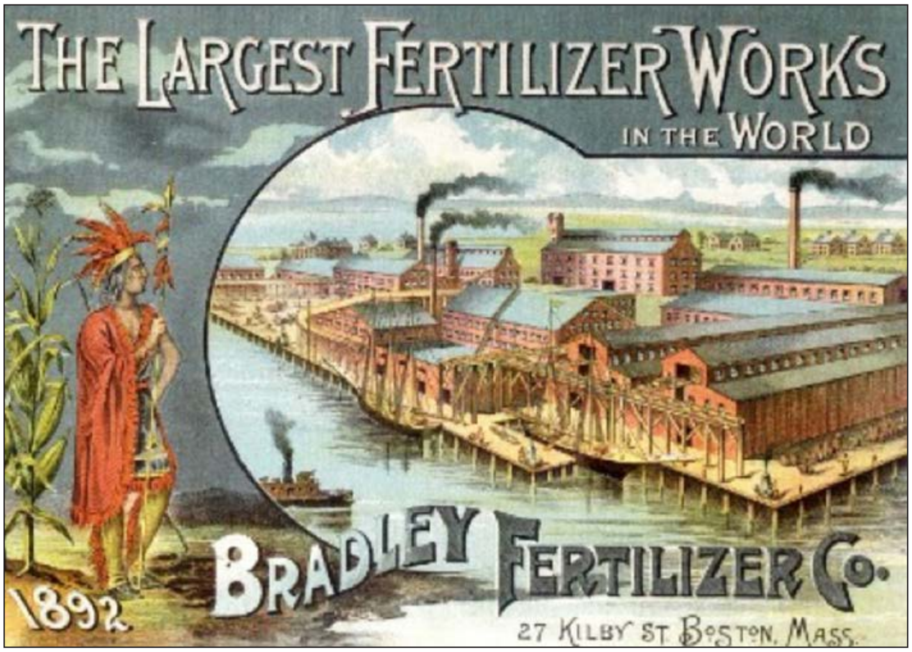
Sources of Phosphorus for Plants: Past, Present, and Future

By Robert Mikkelsen

When humans first transitioned from hunting and foraging to farming, soil P depletion began as crops were harvested and removed from their fields. Early farmers learned to enrich soils with animal manure or adopt shifting cultivation. However, as cities developed, nutrients were systematically withdrawn from the field and concentrated near the city.



Plant nutrient depletion and agricultural sustainability has been addressed in various ways by different civilizations. Newman (1997) describes how P depletion as a result of crop production was handled in the U.S. Prairie (by exploiting P from organic matter mineralization), on a typical medieval English Farm with declining wheat production (running a P deficit of 0.7 to 0.9 kg P/ha/yr), for Egyptian fields which remained in P balance from annual flood water, and in Northern China, where P deficits occurred even with the traditional spreading of human excreta (with the accompanying fecal-borne diseases).

Slash and burn agriculture was commonly employed to clear land and enrich the soil with nutrients from the residual ash. One study reported that forest ash contained 11 kg P/ha and 27 kg N/ha after burning, of which more than half was blown from the field in wind (Giardina et al., 2000). Additionally, in medium to high-intensity fires, heat-induced reactions can increase P sorption by soil minerals, leading to reduced P recovery by crops. During the U.S. colonial period, slash and burn techniques forced inland migration from the Atlantic Coast as agricultural fields were successively exhausted of their nutrients with no means of restoring the fertility. When added to soil, the liming effect from ash and the input of mineral P and K made it a good amendment for growing a N-fixing crop.

In the early 1800's, it was discovered that P is beneficial for plant growth. As the value of "pounded" bones was recognized as a P source, the demand grew quickly in the early 19^{th} century. Unprocessed bones (hydroxyapatite; $Ca_5F(PO_4)_3OH$) were crushed and applied to the soil at a rate of 1 t/A or more. In England, the demand for bones outstripped the domestic supply and by 1815, bones were imported from the Continent, reaching a maximum of 30,000 t/yr (Nelson, 1990). This led the famous plant nutritionist Justus von Leibig to complain:

"England is robbing all other countries for their fertility. Already in her eagerness for bones, she has turned up the great battlefields of Liepsic, and Waterloo, and of Crimea: already from the catacombs of Sicily she has carried away the skeletons of many successive generations. Annually she removes from the shores of other countries to her own the manuerial equivalent of three million and a half men…. Like a vampire she hangs from the neck of Europe" (Liebig).

The observation that not all bones were equally effective as a plant nutrient source led to experimentation to acidify the bones before adding them to soil. One early innovator, John Lawes applied raw bone to his farm fields without

SUMMARY

The phosphate fertilizer industry developed in the 19th century to provide farmers with plant nutrients that are efficient to manufacture, affordable for farmers, and agronomically effective. Continued advances in chemistry and engineering have led to a variety of commercial products that are now widely used to restore degraded soils and replace this essential nutrient that is continually removed from fields in harvested crops.

KEYWORDS:
fertilizer production; phosphate fertilizer development

ABBREVIATIONS AND NOTES:
P = phosphorus; N = nitrogen; K = potassium; S = sulfur; Ca = calcium

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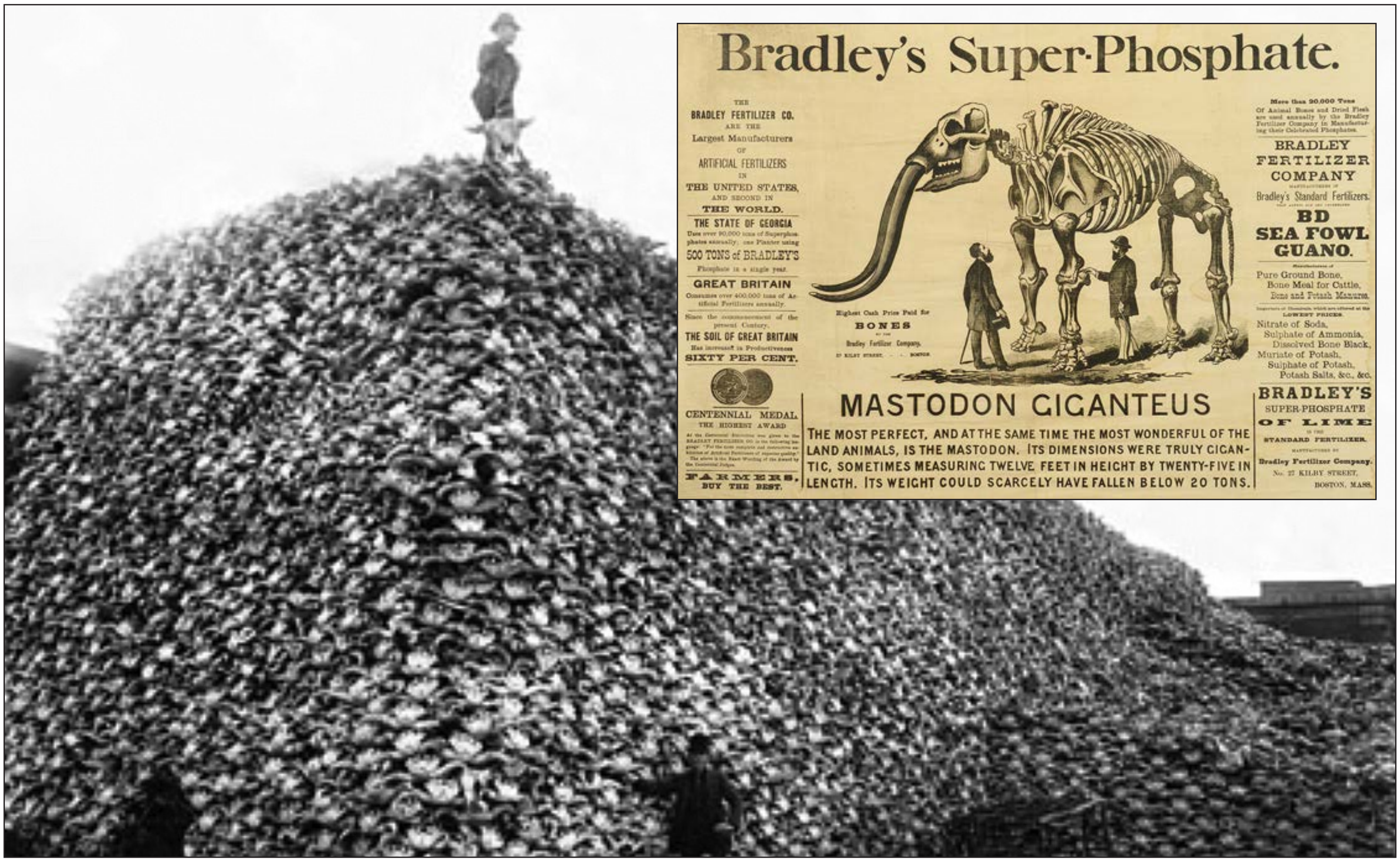


Large pile of bison skulls that will be ground into fertilizer in the U.S. around 1870 (left). Advertisement for Bradley Fertilizer Co. in 1881 (inset).

seeing any additional crop growth. This led him to experiment with treating bones with sulfuric acid, which proved to be very effective. In 1842 he was granted a patent for "superphosphate of lime", composed of calcium hydrogen phosphate and calcium sulfate. The manufacturing of superphosphate quickly spread around the world and marked the beginning of the modern fertilizer industry.

$2\ Ca_5F(PO_4)_3$ phosphate rock + $7\ H_2SO_4 \rightarrow$
$3\ Ca(H_2PO_4)_2$ [superphosphate] + $7\ CaSO_4$ + $2\ HF$

The manufacturing of superphosphate consisted of placing ground bones into a pit and then stirring in sulfuric acid as the mixture solidified for several hours. The solid paste was then allowed to mature in a curing pile for a few weeks until it was ready be broken apart with picks, crushed, screened, and bagged. The lumpy texture could make it difficult to spread uniformly in the field. This simple process also encouraged farmers to make their own superphosphate for on-farm and local use (New England Farmer: July 1869).

The name "superphosphate" is thought to have first appeared in a pamphlet by Joseph Graham who explained how *"phosphate of lime (as it exists in bone) is totally insoluble in water…when deprived of a portion of the lime constituting its base, (it is) reduced into a state of superphosphate, becomes soluble…"* (Cooper and Davis, 2004). The "super" likely refers to its superiority over ground untreated animal bones. In addition to making fertilizer, much of the bone-derived P was calcined and reduced in a furnace to elemental P for use in making matches.

Mining guano off the Peruvian coast (about 1860).

Phosphate rock mining operation in North Carolina, USA.

The eventual shortage of bones led to the exploration of other potential P sources. Guano, which had accumulated from dried bird manure in large quantities in the arid islands off the coast of Peru and in the South Pacific, became an important source of P fertilizer between 1840 and 1870. However, the most nutrient-rich guano deposits (typically 4 to 5% P) were quickly depleted and it's use declined in the latter half of the 19th century as low-grade mineral deposits were discovered around the world.

When Peruvian guano first became available in the U.S., it quickly began to substitute for bulky, locally derived recycled organic materials and led to the development of the commercial fertilizer industry in the U.S. Not surprisingly, the major U.S. meat processing companies and slaughterhouses were also major fertilizer manufacturers, distributing both N and P-based products for crop production.

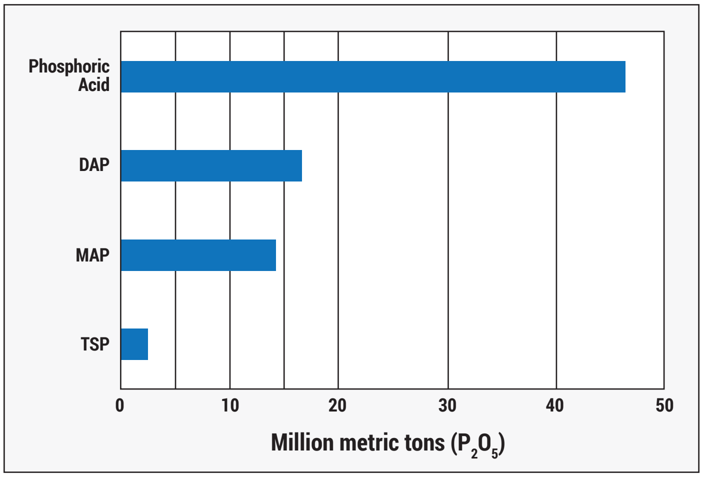
Mineral deposits of phosphate rock (apatite) were later developed and substituted for bones in the production of superphosphate. The P fertilizer industry entered the modern era as phosphate rock sources became readily available and accessible from geologic deposits around the world (e.g., England, 1847; Norway, 1851; France, 1856; USA, 1867; Tunisia, 1897, Morocco, 1921; Russia, 1930).

All common P fertilizers are now produced from phosphate rock as the starting material. Most sources of phosphate rock are too insoluble for direct use as a P source for plants. Phosphate rock from a few geologic deposits are suitable for direct application, especially if used for perennial crops growing in acidic soils, where the acidity and low Ca concentrations help speed rock dissolution and the release of P.

Superphosphate became the dominant P fertilizer in the world for over 100 years, but is no longer widely used and traded (with the notable exception of pastures in Australia and New Zealand). Other P sources remained available in limited quantities (such as manure, guano, ground phosphate rock and basic slag) and new P fertilizers were tested (such as triple superphosphate, ammoniated phosphates,

Table 1. Properties of common phosphate fertilizers.

Fertilizer	Acronym	Chemical formula	Common nutrient content P	Common nutrient content P_2O_5	Solution pH
Single superphosphate Ordinary superphosphate	SSP OSP	$Ca(H_2PO_4)_2 + 2\ CaSO_4$	7 to 9	16 to 20	<2
Triple superphosphate	TSP	$Ca(H_2PO_4)_2$	20	45	1 to 3
Monoammonium phosphate	MAP	$NH_4H_2PO_4$	23	52	4 to 4.5
Diammonium phosphate	DAP	$(NH_4)_2HPO_4$	20	46	7.5 to 8
Monopotassium phosphate	MKP	KH_2PO_4	23	52	4.5
Ammonium polyphosphate	APP	$[NH_4PO_3]_n$	15 to 16	34 to 37	6
Phosphoric acid (fertilizer/merchant grade)	PA	H_3PO_4	23	52 to 54	1
Superphosphoric acid (orthophosphoric and polyphosphoric acid)	PA	H_3PO_4	28 to 33	65 to 75	1 to 1.5



World production of phosphoric acid and P fertilizers in 2017 (IFA, 2018).

nitric phosphates), but they were not commercially competitive for many years.

The additional advantage of treating the phosphate rock with phosphoric acid instead of sulfuric acid was discovered in the 1870's. This process resulted in the production of fertilizer with soluble P concentrations almost three times higher than superphosphate, named triple superphosphate (TSP). However, TSP did not gain widespread usage until much later. This new concentrated P source greatly reduced fertilizer transportation costs and the manual labor required to spread powdered P fertilizer on the field, as granulation technology did not become widespread until 1950's.

$Ca_5F(PO_4)_3$ phosphate rock + 7 H_3PO_4 →
5 $Ca(H_2PO_4)_2$ [triple superphosphate]+ 2 HF

The nitrophosphate (Odda) process was developed in Norway in the late 1920's. This reaction involves mixing phosphate rock with nitric acid to produce calcium nitrate and phosphoric acid. A compound fertilizer containing both N and P (and K is frequently added) is also commonly produced from this process.

The Modern Era

In 1933, the National Fertilizer Development Center (NFDC) of the Tennessee Valley Authority (TVA) was given the mission of improving the efficiency of fertilizer manufacturing and fertilizer use on farms. This organization was pivotal in advancing global fertilizer technology and use. The majority of fertilizers produced in the world are still made with processes first developed by the TVA. The successor organization, the International Fertilizer Development Center (IFDC) still continues research and development projects on new fertilizer technology.

Diammonium phosphate (DAP) became the dominant P fertilizer following the introduction of the TVA process in the early 1960's where phosphoric acid is reacted with ammonia, using a pipe-cross reactor. TVA also introduced processes for manufacturing nitric phosphate, solid ammonium polyphosphate, and urea phosphate. The popular fluid ammonium polyphosphate became widespread after TVA introduced a method for combining superphosphoric acid (a mixture of phosphoric acid and polyphosphoric acid), with ammonia in the T-pipe reactor. The polyphosphate in superphosphoric acid keeps metal impurities from precipitating from solution.

As fertigation becomes more common, introducing soluble P fertilizer into irrigation systems requires careful management to prevent precipitation with constituents in the water that can lead to fouling and plugging of the irrigation system (Mikkelsen, 1989). A variety of excellent water-soluble P sources can be used for fertigating crops (such as monopotassium phosphate or urea phosphate), but close attention to the system chemistry is required.

The most common P fertilizers in the world are currently DAP, monoammonium phosphate (MAP), and TSP. A large amount of P is traded as phosphoric acid, of which 80 to 85% is used in the production various P fertilizers.

The current global outlook is for steadily declining positive growth rates for P fertilizer. However, this global average masks specific regional trends such as the slowing P demand in China and increasing demand for P fertilizer in Africa (IFA, 2018).

The Future

Phosphorus fertilizers have achieved farmer acceptance by being: 1) efficient to manufacture, 2) affordable, and 3) agronomically effective. New P fertilizer materials will additionally need to satisfy various environmental criteria (such as during mining and reclamation, manufacturing, and field use), social demands (such as energy consumption, greenhouse gas production, phosphogypsum management), and consumer expectations (such as minimizing trace elements in fertilizer, using sustainable mining practices, minimizing water quality impacts). These new considerations place additional constraints on the development of new fertilizer products.

Improved recovery of P that is directly consumed in human food and in animal feed will certainly gain more importance as P recycling from various waste streams is emphasized. Future efforts to more effectively reuse and recycle P derived from waste streams will likely include:

1. **Manure-based fertilizers and composts:** Phosphorus may be separated by solid-liquid processing and the products may be further concentrated by drying, composting, fortifying, or pelletizing.
2. **Combustion products and ash from manures and sludges:** Incineration at 800 to 900°C concentrates the mineral fraction without cause significant P volatilization losses. Heating P-containing waste products to higher temperatures will vaporize ele-

mental P which can be condensed and oxidized to phosphoric acid.

3. **Extract P from organic waste streams:** A variety of useful P fertilizers can be produced from various waste products, including struvite and calcium phosphate minerals such as brushite and hydroxyapatite.

Additional work has recently focused on the behavior of organic P materials in the soil, and manageable factors that control the value of these P sources for plant nutrition. The use of microbial inoculants and biofertilizers is under investigation to improve fertilizer P recovery by plant roots. While recent attention has focused on root-fungi interactions for enhancing P uptake, other plant-growth promoting organisms may significantly contribute to P solubility and rhizosphere activity.

Rapid advances in the field of material sciences also offer new matrices and delivery mechanisms for supplying P to crops. Many new approaches have been suggested, but the economic barrier has so far prevented widespread adoption of new P fertilizer technologies.

Conclusion

The development of the modern P fertilizer industry has provided farmers with easy and safe access to effective and affordable crop nutrients. These products replace P that is removed from the field during harvest and enhance the fertility of nutrient-depleted soils. The commonly used P fertilizers have their origins in chemistry and processes that are well established.

Emerging insights into material science and engineering may provide breakthroughs in innovative P fertilizer sources. Closer integration of new fertilizer products and root biology may also improve recovery of applied P. The development of innovative P fertilizers that sustain agricultural productivity and minimize off-site environmental impacts would make a significant contribution for agricultural science. **BC**

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Soil ‘Organic’ Phosphorus: An Untapped Resource for Crop Production?

By Malika M. Mezeli, Phil Haygarth, Timothy S. George, Roy Neilson, and Martin S.A. Blackwell

Farmers in Scotland prepare a field for planting by spreading and incorporating manure.

Phosphorus is essential for plant growth and since its discovery 350 years ago, the use of P fertilizers has significantly increased crop production. However, for plants to take up P it must be: a) in the right form as inorganic free ions, and in solution; b) in the right place at the soil root interface; and c) available at the right time when the crop demands. However, a significant portion of applied P fertilizer is not taken up by plants in the first year (Syers at al., 2008), which can then become unavailable to plants. This is due to a number of confounding factors. Soils vary in their capacity to fix P because phosphate ions have a propensity to: a) form complexes with other soil minerals and constituents including Fe, Al, and Ca; b) adsorb to the soil solid surfaces; and c) be taken up by soil organisms and then converted to organic forms following metabolization, excretion, and decay. Following such adsorption and conversions, P is not readily plant available.

Historically, agronomic management strategies have coped with such phenomena by relying on saturating the system with P, using fertilizers derived from non-renewable rock phosphates, manures and wastes, thus ensuring adequate P for crop growth (Syers et al., 2008). This practice has led to a build-up of soil ‘legacy’ P (Haygarth et al., 2014). Could this P ‘bank’ represent an untapped hidden reserve? How much of crop P could this ‘bank’ provide? What agronomic management strategies would be needed to efficiently use this resource? What is the research community doing?

SUMMARY

Soils with a history of P fertilizer application may represent a significant ‘bank’ of residual soil P. The P research community offers potential and emerging strategies for land managers to access this soil resource to create sustainable P management strategies that may rely less on inorganic fertilizers and aid in closing the P cycle.

KEYWORDS:

organic P; P ‘bank’; P cycle; residual P

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus; Ca = calcium; Fe = iron; Al = aluminium

http://doi.org/10.24047/BC1030122

How much of phosphorus crop requirements could this 'bank' provide?

Estimates suggest that between 1965 to 2007 there has been an accumulation of over 1,115 kg P/ha in croplands of Western Europe (Sattari et al., 2012). As there has not been significant decrease in P application since this period, soil stocks are expected to be similar today. A recent review by Menezes-Blackburn et al., (2018) estimated that approximately 57% of the global soil P 'bank' is in inorganic form and 33% in organic form, or broadly speaking, any P compound associated with a carbon atom. Potentially this would provide approximately 201±23 and 117±6 years of P for agronomic use from these respective pools (Menezes-Blackburn et al., 2018). This equates to about 352±26 years of agricultural production at current P offtake rates. Some data used by Menezes-Blackburn et al., (2018) is presented in **Figure 1**. The majority of soils show available P (Olsen P) is well above recommended levels, with significant levels of other forms that represent a potential P 'bank'.

What agronomic management strategies would be needed to efficiently use this soil P 'bank'?

The first obvious strategy to increase the use of the soil residual P 'bank' would be to ensure only recommended amounts of P fertilizer are applied to soil. Simply suspending P application to agricultural soils would put many crop production systems into arrest, even if those soils had a high residual P 'bank' (Nawara et al., 2018). This is because readily available soil P would deplete at rates faster than the solubilization and desorption of the residual P 'bank', causing a net loss of available P. Further work needs to be done to calculate the economic trade-off between net loss of crop yields against the savings made on P fertilizer across different crop and soil types, accounting for crop market value, and P fertilizer costs. This would allow land managers and farmers to implement sustainable P strategies while remaining economically viable. However, this would also require further developments in residual P research to establish necessary model parameters.

Secondly, coupling reductions in P fertilizer application rates with agronomic strategies that actively promote P desorption, solubilization, and mineralization may be more attractive in some agricultural systems. For example, research investigating the implementation of intercropping systems to increase plant uptake of soil organic P has provided promising results. Work by Giles et al., (2017) showed that intercropped legume and barley cultivars with varying root exudate and morphological traits related to varying uptake of residual P forms. By calculating the Land Equivalent Ratio (Darch et al., 2018) of such systems, these data can be used to estimate the loss of productive land and savings on P fertilizer made by employing intercropping systems. Such work employs crop choice and land-management techniques to increase use of the soil residual P 'bank'. Several studies have also been conducted in legume-based grazing systems where cultivar choice can have significant impacts on P fertilizer use efficiency and reduce demands on N (Haling et al., 2016).

Contrasting work in arable cropping systems in North Western Australia demonstrated that deep placement of P fertilizer can improve both P and water use efficiency (Lester et al., 2018).

Other strategies look towards reducing additions of P in organic forms that contribute to the residual P 'bank'.

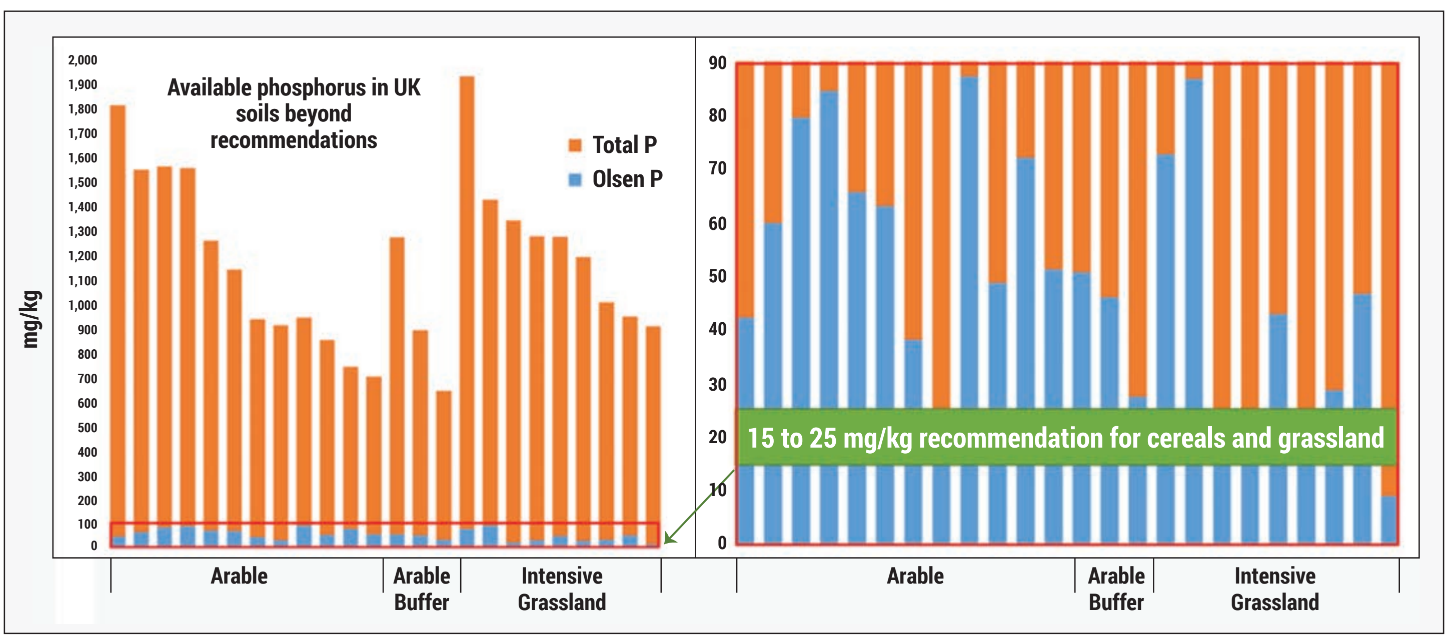

Figure 1. Phosphorus forms in a range of UK agricultural soils (Taken from: Stutter et al., 2015). These data show that the majority of soils have Olsen P test values above recommendations and represent a significant P 'bank' for potential plant use.

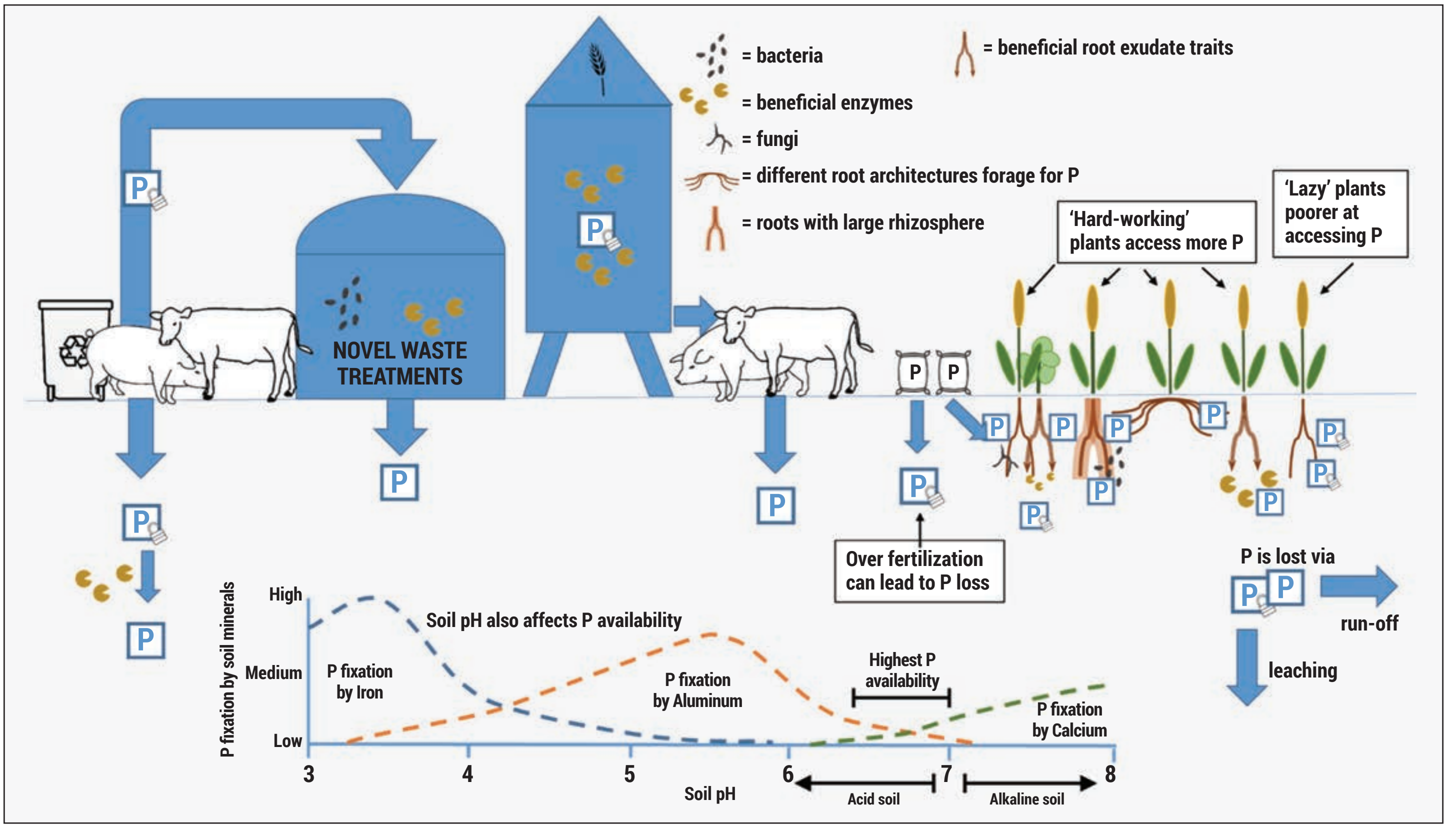

Figure 2. Management practices and technologies available to improve soil phosphorus use by crops and pastures which could aid in closing the phosphorus cycle.

Manures, specifically those from monogastric livestock fed on grain diets contain significant amounts of recalcitrant organic P forms (Turner et al., 2002). One strategy is to reduce grain consumption by livestock, thereby reducing the amount of recalcitrant P forms entering the system. In addition, the application of specific enzymes capable of hydrolyzing organic to inorganic P forms can be employed at various stages to increase P bioavailability. Direct application of enzymes to grain prior to livestock consumption is a practice already prevalent in the feedstock industry, or after field application of manures, slurries, and digestates. However, treatment of manures prior to application could result in the overloading of soluble P sources to the system. Such scenarios could pollute the natural environment via run-off or leaching, or could become sequestered prior to crop demand. The P research community offers the fertilizer industry novel opportunities for the development of more economically and environmentally sustainable P sources, including strategies that tap into legacy P stores in agricultural soils. Engaging such opportunities has potential to place the industry at the forefront of tackling such global challenges as food security and environmental protection. Some of these strategies are illustrated in **Figure 2**.

What is the phosphorus research community doing?

Many promising technologies and agronomic management strategies exist that have the potential to significantly increase the use of the soil residual P 'bank', thus reducing demands on phosphate rock-based fertilizers. There is a consensus that a multi-pronged approach by both land managers and the research community will be required for the proper design and implementation of sustainable P management strategies. This will need to be on a case-by-case basis as soil type, management practice, and soil P status vary greatly.

> **TAKE IT TO THE FIELD**
>
> Understanding the total P in field soil can offer potential for using the soil residual P 'bank' on agricultural land. The adoption of multi-pronged approaches from P research can aid in the development of on- and off-farm sustainable P management strategies.

The proposed consideration of the soil residual P 'bank' directly addresses the two main tenets of the statement of intent declared by members of the P research community who attended the international organic phosphorus workshop in 2016:

(i) To reduce our reliance on inorganic P fertilizers, as strategies to do this will increase the relevance of soil organic P for plant nutrition.

(ii) A need to develop a more circular P cycle, which will likely lead to an increase in the amounts of organic P 'waste' products being recycled to land (George et al., 2018).

To achieve the necessary impact of soil P research, there is a need to engage researchers outside of the discipline, align the research with pressing societal issues, and become more global, collaborative, inclusive, interdisciplinary, and longer-term in nature. Also, the key to fostering this change will depend on logically communicating with stakeholders, and ultimately pushing this important area of research up the agenda of policy makers and funding bodies on a global scale (George at al., 2018). **BC**

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Manure Phosphorus Management from a Global Perspective

By April Leytem and James Mutegi

Livestock manures contain significant amounts of the primary nutrients N, P, and K and secondary nutrients (i.e., Ca, Mg, and S) as well as a wide variety of micronutrients which make them an excellent nutrient source for crop growth. In addition, the application of livestock manures can improve soil health via the addition of organic C, which can improve soil structure, water holding capacity, and water infiltration.

Globally, the total amount of P excreted in manure in 2011 was estimated at 23 million tonnes (M t) (Liu et al. and likely exceeds the amount of fertilizer P produced each year (IFA, 2018). Manure-based nutrient application exceeds fertilizer application in parts of South America and Africa, as well as small portions of the eastern U.S., Eastern Europe, Central Asia, Southeast Asia, and Northeastern Australia (MacDonald et al., 2011). Potter et al. (2010) estimated that the global ratio of manure P to fertilizer P in the early 2000's was approximately 1.7, while in some countries such as the U.S. the ratio is close to 1.0 (Yang et al., 2016). The highest rates of P in manures produced are found in the midwestern U.S., southern Brazil, western Europe, northeastern China, northern India, Bangladesh, and New Zealand (where the highest average P production rate, 64 kg/ha, is found) (Potter et al., 2010). MacDonald et al. (2011) provided an analysis of the relative P surplus or deficit resulting from fertilizer P and manure use on cropland around the world (**Figure 1**).

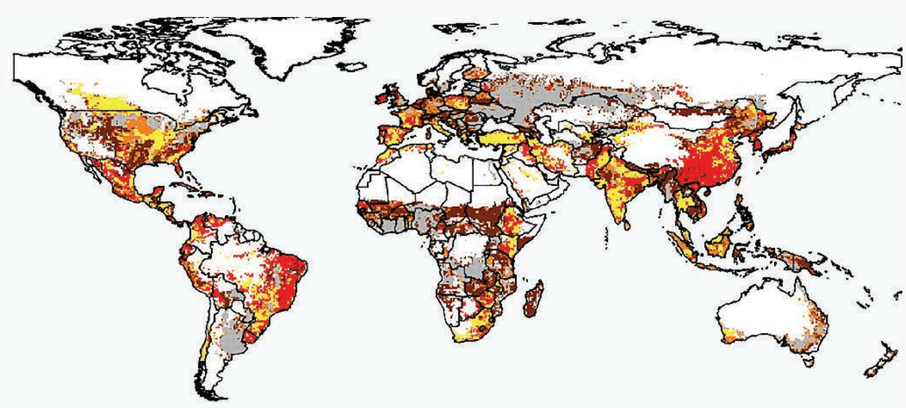

Figure 1. The magnitude of P surplus or deficit (P balance) on cropland around the world can be estimated based on fertilizer use, manure production and crop removal (From MacDonald et al. 2011).

Although the availability of manure P sources is often greater, or similar, to mineral fertilizer P use, manure P is not always effectively used in crop production. Inefficient manure P use can be attributed to several factors including: uneven distribution of manure by grazing animals, incomplete collection and inappropriate storage of manure from housed animals, poor timing of manure application, high cost of transportation, and relatively low prices for mineral P fertilizer. Due to the high moisture content and bulky nature of manures, they are generally applied to crops within a small radius of where they are produced, which leads to buildup of P in soils surrounding livestock farms. This excessive P application has led to P surpluses in croplands, decreased P use efficiency, and increased P losses to surface waters. The poor spatial distribution of manure P use has been exacerbated in recent decades in developed countries by structural shifts of livestock operations from small farms to larger-scale confined operations that have resulted in more unevenly distributed patterns of manure P loads to soil.

Elevated P concentrations in receiving waters can lead to eutrophication, which can be costly. For example, in England and Wales it has been estimated that damages due to agricultural losses of P are near US$24 M (Bateman et al., 2011). In some countries, direct discharge of P in wastewater to surface waters is still common. For example, in Thailand, P-containing wastewaters discharged directly to surface waters from dairy-cow and swine farms were estimated

SUMMARY

While livestock manure is a significant global reserve of P, it is not always used efficiently in agricultural production. Due to the segregation of livestock and cropping systems in many countries, poor redistribution of manure P has led to regions with both surpluses and deficits. As phosphate rock must be considered a finite source, the recycling of P from manures regionally, nationally, and even globally needs to be improved for food security in the future.

KEYWORDS:

soil nutrient balance; manure availability; P recycling; sub-Saharan Africa

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; C = carbon; LSU = livestock unit

http://doi.org/10.24047/BC103126

to be 554 and 261 t P/yr, respectively (Prathumchai et al., 2018). These discharges have a direct negative impact on surface water quality in these regions.

Phosphorus Imbalances – Farm, Local, Regional, National, and Global

Seventy one percent of global cropland area was estimated to have an overall P application surplus in 2000, including most of east Asia, sizeable tracts of western and southern Europe, the coastal U.S., and southern Brazil. This P surplus is desirable during the build-up phase of soil fertility, but then should decrease to avoid excessive P accumulation. In contrast, croplands in all sub-Saharan Africa (SSA) countries are characterized by annual soil P deficits (Macdonald et al., 2011). These P deficits in SSA soils have been attributed to a number of things, key amongst them being low native soil P, high export of P with crop biomass, and P losses (approximately 3 kg P/ha/yr) without proportional replenishment (Lun et al., 2018). The low native soil P that characterizes soils in SSA and other tropical regions like South America reflects a high degree of weathering and/or a low concentration of P in the parent material (van der Waals and Laker, 2008). In particular, while Ultisols and Oxisols represent about 70% of P-deficient soils globally, about 20% of these soil orders are found in SSA (Fairhurst et al., 1999).

Approximately 9.6 M t P/yr, or 40% of total manure P excreted by livestock in 2000, was used for cropland application based on estimates of recoverable manure for 12 regions and for U.S. states (MacDonald et al., 2011). **Figure 2** indicates that P surpluses increase with greater livestock density at the national scale, especially at livestock densities above 2 LSU/ha (Liu et al., 2017; Nesme et al, 2015). One

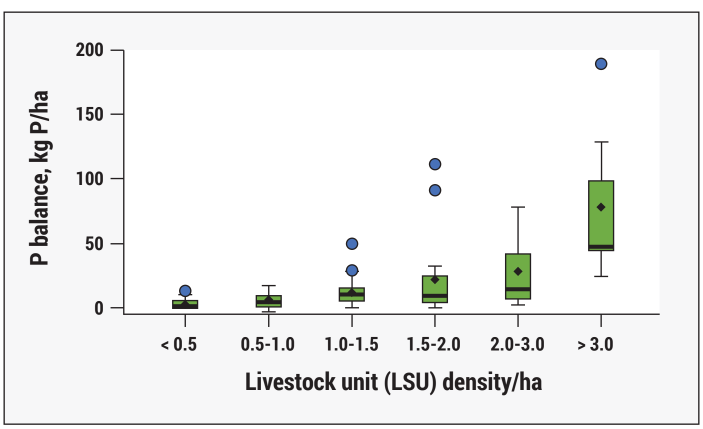

Figure 2. High livestock density generally results in a country-wide P surplus. The mean P balance for the whole food production–consumption system is shown at the country level for 150 countries. The LSU reference unit aggregates livestock from various species and age based on the nutritional or feed requirement of each type of animal. Boxes show the 25th to 75th percentiles, horizontal lines indicate median values, filled symbols show the mean, whiskers indicate the 5th and 95th percentiles and open symbols indicate outliers. Reproduced from Liu et al. (2017) with permission from CSIRO Publishing.

J. Mutegi/IPNI Images

Examples of in-row and surface application of cattle manures in sub-Saharan Africa.

of the main causes of these surpluses is the large amount of P imported in feed coupled with low P use efficiency of most livestock. Therefore, there is often a clear relationship between livestock density and P balance at the farm level.

At the local scale, the transfer and recycling of manure P, and reduced fertilizer P use, remain compatible. At the regional scale, such transfers are virtually absent due to manure transport costs; manure P recycling on croplands is hampered and mineral fertilizer P use is instead favored to meet crop demand (Nesme et al., 2015). However, as farms grow in size, even local and within farm imbalances can occur due to the high transportation costs of manure.

In several countries such as the U.S., Netherlands, Norway, Denmark, and Finland, manure P can meet or even exceed the amount needed to achieve sustainable crop productivity (Smit et al., 2015; Hanserud et al., 2016; Yang et al., 2016; Parchomenko and Borsky, 2018; Svanbäck et al., 2019). Despite this large potential for within-country P recycling, areas with the largest amounts of manure P are not co-located with areas having the highest P deficits, which can create hotspots of excess manure P. Compounding the issue in these regions, fertilizer P is still often applied with the excess manure, resulting in high soil test P concentrations. Globally there are regions, including portions of SSA, Eastern Europe, and South America that are experiencing the opposite extreme of high P deficits, where P from manure is sought after in order to enhance both soil fertility and quality. Most of these imbalances are related to higher P removal/losses relative to P application via manure and other sources.

Sub-Saharan Africa is a case of extreme P deficit where manure application to croplands does not provide an adequate solution for meeting the crop P demand. Depletion of P and other macronutrients from the soil is widely reported in the region. The low capacity of manure to reverse the trend is associated with low quantities of manure production, due to limited livestock populations (Titonell and Giller, 2013), and the low quality of livestock feeds. Low-quality livestock diets, affordable to the majority of smallholder farmers', results in a low nutrient concentration of manures, including relatively low P. A good example is the case of a Zimbabwe trial where 17 t/ha of cattle manure resulted in an annual application of 31 kg P/ha (Zingore et al., 2008). Surprisingly, after three seasons of manure application, the soils showed a decline of about 0.6 mg P/kg relative to an unfertilized control. This observation was hypothesized to result from the drop in pH from 5.1 to 4.9 resulting in increased P fixation as well as greater P export via the increased harvested yield.

Phosphorus Fertilizer-Manure Substitution

Livestock manures are a valuable global reservoir of reusable P and hold the most conspicuous potential for mineral fertilizer substitution. Although this makes theoretical sense, the practicality of distribution of manure P hinders its efficient recycling. If manure P is to be reused in the agricultural P cycle, cost-effective methods for redistribution of manure P from areas of surplus to areas of deficit will need to be developed. In many countries, there is currently a lack of regulatory and economic incentives for farmers in livestock-dense areas to transport surplus manure P over greater distances. Therefore, regulations, economic incentives and technical solutions for enhanced relocation of livestock manure P from areas with surplus to areas with deficit will be crucial.

Achieving more effective manure P recycling at the global scale will require broader management or structural changes in livestock farming. Adequate manure collection, storage, and application techniques are critical prerequisites for efficient use of manure P. Education about manure P and its bioavailability is needed, as the fertilizer value of manure P may be unknown to producers or disregarded. It is commonly reported that, in most cases, the P content of manures is often not accounted for when calculating fertilizer recommendations. Development of tools, such as the Nutrient Expert® decision support tool (Pampolino et al., 2012), that consider the nutrient supply of manure into fertilizer recommendations, can help reduce the risk of P overapplication. Support for processing and trading of manure-based nutrients can help reduce P imbalances between crop and livestock farms. Changes in livestock diets to enhance P use efficiency may also be needed to decrease P surpluses in areas with intensive livestock production. Technologies for capturing P from manure streams and concentrating it into a more easily transportable form will be essential for long range redistribution.

TAKE IT TO THE FIELD

Despite the potential for P recycling, areas with the largest amounts of manure P are often not co-located with the highest P deficits. P "hotspots" result where manure P exceeds the amount needed to achieve sustainable crop productivity.

Closing Thoughts

While livestock manure is a significant global reserve of P, it is often used inefficiently in agricultural production. Due to the segregation of livestock and cropping systems in many countries, poor redistribution of manure P has led to regions with both surpluses and deficits. As phosphate rock is a finite source, the recycling of manure P regionally, nationally and even globally may be necessary for food security in the future. Therefore, technologies, regulations and economic incentives to enhance the reuse of manure P in agricultural systems are essential. **BC**

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Congratulations to this year's crop of winning photo submissions! In addition to their cash award, each will receive our most recent USB flash drive collection featuring hundreds of images. More details on our image collection are available at: http://ipni.info/nutrientimagecollection.

Thanks to all for supporting our contest! **BC**

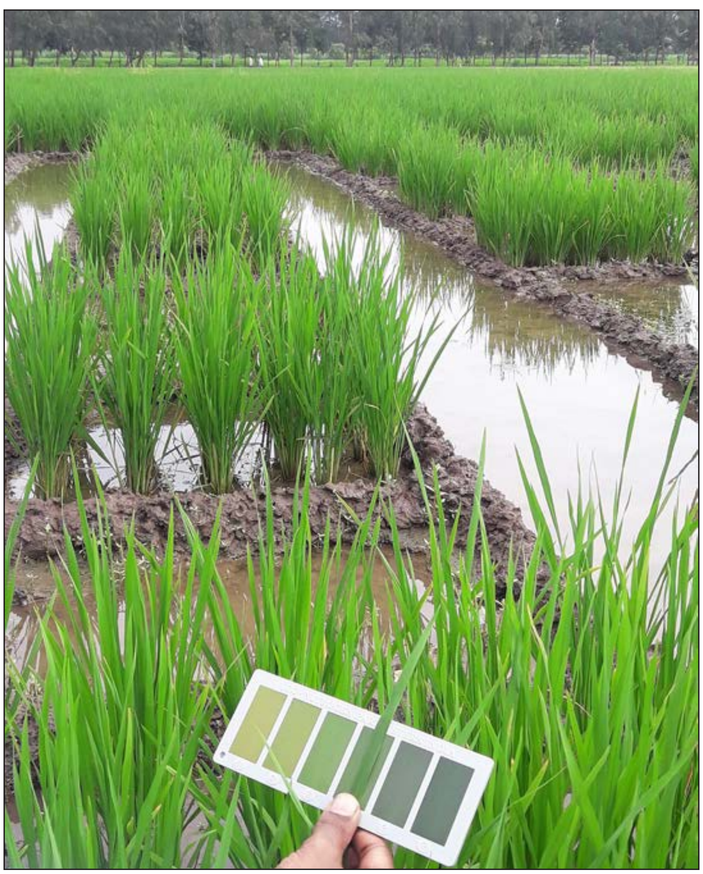
4R Nutrient Stewardship Category

FIRST PLACE:

Stabilized Urea in Maize

André Luis Vian, Experimental Agronomic Station of Universidade Federal do Rio Grande do Sul, Brazil.
e-mail: andreluisvian@hotmail.com

Mr. Vian submitted a close-up example of a topdress application of a stabilized nitrogen (N) source (urea with urease inhibitor) for a maize crop. Use efficiency for N was maximized given this right source applied at a right rate and time (i.e., 250 kg N/ha during V8 stage with eight completely formed leaves). Fertilizer placement near the root system provided for an opportunity for maximum response to N given the crop's productive potential.



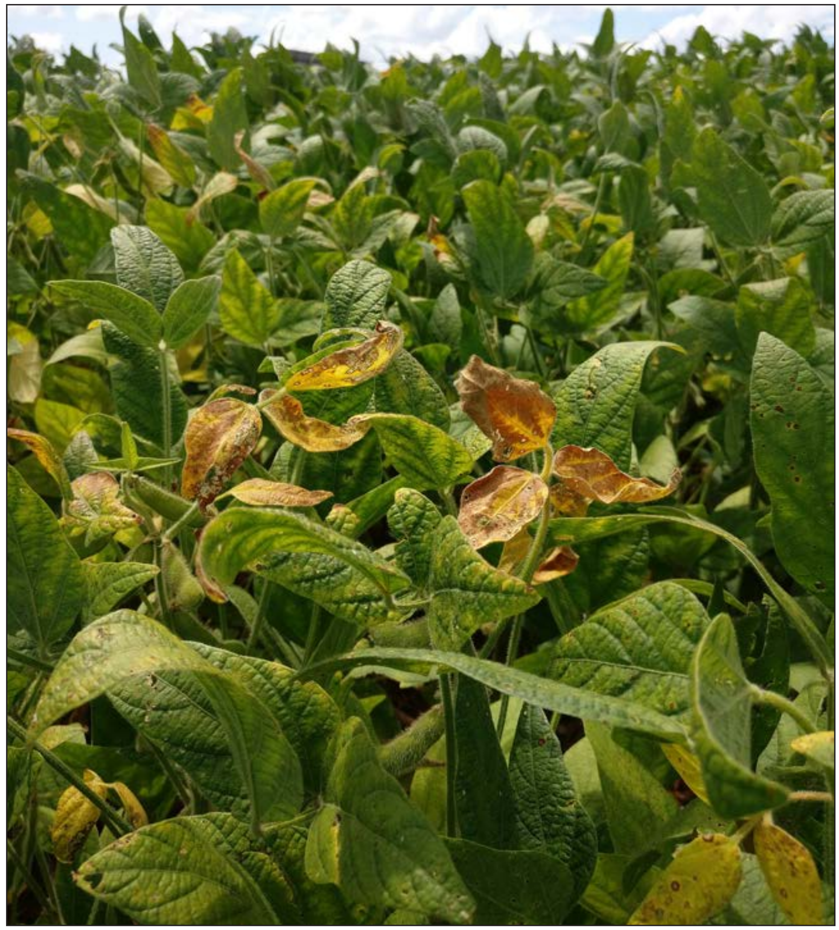
SECOND PLACE:

Real Time Nitrogen Management in Rice

Nitin Gudadhe, Navsari Agricultral University, Gujarat, India.
e-mail: nitbioworld@gmail.com

Real time N management is demonstrated at this Instructional Farm through the use of a leaf color chart (LCC) in rice. Leaf color chart panel number 4 was used to check the N fertilizer requirement of rice at tillering and panicle initiation stages. Ammonium sulfate was applied as a topdressing when the color of panel 4 matched the rice leaf color. Right timing of fertilizer application, guided through the use of a LCC, can increase rice crop yield by up to 10% over farmer's practice.

Primary Nutrient Category



FIRST PLACE:

Potassium Deficiency in Soybean

Gustavo Dos Santos Cotrim, Londrina, Paraná, Brazil.
e-mail: gustavodscotrim@outlook.com

Selected for its sheer clarity, Mr. Cotrim captured this example of potassium (K) deficiency in a soybean field near Londrina, Brazil. The crop is in the midst of its seed production stage (i.e., R5.5).

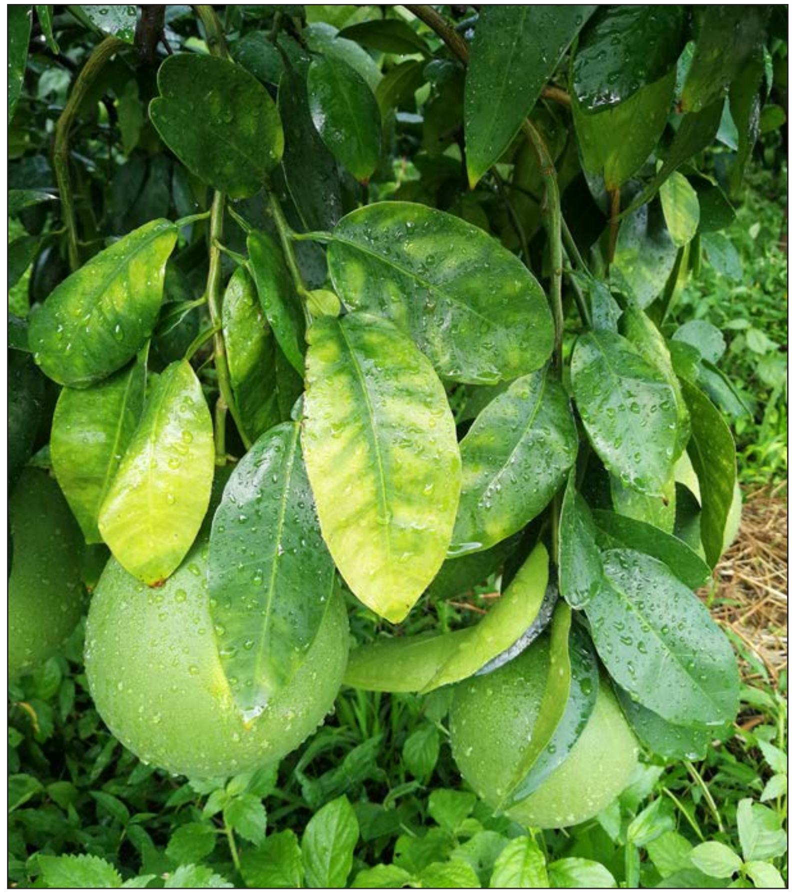
SECOND PLACE:

Potassium Deficiency in Wheat

Mark Reiter, Virginia Tech, Accomack County, Virginia, USA.
e-mail: mreiter@vt.edu

Dr. Reiter reported that this wheat field had an issue with poor growth down its center. The field history for the past seven years include poultry litter applications at 3 t/A prior to corn in a corn-wheat-double crop soybean rotation on sandy loam soil. Field soil potassium (K) values range from low (L+) to medium (M). This photo was taken where 127 lb/A K was sampled (M) using Mehlich-1 extract, with soil water pH of 6.1. Plant flag leaf concentration was deficient at 1.31% K. The plant also exhibited poor root growth and a hardpan at 6 in. The farmer applied 100 lb N/A in two split applications in the spring using 30% urea-ammonium nitrate solution. Phosphorus concentrations were very high (128 lb P/A). The farmer bales his straw each year to aid in soybean establishment.

Secondary Nutrient Category



FIRST PLACE:

Magnesium Deficiency in Pomelo

Guo Jiuxin, International Magnesium Institute, College of Resources and Environment, Fujian Agriculture and Forestry University, China.
e-mail: jiuxinguo@hotmail.com

Soils in this region are strongly acidic (pH 4.3), have low organic matter (1.5%), have high K concentrations (315 mg/kg), and are deficient in the available magnesium (58 mg Mg/kg). The Mg concentration for these chlorotic leaves was 0.23%. The smallholder farmers tend to use unbalanced fertilization strategies involving excessive NPK fertilizer (more than 2,500 kg/ha/yr), while neglecting secondary and micronutrient applications. This Mg deficiency was corrected by application of a Mg fertilizer, specifically $Mg(NO_3)_2$.

SECOND PLACE:

Magnesium Deficiency in Mango

K. Venkatesan, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam, India.
e-mail: venkat672003@gmail.com

This inverted ‘V’ shaped chlorosis of older leaves typical of magnesium (Mg) deficiency was observed in this 25-year-old mango orchard at harvesting stage. The orchard soil had low organic matter content and a pH of 7. In the deficient leaves, Mg content was very low at 0.17%.

Micronutrient Category

FIRST PLACE:

Boron Deficiency in Sweet Potato

Susan John Kuzhivila, ICAR-Central Tuber Crops Research Institute, Kerala, India.
e-mail: susanctcri@gmail.com

The symptom of boron (B) deficiency was manifested as typical cracking and splitting of the tubers, which cannot be marketed. These crops were supplied with recommended NPK at 50-25-50 kg/ha through urea, rajphos, and MOP as basal and topdressings at 20 and 40 days after planting. Placement was at the bottom of the plant mounds. The soil analytical data indicated a B content of 0.5 ppm, which is the critical level. The plant analytical data on B content of the leaves bearing these tubers was 32 ppm, which is below the critical level of B for sweet potato (40 ppm) indicating that the deficiency of B in the plant might have affected tuber cracking.

SECOND PLACE:

Boron Deficiency in Sugarcane

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The picture demonstrates a classic boron (B) deficiency symptom in sugarcane 200 days after planting. Since B is not mobile in the plant, the more intense symptoms are found in the youngest leaves with little effect on older leaves. The soils in the area are derived from a sandstone parent rock known as Arenito Caiuá, hence the soil is very sandy. This type of soil is naturally poor in B and the element is prone to leaching, especially because of the intense rains in the area, usually amounting to 1,500 mm of precipitation per year. Soil tests indicated a very low level (0.05 mg/dm³) of B in the top 20 cm of soil and 0.2 mg/dm³ in the 20 to 40 cm layer. The critical level is considered to be 0.6 mg/dm³. Leaf tests of the index leaf indicated 0.14% B. The lower limit of the B sufficiency range is 0.1 to 0.3%. This sugarcane cultivar (CTC 9001) was planted using 540 kg/ha of the NPK (10-26-26) without B.

Reducing Unintended Consequences of Agricultural Phosphorus

By Don Flaten, Andrew Sharpley, Helen Jarvie, and Peter Kleinman

Phosphorus nutrition of crops provides a foundation for food, bioenergy, and biomaterial production. Indeed, it has been argued that P is at the heart of the food, water, and energy nexus (Jarvie et al., 2015). However, small, agronomically insignificant amounts of P in water that drains from agricultural land can cause large problems with surface water quality, especially in freshwater systems, where growth of algae is very sensitive to the concentration of P in the water (Schindler, 1977). As a result, the impairment of surface water bodies by P, especially nonpoint sources, remains a challenging, persistent, and widespread problem that threatens not only water quality but also water security (Shortle and Horan, 2017).

Beneficial Conservation Practices that Reduce Agricultural Phosphorus Loss

Nutrient management conservation practices (CPs) provide an essential toolbox for reducing P losses from agricultural land to surface water. Fortunately, the core principles for using the "right" nutrient application rates, sources, placements, and timings (i.e., the "4Rs" of nutrient stewardship; International Plant Nutrition Institute, 2014; International Fertilizer Association, 2009) are applicable to the management of agricultural P losses and effective over a wide range of geographic and land management situations. Many common nutrient management CPs have proven their effectiveness for reducing agricultural P losses in many regions of the world. These include measures such as:

- applying P at rates recommended from soil tests to avoid excessive accumulation of P in soil;
- avoiding repeated annual applications of livestock manure to meet crop N requirements on the same land;
- applying or incorporating fertilizer and manure P to place it under the soil surface; and,
- avoiding application of fertilizer or manure on frozen or snow-covered soils.

Soil and water management focused CPs provide another important toolbox for reducing P loss. Most soil and water management CPs are designed to prevent P movement off fields or intercept P that is moving away from the field and into surface water. This group of CPs includes a broad range of erosion control practices, such as conservation tillage or no-till, vegetative buffers, streambank stabilization, and wetland protection. However, the effectiveness of soil and water management practices in reducing P loss varies with the biophysical environment of agricultural land within local watersheds. For example, conservation tillage systems can reduce losses of particulate P, but the accumulation of fertilizer, manure, and vegetative P at the surface of conservation-tilled soil can lead to increased losses of dissolved P (Sharpley and Smith, 1994; Tiessen et al. 2010).

NASA MODIS Sensor/NOAA Centers for Coastal Ocean Science

Algal blooms in Western Lake Erie demonstrate the effect of excess P on water quality and the unintended consequences of some conservation practices (Jarvie et al., 2017).

Conservation Practices for Improving Water Quality are Often Less Effective and More Complex than Expected

Worldwide, flagship programs (e.g., Mississippi Basin, Baltic Sea, Murray Darling River) have promoted adoption of CPs to reduce P runoff, but often the improvement in water quality has been less than, or slower than, expected (Jarvie et al., 2013). In some cases, for example the Lake Erie Basin of North America, water quality has actually worsened, linked to increased riverine loads of soluble P, despite

SUMMARY

This article reflects upon the challenges we face in agricultural P management and provides a discussion about opportunities to promote more comprehensive and sustainable management of this valuable resource (Sharpley et al., 2018).

KEYWORDS:

conservation practices; P loss; adaptive management; environmental health

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus

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the implementation of CPs (Jarvie et al., 2017). These slow and/or undesired water-quality responses may arise from a range of factors, such as:

- incompatibilities and trade-offs between CPs (Smith et al., 2015; Jarvie et al., 2017);
- lag times associated with hydrologic flow paths and watershed response times (Meals et al., 2010);
- legacies of historic land management whose continued impact cannot be readily reversed (Sharpley et al., 2013; Vadas et al., 2018).

Nevertheless, experience with nonpoint source P management has yielded valuable lessons that can help us improve the effectiveness of CPs. For example, implementation of CPs requires more attention to locally relevant and precise approaches that maximize benefits and minimize trade-offs; the 'right strategy, right place' principle (Dodd and Sharpley 2016). Also, new information and performance assessments necessitate continuous refinement of CPs, so adaptive management is almost universally required (Kleinman et al., 2015).

"….perhaps we should treat environmental health more like human health."

As we consider the complexity of interactions between various agricultural nutrient, water, and soil management CPs, and their effect on water quality, perhaps we should treat environmental health more like human health. In doing this, we should invest more effort to precisely diagnose and treat the root causes of poor water quality, as well as the broader goal of improving overall environmental health. This would be of particular importance where different components of environmental health might be compromised as the result of an unexpected trade-off, or "side-effect" from a "beneficial" management practice aimed at another component of environmental health.

USDA-NRCSScience

Riparian and grassed buffers can stabilize streambanks and intercept P in runoff In many situations.

Benefits of this approach are:

1. *Triage:* It is useful to target nutrient, soil, and water management CPs where they can generate the most benefit for the least cost. Such targeting is a form of "triage" where situations are prioritized to make the best use of limited resources. For example, the concept of identifying locally valid, critical source areas can be a helpful tool for this purpose.

2. *Carefully diagnose the real cause of the problem on an individual basis:* Agricultural P management strategies should be considered like treatments for human health where the benefits, as well as the risks and side effects of prescribed medications are carefully considered and clearly stated. In order to ensure that the correct cause is identified, it is important to assess each case individually and comprehensively, and to identify the real cause of the most important problems, weighing known benefits and risks (e.g., side effects or trade-offs) for that local situation. Here, consideration of systemic issues as well as proximate concerns are needed. For example, are dissolved or particulate P species the main source of impairment? Does the P source originate from in-field management or from in-stream recycling? Is the main pathway of P transport surface runoff or subsurface flow?

3. *Prescribe and treat with a "cure" that works for that individual case:* Once a diagnosis is completed, the next step is to prescribe the right cure, making sure the "cure" works for that local situation, then implement the treatment with care and precision. Many well-established conservation practices decrease P-related impairment of water quality under a wide range of geographic and land management settings. This can translate to unrealistic expectations of CPs as "cure-alls" … effective all the time, in all situations, and won't have any undesired side effects.

In addition, and somewhat lacking in the past is to consider all the co-benefits, as well as all the side effects and potential incompatibilities and negative interactions between management practices. Just as one would monitor a patient, it is necessary to continuously monitor CPs so that, if undesired side effects are detected, strategies can be altered or, more commonly, fine-tuned. We also need to consider a variety of other broad challenges, such as: How do we integrate the criteria for P loss and water quality into an overall assessment of environmental health? How do we balance among environmental objectives, for instance P loss versus N loss, versus greenhouse gases? How do we balance economic, social, and political perspectives with the biophysical aspects of environmental health?

4. *Provide long term, on-going care:* Similar to the long-term value of healthy diet and appropriate exercise for human health, many nutrient, soil, and water management CPs for reducing agricultural P loss require sustained effort over a long period to achieve the desired benefits. However, one of the challenges of these long-term CPs is that, to be effective, they must be maintained long after a nonpoint source mitigation program's initial resources have waned.

Conclusion

There are many challenges to developing and implementing locally relevant, precise, yet comprehensive approaches to reducing agricultural P loss and improving surface water quality. However, if we employ some of the same strategies for improving environmental health as we successfully use for improving human health, we have many opportunities to progress towards more sustainable use of agricultural P. **BC**

T. Bruulsema/IPNI

Regular innovation and adaptation is required to ensure the conservation practices complement and enhance existing management systems. This implement was designed to band P under the soil surface in a strip-till system, in this case, into winter wheat stubble in the fall.

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Root/Rhizosphere Management for Improving Phosphorus Use Efficiency and Crop Productivity

By Liyang Wang and Jianbo Shen

J. Shen Image

Field performance of maize based on rhizosphere nutrient management.

The rhizosphere (root-soil interface) is the most important area for plant-soil-microorganism interactions, and is the hub for controlling nutrient transformation and plant uptake (Zhang et al., 2010), particularly for P due to its high fixation, low mobility, and low bioavailability in soil. Although the rhizosphere is often conceptually considered to be a thin layer of soil surrounding the root, the rhizosphere is actually a wider, interactive dynamic zone affected by various soil physical, chemical, and biological processes (York et al., 2016). Plants are able to sense changes in their surrounding environment and optimize the absorption of water and nutrients by modifying rhizosphere processes. Keeping an appropriate supply intensity of nutrients in the root zone can promote root growth and enhance rhizosphere processes, but a limited or oversupply of nutrients can repress these positive effects. Although plants have developed adaptive mechanisms to their environmental conditions through evolution, it is important that we maximize beneficial rhizosphere processes to take full advantage of the biological potential of roots to improve nutrient use efficiency and crop productivity in farming systems.

Rhizosphere Management Strategies

Rhizosphere management is defined as the manipulation of different components of the rhizosphere ecosystem, based on a better understanding of rhizosphere processes, to optimize plant root-soil-microbial interactions and achieve sustainable, positive effects (Zhang et al., 2010; Shen et al., 2013). The efficiency of rhizosphere processes is highly dependent on the combined influence of a soil's inherent fertility and the input of external nutrient resources, and is greatly reduced if root growth and expansion are limited by soil nutrient deficiency. With increasing nutrient supply, the efficiency of rhizosphere processes can be increased. However, excessive application of fertilizers may lead to high concentrations of soluble nutrients in the root zone, which can also restrict root growth and rhizosphere efficiency

SUMMARY

Rhizosphere processes affect soil P availability and efficient use of P by plants. This paper summarizes the principles of root/rhizosphere management, and highlights case studies on how to exploit root-soil-microbe interaction processes to improve crop productivity and P use efficiency.

KEYWORDS:

root zone, rhizosphere processes, localized nutrients, intercropping, plant-microbe interactions

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus; AMF = arbuscular mycorrhizal fungi; PGPR = plant growth-promoting rhizobacteria; ACC = aminocyclopropane carboxylic acid

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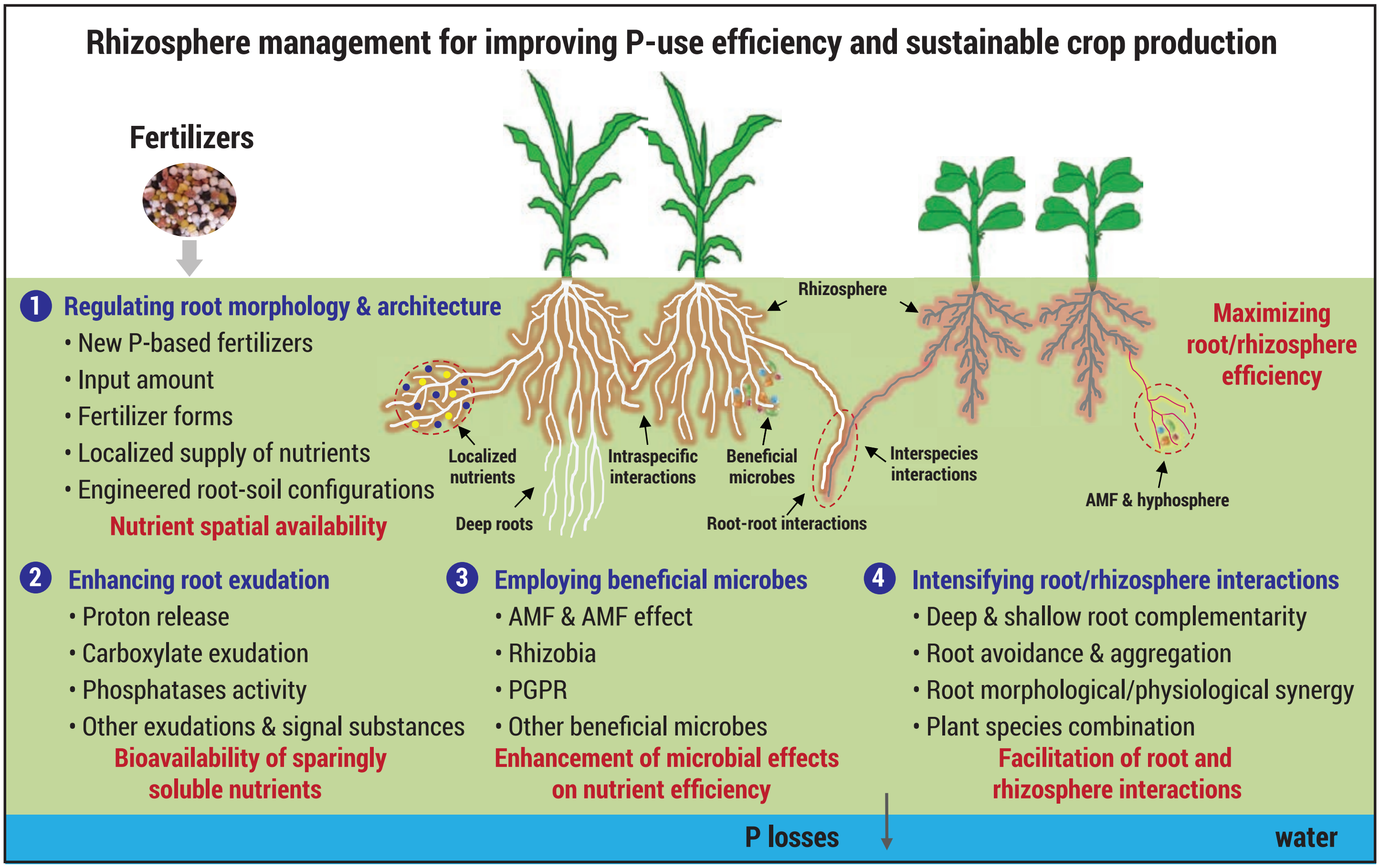

Figure 1. Rhizosphere management strategies for sustainable P use in cropping systems.

(Shen et al. 2011). The regulation of root growth by nutrient supply intensity in the root zone is closely related to crop growth stage. For example, spring maize root systems are very small and soil P availability is relatively low due to low temperature during their early growth stages, but seedlings have a high P requirement. To tackle these incongruities, precision regulation of rhizosphere and root zone nutrients is needed. Therefore, the alteration of root growth and rhizosphere processes can provide an effective approach to improve nutrient use efficiency and crop productivity.

Rhizosphere management strategies emphasize maximizing the efficiency of root and rhizosphere processes involved in nutrient mobilization, acquisition, and use by crops, rather than relying solely on the high use of mineral fertilizers in intensive farming systems (Shen et al., 2013; Jiao et al., 2016). Rhizosphere management strategies include: 1) regulating root morphology and architecture by adjusting the quantity, composition and manner of nutrient supply; 2) increasing the bioavailability of sparingly soluble nutrients by manipulating root exudation; 3) improving the uptake of immobile nutrients by employing mycorrhizal fungi and other beneficial microorganisms; 4) intensifying rhizosphere interactions through interspecies interactions by intercropping (**Figure 1**). The overall goal of rhizosphere management is to increase nutrient use efficiency, improve crop yields, optimize mineral fertilizer inputs, and achieve sustainable crop production by optimizing and integrating a range of beneficial rhizosphere interactions.

Case Studies on Rhizosphere Management for Improving Phosphorus Use Efficiency

1. Root Zone Nutrient Management by Localized Nutrient Supply

Plants can acquire P from soils, which is essential for their growth. Plant roots can influence the processes occurring at the root-soil interface through physiological metabolic activities, to improve the bioavailability of soil P. Studies have shown that plants can efficiently obtain soil P by changing root morphology and physiological characteristics. For example, P-efficient maize roots can occupy greater soil volumes by increasing the density and length of lateral roots under conditions of P deficiency. The intensity of P supply regulates root growth and modifies the chemical and physiological processes in the rhizosphere. A study in the North China Plain showed that maize maintained optimal root efficiency in terms of mycorrhizal infection, root surface area, and root growth vitality at a topsoil (0 to 20 cm) Olsen-P of 5 to 10 mg/kg, and at the same time maintained the maximum yield (Deng et al., 2014). The results showed that maintaining the correct P supply intensity in the root

Figure 2. The responses of root morphology and physiology to P supply. (a) Roots and root hairs of maize proliferated in P-banding zone. (b) Purple color indicated rhizosphere alkalization (+P, 250 µmol/L P) and yellow color indicated rhizosphere acidification (-P, 0 µmol/L P) of alfalfa. (c) Yellow color indicated rhizosphere acidification of maize in P-free nutrient solution.

zone can enhance P use efficiency by crops.

Plant roots have high plasticity to the heterogeneous distribution of nutrients in soils (**Figure 2**). Drew (1975) showed that localized supply of nitrate (NO_3^-) or P increased the number of lateral roots in barley. The nutrients serve as signals to stimulate root development and growth. Studies suggested that localized supply of superphosphate combined with ammonium-N (NH_4^+-N) significantly stimulated root proliferation, especially of fine roots, and thus improved maize growth in a calcareous soil. The supply of NH_4^+-N promoted H^+ release from the roots and thus decreased rhizosphere pH, resulting in increased P bioavailability (Jing et al., 2010). Further studies indicated that localized supply of P and NH_4^+-N at both seeding and later growth stages increased maize yield by 8 to 10%, P uptake by 39 to 48%, and localized increases in root density and length of 50% (Ma et al., 2013). Compared with conventional nutrient management in an intensive, high input-high output system having excessive amounts of fertilizer being broadcast on the soil surface, this strategy fully considers soil conditions and the biological potential of roots, enhancing nutrient use efficiency by fertilizing roots, not the soil, to maximize root/rhizosphere efficiency.

2. Rhizosphere Interactions in Intercropping

Intercropping systems can improve nutrient use efficiency and crop productivity (Zhang et al., 2010). Most studies on intercropping have focused on aboveground interactions. However, underground interactions can affect the spatial distribution of roots, the morphological characteristics of roots, and physiological processes in the rhizosphere. In maize/fababean intercropping systems, fababean increases P uptake and growth for both itself and neighboring maize plants by secreting organic acids and H^+ into the rhizosphere, thus mobilizing sparingly soluble P (Li et al., 2014). Optimizing nutrient supplies in intercropping systems, as described in the previous section, can further improve nutrient use efficiency and crop yield. Localized supply of P and NH_4^+-N was shown to promote the uptake and use of P in a maize/fababean intercropping system. Root/rhizosphere interactions in maize/fababean were also promoted by having a localized P supply and neighboring crop (Zhang et al., 2016). Exploring root/rhizosphere interactions in cropping systems can greatly reduce P fertilizer input requirements by effectively using P that is already present, but bound, in the soil.

3. Plant-Microbe Interactions in the Rhizosphere

The root-microbe interactions in the rhizosphere are important for plant growth, nutrition, and health (Zhang et al., 2017). Arbuscular mycorrhizal fungi (AMF) help more than 80% of terrestrial plants to acquire P from the soil. Rhizobia can fix N, while P-solubilizing bacteria can increase the amount of available P for plants and assist roots to take-up these nutrients. Plant growth-promoting rhizobacteria (PGPR; e.g., *Variovorax paradoxus 5C2*) can reduce the ethylene content in roots and promote root growth by decomposing the ethylene precursor aminocyclopropane carboxylic acid (ACC) (Belimov et al., 2009). Root exudates play an important role in root-microbial interactions, and

TAKE IT TO THE FIELD

Phosphorus use efficiency can be improved by root zone nutrient management through adopting localized nutrient supplies (subsurface band placement), enhancing root/rhizosphere interactions with intercropping, and manipulating beneficial rhizosphere microorganisms.

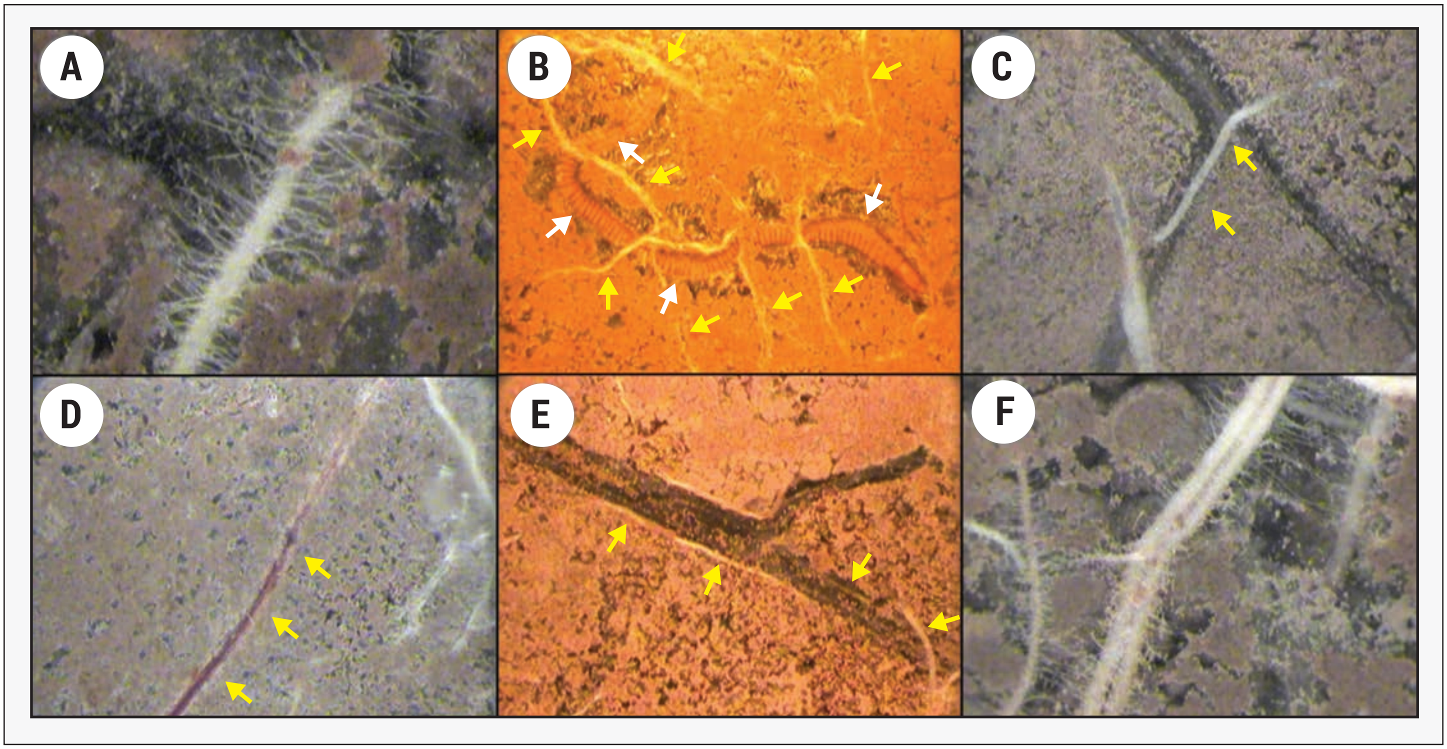

Figure 3. Images showing root-soil-microbial interactions. (a) Maize root hairs and hyphae attach plants to soil particles. (b) Maize roots grow around earthworm and earthworm burrow. (c) Maize root grows along soil pore at an appropriate angle. (d) A biopore formed after a root death. (e) Maize root growing along pores formed by dead root. (f) Maize roots clumped in a soil pore with root hairs contacting sides of pore.

even can act as signals to regulate root-microbe interactions. Some plants secrete large quantities of root exudates into the rhizosphere, which are 'exchanged' for soil nutrients mobilized by soil microbes (Werner et al., 2014). The composition and amount of root exudates affect the composition of microbes in the rhizosphere, and the structure of the rhizosphere microbiome, affecting plant growth and nutrient uptake. For precision rhizosphere management, plant-microbe interactions must be finely tuned to improve P use efficiency by crops (**Figure 3**).

Concluding Remarks

Maintaining crop production with high P use efficiency and low environmental impact to feed a growing global population is a great challenge. Better root/rhizosphere management has been shown to be an effective way of ensuring fertilizer P is efficiently absorbed and used by plant roots. Theoretically, fertilizer P should be applied into the rhizosphere rather than to the whole soil profile, but technically it is hard to achieve this. Precise management of root/rhizosphere processes and interactions can play an important role in the development of effective solutions for the sustainable use of P, given the success of root/rhizosphere-based P management in China. The complexity of root-soil-microbe interactions limits the predictability of impacts of practices like inoculation and other manipulations intended to enhance the benefits. Optimizing root/rhizosphere management and better matching nutrient supply with crop demands to maximize root/rhizosphere interactions are potentially an important way of improving the sustainable use of P in agriculture. **BC**

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Increasing Plant Access to Legacy Phosphorus, with a Focus in the Tropics

By Luís I. Prochnow, Heidi Peterson, and Tom Bruulsema

Phosphorus (P) is one of the most studied nutrients for plant nutrition worldwide and there are many concerns regarding the availability of its finite reserves and resources for future generations. For tropical soils, predominantly with an oxidic or 1:1 mineralogy, P gains even more attention due to its high potential to be fixed into forms less available to plants. Currently, this nutrient is normally applied to soils in higher amounts than removed, which leads to a stock of P in less available forms in the soil (i.e., residual or legacy P). Recently, researchers have been calculating this legacy P and discussing possibilities to increase its recovery and decrease P input dependency in a near future. The cumulative surplus of P applied to cropland between 1900 to 2016, over that removed by crop harvest during the same time interval was recently calculated to be about 30 million (M t) for Brazil (Withers et al., 2018). This is compared to about 40 and 65 M t for the U.S. and Western Europe, respectively, calculated from data presented in Mogollón et al. (2018). Considering that all three of these regions feature highly productive cropping systems, it is reasonable that large legacies of P may have accumulated in other regions with similar levels of productivity.

There are industrial and agronomic practices that may increase efficiency of P use from phosphate rock (PR) mining to field operations. Recovering part of the legacy P in soils seems to be one potentially profitable option. Although much of the legacy P may have been transformed over time into forms of low availability, the agronomic practices discussed in this paper have the potential to help plants to access some of those forms. The focus is specially on acid soils of the tropics, but some of the techniques can be applied to a variety of soils around the globe.

Management of Soil Acidity with Lime and Gypsum Application

Liming improves both positional and chemical availability of plant nutrients. It improves soil aggregation and tilth, resulting in greater root proliferation. When soil pH is optimum, plants develop more finely divided and extensive root systems, and are better able to utilize nutrients present in both surface and subsoils. Changes in soil pH affect the availability of the various plant nutrients differently, as illustrated in **Figure 1**. The availability of most nutrients, including P, is greatest in the soil pH range of 5.8 to 7.0. Besides increasing the availability of nutrients, one of the most important benefits of liming is the reduction in the activity of toxic elements like Al, and sometimes Mn and Fe.

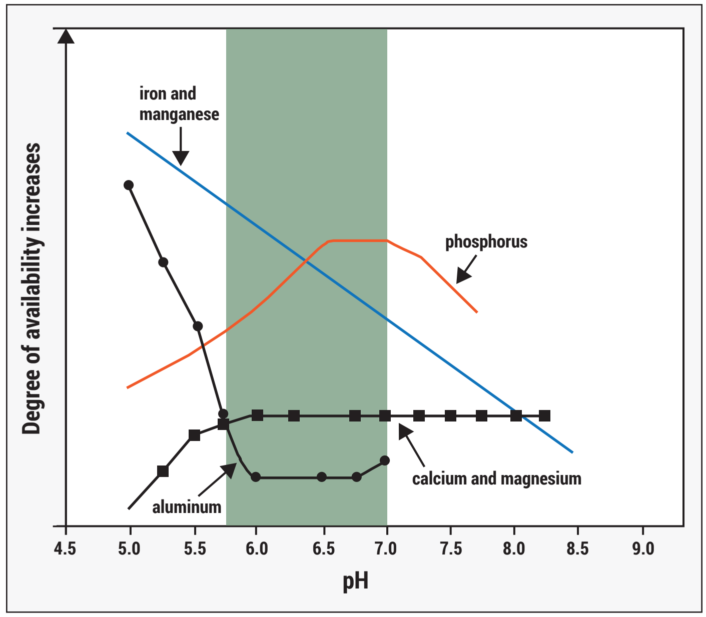

Figure 1. Typical effect of change in soil pH on the availability of some of the plant nutrients and also aluminum (Adapted from Malavolta, 2006).

Chemically gypsum is a neutral salt with no direct effect on soil pH. However, many researchers have shown that it can ameliorate subsoil acidity with positive influences on plant root development. Because gypsum has higher water solubility than lime, it can dissolve and leach through the soil profile adding significant amounts of Ca and sulfate (SO_4^{2-}) at soil depths where lime would not reach. The increase in SO_4^{2-} concentration in deeper soil layers favors the formation of the ion pair aluminum sulfate ($AlSO_4^-$), which diminishes the activity of Al^{3+}. As a result, the toxicity of Al^{3+} is decreased, and at the same time the availability of Ca is increased, thus favoring the elongation of plant roots in

SUMMARY

Tropical soils have a high tendency to convert applied P into less available forms. This article discusses readily adoptable agronomic practices that have good potential to help plants to access this pool of "legacy P."

KEYWORDS:

legacy phosphorus; tropical soils; no-till; gypsum; intercropping

ABBREVIATIONS AND NOTES:

P = phosphorus; Ca = calcium; Al = aluminum; Fe = iron; Mn = manganese

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Beans under no-till done right. Note the favorable amounts of residues from previous crops in the soil surface.

Table 1. Effect of phosphogypsum (PG) application on the development of root systems at different soil depths in different crops from different parts of the world.

	Corn root density (South Africa)[1]		Corn % relative distribution of roots (Brazil)[2]		Apple root density (Brazil)[3]		Alfalfa root length (USA)[4]	
Soil depth	C[(1)]	PG[(2)]	C	PG	C	PG	C	PG
cm	- - - m/dm^3 - - -		- - - - % - - - -		- - - cm/g - - -		- - - m/m^3 - - -	
0-15	3.10	2.95	53	34	50	119	115	439
15-30	2.85	1.60	17	25	60	104	30	94
30-45	1.80	2.00	10	12	18	89	19	96
45-60	0.45	3.95	8	19	18	89	10	112
60-75	0.08	2.05	2	10	18	89	6	28

C = Control; Sources: [1] Farina and Channon, 1988; [2] Sousa and Ritchey, 1986; [3] Pavan and Bingham, 1986; [4] Sumner and Carter, 1988.

this acidic subsoil. **Table 1** shows results from studies in different parts of the world on the development of plant root systems with and without application of phosphogypsum (PG), which is a by-product in the production of phosphoric acid. Clearly, PG application helped develop better root systems at soil depths beyond 30 cm. One major concern with the use of PG is the amounts of radioactive elements it may contain. A careful characterization of PG is therefore necessary before using this material as a soil input to ameliorate subsoil acidity.

Both lime and gypsum create better soil conditions that favor root elongation, plant development, and consequently higher yields. More roots mean more soil explored and more favorable conditions to absorb nutrients and water. Thus, these techniques can increase access to legacy P.

No-till Done Right

It is well-known that no-till done right, in terms of crop rotation and more residues at the soil surface, leads to less erosion, higher amounts of soil organic matter (SOM), and better soil physical conditions. Results have been so successful that land area under no-till has been increasing dramatically over conventional tillage systems in many tropical regions of the world. One of the effects of no-till in terms of nutrient availability is that higher contents of SOM, by protecting sites of P adsorption and/or by replacing P in such sites, leads to higher P availability. Also, better soil physical conditions lead to more soil explored by plant roots and higher chance for P uptake. Among others, these effects indicate that no-till done right can lead to more of the legacy P used by plants.

Crop Rotation and Intercropping Grain Crops with Grasses

Recently, several studies have shown the advantages of integrating grain with certain type of grasses for increasing soil health and yields with time. Many grasses have robust and deep root systems, show high tolerance to water stress, and consequently can develop well in conditions where the great majority of grain crops, and some conventional cover crops, do not.

Many authors have also noticed that some of these grasses improve cycling and availability of nutrients in the soil system, particularly P. As an example, **Figure 2** shows the increase in the plant-available P between 5 to 40 cm when corn was intercropped with palisade grass (*Urochloa brizantha*), as opposed to monocropped with corn. There are indications that the increase is due to more P extracted from slowly soluble forms by the palisade grass. Field studies in Brazil indicated that P recovery over fifteen

Intercropping of corn and the grass *Brachiaria brizantha*.

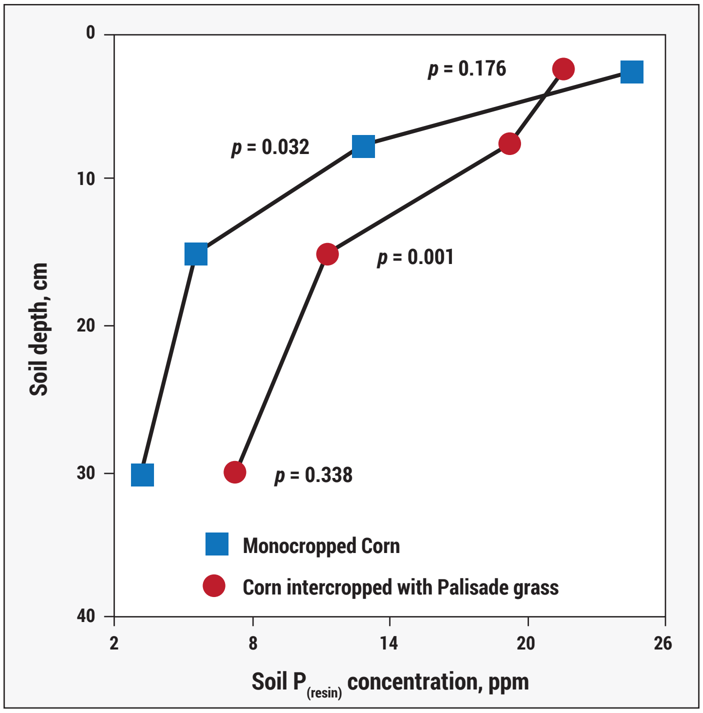

Figure 2. Farming systems including grasses may increase the plant-available soil P through the soil profile in well-managed no-till systems (Crusciol et al. 2015).

or more years under cropping systems including grasses, like *Urochloa brizantha* and *Panicum maximum*, can be in the order of 85% over the years, while just around 40% was recovered when only soybean and/or corn was cultivated. These results suggest that more of the legacy P can be accessed by plants when adequate grasses are intercropped or used in sequence with other species.

Due to differences in the ecosystems and plant characteristics it is important to study the best type of crop rotation for each region. There is no general rule for recommending a crop sequence amongst the diverse agricultural areas of the globe, but keeping green cover over soil for a significant proportion of the year will generally contribute more carbon to the soil, which with time will be agronomically and environmentally beneficial.

Regarding crop rotation and tillage practices that increase SOM, these practices will only be successful in soils where P is not limiting plant growth. Phosphorus inputs will often be necessary to obtain this condition. That means these practices will not be effective in soils with low amounts of plant-available P. Soil fertility needs to be built with time so that other practices can work well.

Phosphorus-efficient Crops and Cultivars

Different crops have different requirements concerning P availability in the soil. As an example, it is estimated that soybean needs a P concentration in soil solution that is 20 times higher than what peanut crops need to reach 95% of their maximum yields. Also, some species have developed strategies to improve their capacity to absorb P from the soil, rending less available forms of P into forms accessible to them under P-limiting conditions. These strategies include improved uptake efficiency (ability to take up more P under P-limiting conditions) and/or improved use efficiency (ability to produce higher dry matter yield per unit of P taken up). Some of the uptake efficiency include modification of root architecture, development of more ample root systems, longer root hair and thinner roots, higher root-shoot ratio, exudation of low molecular weight organic acids, and stronger association with mycorrhiza. Breeding programs can use such traits to improve the use of soil P. From the above it is clear that plant species or genotypes of the same species with higher P uptake efficiency can lead to higher use of the legacy P in the soils.

4R Nutrient Stewardship

Applying the right source, at the right rate, at the right time, and in the right place is key to achieving efficient use of nutrients and higher yields. These practices, in conjunction with other seeding, plant protection, and irrigation management practices can improve plant development favoring plant health, root elongation, and consequently, more absorption of water and nutrients. As an example, it is clear that positioning of P in furrow, and not just broadcasting on the soil surface, can lead to root elongation and more volume of soil explored, which with time may translate into more of the legacy P used by different crops.

Conclusion

All the practices above should be seriously considered in strategic plans to recover a portion of the legacy P from tropical soils, which will optimize P resources, benefiting farmers and food security in the medium to long run. It is expected that scientific development will result in the availability of new management technology, crop varieties, and plant protection products that can lead to better use of the soil's legacy P. **BC**

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Improved Plant Diversity as a Strategy to Increase Available Soil Phosphorus

By Carlos A.C. Crusciol, João P.G. Rigon, Juliano C. Calonego, and Rogério P. Soratto

Crop rotations associated with soil conservation management have been suggested as a suitable strategy to enhance soil health and nutrient availability. Conversely, monoculture systems may not be able to reach sustainable soil management by recycling nutrients. Increasing both the quantity and quality of crop residues in diversified cropping systems can provide multiple ecosystem services, such as recycling nutrients and increasing soil organic matter. The impacts vary widely according to the crop species, residue composition, soil textural class, climate, soil management, and their interactions. However, little attention has been directed toward understanding relationships between functional plant diversity, nutrient cycling, and soil P availability (Faucon et al., 2015). In this article we highlight some strategies to improve the P availability in cropping systems.

Release of Phosphorus by Crop Residue Decomposition

Indirect impact on P availability may be attributed to cropping systems by the biochemical crop residue compositions, including the C:N and C:P ratios, as well as the soil biodiversity. The P concentration of the crop residue is a main factor determining whether P will be mineralized in the short-term as a result of residue decomposition. These characteristics can promote microbial diversity, which may result in a positive effect on P availability and crop growth.

In the crop tissue, the soluble inorganic phosphorus (P_{si}) fraction represents the highest P content, primarily stored in the vacuole, which is released in early stages of crop residue mineralization. However, more recalcitrant P fractions tend to have their proportions increased in residues as they are present in organic compounds that depend on biochemical composition of the crop residue and mineralization for P release. In general, crop species with a lower C:N ratio as well as lower lignin content stimulate the release of P, whereas, the release of P occurs over time in species with a higher C:N ratio and higher lignin content. Cereal crop residues tend to have lower P concentrations and higher C:P and C:N ratios, which results in a lower potential for mineralization during decomposition compared to crops with lower ratios. Therefore, under conditions of low inorganic P (P_i), soil P_i may be assimilated by microbial biomass, decreasing crop P availability. In this sense, the cropping system has the potential to either limit or increase soil P availability.

Cropping systems, as regulators of the plant-available nutrient supply, must be addressed to boost residue P recycling. The inclusion of palisadegrass (*Urochloa brizantha)* in a cropping rotation provided greater available nutrient contents in the soil, increasing soybean, white oat, and maize yield as main crops (Crusciol et al., 2015). A crop rotation experiment assessing the impact of ruzigrass (*Urochloa ruziziensis*) on soybean yield, indicated that the ruzigrass did not affect soybean yield compared to a fallow field (Merlin et al., 2013). However, cropping ruzigrass for consecutive years at the same experimental site did result in a decrease in soybean yield compared with the legume as monoculture (Almeida et al., 2018). According to the authors, ruzigrass may keep P immobilized in crop residue, affecting the P nutrition of soybean. Therefore, P release through crop residue mineralization may be related to a synchrony between soil P availability, the mineralization process, and the demand by the main crop.

Some plants have enhanced capacity to take up P from soil under low concentration by increasing their phosphatase activity and then accumulating P in their tissues (Faucon et al., 2015). This may reduce the chemical fixation, decreasing the time of P exposure to soil particles. This approach could be important for highly weathered soils. Other strategies to increase P uptake may address arbuscular mycorrhizal symbioses. The mycorrhizae provide an effective pathway by which P is scavenged from larger volumes of soil and rapidly delivered to cortical cells within the root, bypassing direct uptake (Smith et al., 2011). However, the diversity of responses to inoculation with mycorrhizal fungi

SUMMARY

Some crop species could be used inside a cropping system as part of a strategy to increase soil P availability due to their capacity to recycle P and shift the equilibrium between soil P fractions to benefit the main crop. The release of P by crop residue decomposition, and mobilization and uptake of otherwise recalcitrant P are important mechanisms capable of increasing P availability and crop yields.

KEYWORDS:

P release from crop residue; main crop yield; P solubilization

ABBREVIATIONS AND NOTES:

P = phosphorus; P_o = organic phosphorus; P_i = inorganic phosphorus; P_{si} = soluble inorganic phosphorus; N = nitrogen; SOM = soil organic matter

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Ruzigrass (*Urochloa ruziziensis*) left, and **Palisadegrass** (*Urochloa brizantha*) right, have been studied in Brazil to determine their impact on P availability to main crops in the rotation system.

is widely recognized due to the ecosystem conditions and cropping management strategies.

Mobilizing Recalcitrant Soil Phosphorus

Although there are not many cases, a few cover crop species are reported to efficiently take up less-labile P forms. Introduction of these species into cropping systems could improve P availability to main crops (i.e., those with less ability to mobilize recalcitrant P forms). Phosphorus-mobilizing crop species improve P nutrition due to rhizosphere related traits of multicropping systems by releasing acid phosphatases or phytases. These conditions hydrolyze P_o to release P_i, protons and/or carboxylates in soils, decreasing P sorption on Al and Fe oxide and hydroxides. Malate and citrate are carboxylates that mobilize P bound to Ca in calcareous soil and P bound to oxides and hydroxides of Al and Fe in acid soils (Hinsinger, 2001). For example, fababean releases protons, malate, and citrate into the rhizosphere, mobilizing insoluble soil P. Chickpea accesses P_o by exudation of acid phosphatases, which hydrolyze P_o into P_i, facilitating P acquisition by wheat or maize grown in an intercropped system (Lambers et al., 2011). According to the literature, some intercropping systems have been reported to encourage interspecific facilitation of P acquisition by P-mobilizing species: wheat intercropping with *Lupinus albus*/chickpea (both

Chickpea (left) and **Fababean** (right) have been shown to mobilize or facilitate access to less-labile forms of soil P.

Table 1. Examples of crop rotations in which yield improvements were attributed in part to improved P nutrition.

Main crop	Cropping systems	Yield, t/ha	Authors
Maize	Monocropping	12.8	[1]Li et al. (2007)
	Fababean/maize rotation	18.9	
	Continuously intercropped with fababean	17.3	
Maize	Monocropping	9.1	[2]Wang et al. (2014)
	Intercropped with fababean	11.0	
	Intercropped with soybean	12.6	
	Intercropped with chickpea	12.4	
Potato*	Monocropping	35.5	[3]Gitari et al. (2018)
	Intercropped with pea	37.7	
	Intercropped with common bean	40.3	
	Intercropped with *Lablab purpureus*	43.1	
Wheat	Rice/wheat rotation	2.4	[4]Bai et al. (2013)
	Maize/wheat rotation	2.7	
	Soybean and maize/wheat rotation	3.1	
Soybean	After 2 years of maize/fallow	3.4	[5]Crusciol et al. (2015)
	After 2 years of maize intercropped with *U. brizantha*	3.7	
White oat	After 2 years of maize/fallow/soybean	1.5	
	After 2 years of maize intercropped with *U. brizantha*/soybean	1.9	
Maize	After 2 years of maize/fallow/soybean/white oat	8.7	
	After 2 years of maize intercropped with *U. brizantha*/soybean/white oat	9.9	

Type of influence in P availability

[1] Facilitated P uptake by maize because fababean acidified its rhizosphere, and exuded malate and citrate into its rhizosphere mobilizing insoluble P_i in soil.
[2] Intercropping enhances soil acid phosphatase activity compared to monocropping.
[3] Suggest the *Lablab purpureus* produces exudates such as phosphatases and carboxylates, increasing P availability to the companion crop
[4] Suggest the release of proton and carboxylates exudation by maize roots and mobilizing soil Pi in calcareous soil.
[5] Suggest the action of low molecular-weight organic acids exuded by the roots.
*Potato equivalent yield.

P-mobilizing species); sorghum intercropping with *Cajanus cajan* (P-mobilizing species); maize intercropping with peanut/fababean (both P-mobilizing species) (Li et al., 2007; 2014).

Intercropping P-mobilizing and non-P-mobilizing crop species creates a temporal and spatial niche enhancing the capability to exploit soil P by colonizing the soil profile and increasing the total soil volume occupied by these species compared to a monoculture (Li et al., 2014).

Research studying the yield improvements arising from interspecies interactions within cropping systems and improvements in P nutrition has been limited, but some examples are listed in **Table 1**. There is some agreement based on the studies reviewed, that increasing soil P availability in cropping systems requires: soil management and P fertilization; incorporating species with the ability to mobilize insoluble soil P into monoculture cropping systems; and a better understanding of the release of P from crop residue decomposition.

Considerations

Studying the recycling of P in cropping systems with a focus on P availability is a challenge due to soil-plant interactions. The strategies summarized in this article address soil management to increase available P, with a focus on recycling P and shifting the equilibrium between soil P fractions towards plant-available fractions in cropping systems. Great efforts are necessary in this applied research field to maintain sustainable strategies on cropping systems management concerning crop P recycling. **BC**

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Phosphorus Use in High Yield Cropping Systems

By Bryan G. Hopkins

Yield and Phosphorus Relationship

Increasing crop production is essential as the global population grows. For example, U.S. crop yields were relatively flat until ~1940, but have steadily increased since the dawn of this "Green Revolution" (**Figure 1**). The P concentration in harvested produce is somewhat consistent regardless of yield. Thus, higher yields result in greater crop P uptake and removal. In many cases, increased yields have depleted soil P in regions where it has not been replenished (IPNI, 2015).

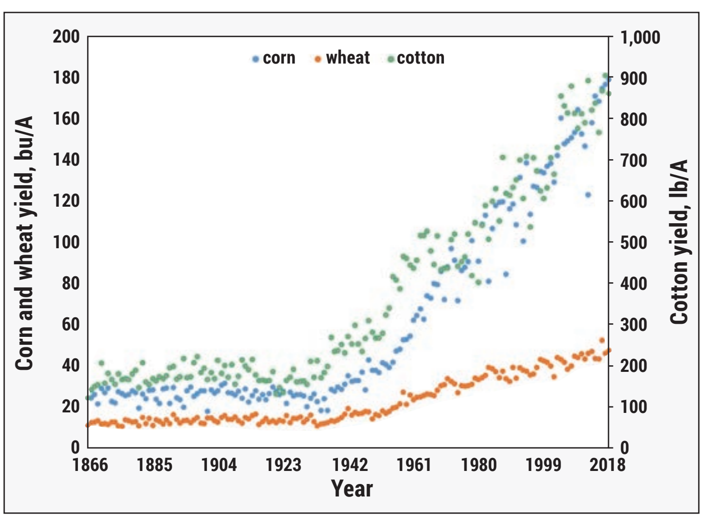


Figure 1. Historic USA corn, wheat, and cotton yields (USDA-NASS, 2018).

Nutrient depletion is not compatible with maintaining

SUMMARY

You don't run a marathon on a diet. Just as high-performance athletes require carefully managed nutrition, producing high-yielding crops necessitates knowledge and care when it comes to nutrient management. This is especially true for P, which is often inadequately supplied to sustain high crop yields.

KEYWORDS:

sustainability; nutrient depletion; P requirement; variability; plant health

ABBREVIATIONS AND NOTES:

P = phosphorus

https://doi.org/10.24047/BC103146

the trajectory of increasingly high yields, as continued responsible replenishment of nutrients is needed. For example, the University of Idaho cooperated with growers and industry partners in the discovery that the soil concentration at which potato responds to P fertilizer and the application rates required to achieve maximum economic yield needed to be increased dramatically. Although higher fertilizer rates may be needed in some scenarios, there are a variety of P fertilizer management practices that should be utilized to efficiently produce high yields, adjusted for specific crop and soil conditions.

Applying lime across a field with variability can have implications for P availability. It is best to measure pH in unique management zones in the field.

Exceptional Yields Require Exceptional Management

In general, best management practices for all facets of nutrient, soil, water, and pest management need to be followed to achieve superior yields. Those specific to P include:

Fertile Soil – Fertilizer is not a stand-alone nutrient supplier, but rather a partner with soil minerals and organic matter in providing for plant requirements. For P-depleted soils, there is proven benefit in adding P in modest excess of crop removal to maximize production and to improve soil health. Once a moderately high soil reserve is built, P fertilizer application rates can be reduced to maintain this level. Of course, excessive P concentrations can be an environmental risk and should be avoided (Hopkins, 2015). Tracking soil P concentrations over time will assist in making nutrient use decisions, while using consistent sampling methods, depths, and analytical processes.

Species Management – Each species differs in its P requirement. For example, potato tends to have shallow, ineffective roots with few root hairs. As such, it typically requires at least twice as much P in the soil to achieve high yields than does corn and most other crops.

There are also intra-species differences in P requirement. For example, the most commonly grown potato variety is 'Russet Burbank'. This variety requires much more P than some newer developed cultivars, such as 'Alturas'. In general, older corn hybrids had P uptake rates that plateaued with the onset of reproduction, but newer hybrids continue to take up P throughout the reproductive stage (**Figure 2**).

Variable Fertilization – Farm fields have a range of soil properties that result in spatially variable yield potential. Phosphorus availability is one of these variable properties. Areas with low P concentration may need to have relatively more fertilizer applied (assuming other yield-limiting prop-

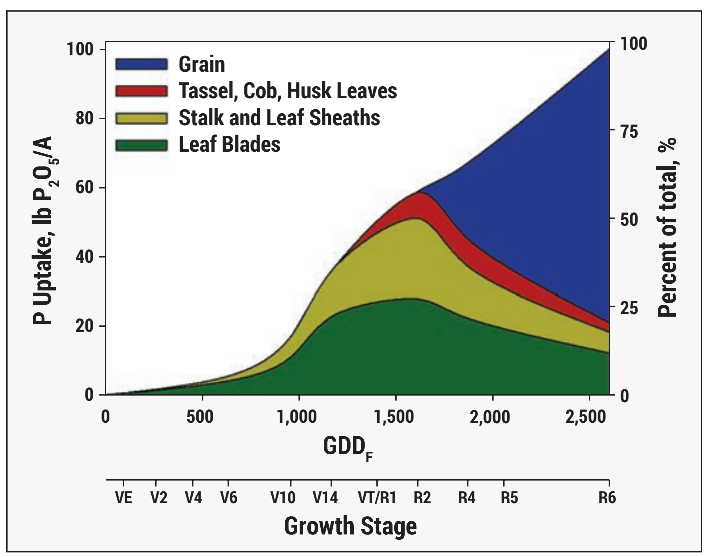


Figure 2. Total corn P uptake and partitioning across four plant stover fractions (leaf, stalk, reproductive, and grain tissues) at Urbana, and DeKalb, Illinois, USA (2010). GGDF = growing degree days in Fahrenheit (Bender et al., 2013).


istockphoto

Its important to understand how a crop's root system grows in order to best place concentrated bands of P.

1% soil lime, up to 80 lb. Other crops also likely benefit from additional P in calcareous soils, but this is not as well documented with research.

Placement – Phosphorus is used most efficiently when it is placed in close proximity to the root system. Subsurface application of P fertilizer is generally most effective, but may not be compatible with cropping systems using reduced tillage techniques.

Starter Fertilizer – Although there is benefit from the bulk soil having an ample P concentration, the most efficient use comes from fertilizer placed in a concentrated band in the path of growing roots. A relatively small amount of low-salt index, starter P fertilizer helps satisfy the nutritional demands for vigorous seedling growth. In general, the smaller the seed size, the greater the need for early-season P, but also the greater the susceptibility to potentially harmful effects of soluble fertilizer salts.

Concentrated Bands – Relatively high P application rates are possible when the fertilizer band is placed a few inches from the seed, often 2 in. (5 cm) to the side and down for crops with typical diagonal root patterns. But, understanding root morphology, architecture, and growth patterns are important.

For example, sugarbeet has a largely downward-growing taproot with little lateral growth during the first 8 to 10 weeks after planting. Its roots explore the subsoil, which typically has little P, during the critical time when it is setting the final yield potential. A band of P fertilizer directly below the seed is often a key to obtaining high yields, even in soils with a relatively high P concentration.

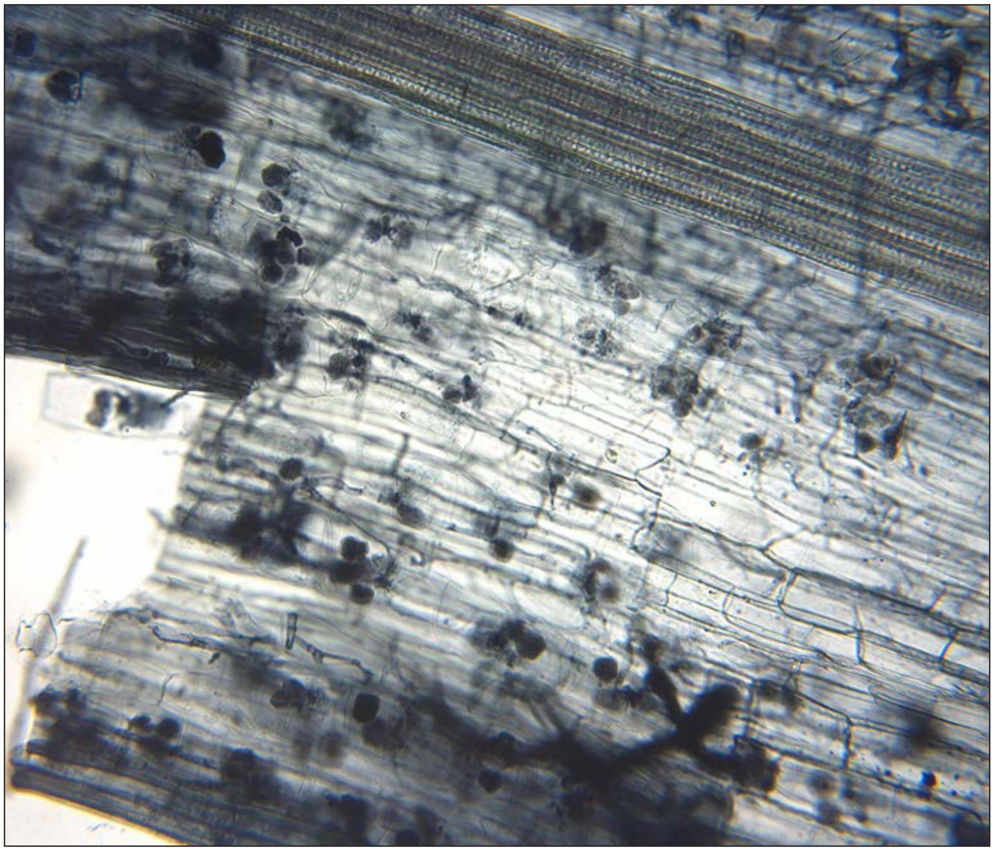
An alternative example is potato where the root growth pattern is much more fibrous and diagonal. Potatoes are planted with a large seed piece that contains a relatively large reserve of P. The fertilizer band in this case is often applied prior to planting when the soil beds are formed. Planting depth is relatively deep and risks disturbing the band. Thus, the band needs to be placed diagonally from the seed piece, but relatively deeper. The greater distance is not a problem during early season growth because of the P reserve in the seed piece.

Enhanced Efficiency – There are various P fertilizer sources and/or additives that may provide enhanced efficiency. For example, certain organic acids blended or chem-

erties can also be addressed). Areas of the field with high P concentrations may have higher crop yields that result in a net removal of soil P if the field is not fertilized to account for its soil P fertility. Each distinct field area should be identified, sampled, and fertilized uniquely. Soil color and slope/aspect are often the best factors to identify low P soils in eroded upslope areas, but yield history, canopy health, and intensive sampling with chemical/physical/microbial analysis are also valuable.

Manage pH – Phosphorus solubility and plant availability is optimum at a soil pH between 6 and 7. It is best to measure pH in unique management zones in the field. If the soil is acidic (<6), add lime to raise pH. If alkaline (>7), lowering the pH is possible, but generally not practical or economical. Rather, add relatively more P according to calibrated soil tests.

Alkaline soils typically occur in arid regions. These soils have carbonate minerals (lime) present. In addition, they are often irrigated with "hard water" high in dissolved lime. Carbonates further reduce P solubility and buffer the soil pH against change. When present, carbonates require the addition of more P fertilizer compared to where carbonate minerals are not present. For example, an additional 10 lb P_2O_5/A is recommended to be added to potatoes for each



en.wikipedia.org

Microscopic view of symbiotic, mycorrhizal infection of a plant root that can offer benefits for plant P recovery.

ically bonded with P can sometimes improve nutrient uptake and yields, especially in calcareous, low organic matter soils. Other additives and controlled-release P sources have also been shown to be effective in some circumstances. In these cases, it is noteworthy that use of these products on soils with high P concentrations, or at high rates of application often results in no yield benefit, or perhaps a negative yield response.

Tissue Analysis – Chemical analysis of the plant tissue is used to inform in-season P fertilization decisions. In some circumstances, crops have shown a response to in-season P fertilization via fertigation or foliar application, even though it is relatively less effective than preseason soil application (or not effective at all) in some cropping systems. Phosphorus is not very mobile in soil and thus it is important that there are abundant fine roots in moist soil near the surface for in-season P applications to be effective. Adjustments need to be made in future years to deliver all of the crops P needs into the soil prior to planting—using tissue analysis to verify if this objective is met.

Vascular Health – Root hairs are the site of most P uptake for plants and it is subsequently transported throughout the plant via the vascular system. Roots need to continuously explore new soil for continued P supply due to low soil mobility. Good overall plant health, including avoiding pest and mechanical damage to roots, is key in achieving maximum nutrient efficiency and plant growth. Vascular health can be evaluated by visually inspecting both the exterior and interior of root and shoot tissues, and where appropriate, tested for pathogens. Albeit not desirable or efficient, foliar applications can sometimes be a rescue treatment to deliver nutrients to the foliage when root growth is impaired.

Microbial Health – Although some soil microbes are damaging to plant growth, most are beneficial. The prospect of obtaining high yields is enhanced with a large and diverse microbial population that has sufficient soil organic matter as an energy source. This biodiversity increases competition against many important crop pathogens. Additionally, some rhizosphere microbes are specifically beneficial for P recovery (although beware that there are many claims in this area that do not prove to be effective). For example, mycorrhizal fungi have a symbiotic relationship with roots as they take energy from the plant in exchange for water and nutrients they bring in from their extended hyphal network. This relationship is well known in low fertility/water systems, but its importance in high-yield environments is beginning to be understood and managed. As with all practices, it is vital to follow scientifically proven practices specific to each cropping system.

Closing Thoughts

The essential role of P in sustaining crop yields is well known. Using the specific management practices outlined herein helps maximize the use of P fertilizer to achieve these yields. Although P fertilizer has contributed to world food security and improving the lives of billions of people, there are many aspects related to improved P management that will need to be better understood and implemented in the field. **BC**

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Phosphogypsum: P Fertilizer By-Product and Soil Amendment

By Valery Kalinitchenko and Vladimir Nosov

Phosphogypsum (PG) is a reaction product from the making phosphoric acid by treating phosphate ore (apatite) with sulfuric acid according to the following reaction:

$$Ca_5(PO_4)_3F + 5\ H_2SO_4 + 10\ H_2O \rightarrow$$
$$3\ H_3PO_4 + 5\ (CaSO_4 + 5\ (CaSO_4\ \cdot 2\ H_2O) + HF$$

Annual world production of PG has been estimated at 300 million (M) t (Yang et al., 2009), but only a small percentage [4% according to Recheigl and Alcordo (1994)] finds use by either agriculture or industry. The remainder is either disposed of in the ocean or stockpiled near production facilities.

PG is considered a low-cost source and one of the most effective amendments for problematic soils including those affected by general salinity, high Na (sodic or solonetzic), and soil compaction (Belyuchenko et al., 2010). Russia is significantly impacted by sodic and saline soils, which occupied 20% of its agricultural land area in 2007 (The Nature of Russia…, 2016). This article discusses a range of ameliorative and nutritive uses for PG in specific Russian cropping systems, but these issues are common elsewhere and the examples of PG use presented here are transferable to other settings through adaptive management.

Chestnut solonetz soil profile. Photo courtesy of Dr. L.P. Iljina, Southern Scientific Center of Russian Academy of Sciences, Rostov-on-Don.

SUMMARY

This review outlines the use of phosphogypsum, a by-product from the phosphate fertilizer industry, in Russia including its ameliorative roles for Na-affected and compacted soils; its value as a multi-nutrient fertilizer; in composting with various organic wastes to produce organo-mineral fertilizers; and in remediation of oil-contaminated soil.

KEYWORDS:

phosphogypsum; soil amelioration; soil fertility; crop productivity.

ABBREVIATIONS AND NOTES:

N = nitrogen; P = phosphorus; S = sulfur; SO_4^{2-} = sulfate; Ca = calcium; Cu = copper; Na = sodium; Ni = nickel; Zn = zinc; F- = fluoride; Pb = lead; Cd = cadmium; Sr = strontium; MAP = monoammonium phosphate; FYM = farmyard manure.

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Phosphogypsum Research

Amelioration of sodic soils requires the replacement of Na adsorbed on the cation exchange complex of the poorly structured, illuvial soil horizon, with Ca. Rates of PG ameliorants are generally calculated based on the amount of Ca required to displace equivalent quantities to Na adsorbed on the soil exchange. The addition of various mineral and organic substances like composts can strengthen the ameliorative effect of PG (Belyuchenko et al., 2010). Acidic ameliorants are most preferable for saline solonetz soils with high concentrations of exchangeable Na. Granulation of PG may be considered to achieve a more effective application (Granular Gypsum, 2016). An advanced reclamation scheme for sodic soils includes rototilling to the depth of up to 60 cm and a simultaneous PG application into the appropriate soil layer (Kalinichenko, 2010). Such a technology has the highest ameliorative effect because of the placement of PG directly into a sodic horizon rather than simply spreading it on the surface.

Long-term field research on solonetzic soil in southern Russia found a single application of PG at 11 t/ha produced 15 to 25% yield increases for various crops over 30 years (Sukovatov, 2009). Chernozem soils in the south often become alkaline or compacted over time and their amelioration also becomes necessary. Mischenko et al. (2009) reported that PG application to a compacted chernozem a (10 to 40 t/ha with tillage of the 30 to 60 cm soil layer) increased sunflower and maize grain yields by 16 and 23%, respec-

Phosphogypsum is commonly stock in large open areas a by-product from the phosphate fertilizer industry.

tively. Imgrunt (2004) found PG application at 10 t/ha to be helpful in improving an extremely compacted chernozem, with positive changes being both decreased soil clay content and bulk density. The presence of gypsum and carbonates has been found to prevent dispersion of labile soil minerals, and appears to have a stabilizing effect (Prikhodko, 2003). Special microscopic studies have shown that fine soil particles and applied organic matter are tightly fixed to colloidal PG particles, which improves soil aggregation, aeration, and water permeability (Slavgorodskaya, 2009).

The effect of PG amelioration for sodic soils developed in the presence of excess moisture, such as hydromorphic soil in southwestern Siberia appears to be more limited. Studies with PG in this region have found improvements in physical and chemical properties (Semendyaeva et al., 2015); however, the effect is generally not stable over time. A surface application of PG without incorporation into the soil can explain why exchangeable Na concentration may not change at depth (20 to 40-cm soil layer). Besides the placement of PG into the appropriate soil layer, the hydrological regime of these soils often needs to be changed to ensure a more lasting impact. However, the risk of soil salinization may even be increased after successful amelioration due to an improvement in the soil physical properties and, in turn, a decreased depth to groundwater (Semendyaeva and Elizarov, 2014).

Under irrigation, PG amelioration of sodic soils can be highly effective. Kalinichenko (1990) reported a decrease in exchangeable Na percentage from 15 to 2% in the 20 to 30-cm soil layer of a southern solonetzic soil after an application of 8 t PG/ha, which resulted in a 27% yield increase in maize silage. Yurkova (2012) demonstrated improved soil physical properties of degraded chernozems irrigated with saline water due to both PG applied at 10 to 12 t/ha and PG-based composts. Soil bulk density was decreased while soil porosity and water-stable aggregates were improved. Improvements in crop production were between 36 to 44% for various crops due to the use of PG-based composts. Martynenko (2014) studied drip irrigation with calcinated water prepared from a stock PG solution of 1.5 g/L and PG application at 1.9 and 3.0 t/ha on solonetzic soil growing onion. Bulb yields were increased by 15% compared to a control treatment irrigated without PG.

Rice-based cropping in Krasnodar Krai, Southern Russia.

Amelioration of chernozem soils degraded under rice-based cropping has been widely studied in the south. An excessive mixing with water results in cracked soil structure and increased bulk density to a level that is unfavorable for root development (Sheudzhen et al., 2013). The long-term use of sodic soils under rice-cropping systems without chemical amelioration causes solodization and secondary salinization and increases the labile fraction of soil organic matter and its loss through leaching. There is also a risk of Ca losses through leaching. The sum of exchangeable cations and the percentage of the CEC occupied by Ca can be improved with PG application. PG applied at 10 and 40 t/ha was effective in improving the physical properties of solonetzic soil, resulting in a 17 to 29% increase in rice yield (Radevich and Baranov, 2015).

Skuratov et al. (2005) reports that physical and chemical properties of southern chernozems and chestnut soils under rice-cropping have been improved through combined amelioration with both PG and FYM and a deep soil loosening. Salt concentrations in a surface layer (0 to 40 cm) of solonetzes noticeably decreased over the first year due to soil reclamation programs including PG application at 4 and 6 t/ha. Its application resulted in a 20 to 24% rice yield increase but the combination of PG and FYM was more effective, giving a 29 to 32% yield increase compared to a control treatment (Rice cropping…, 2009; Dedova et al., 2015). PG improves soil organic matter synthesis, optimizes the soil calcium carbonate equilibrium, and complexes with heavy metals (Kalinichenko et al., 2018).

Phosphogypsum as a Nutrient Source

PG is especially effective as a multi-nutrient fertilizer (i.e., source of P, Ca, S, and micronutrients) in the rice-cropping systems in the south (Baibekov et al., 2012). Constant nutrient removal from crop harvest and nutrient losses in rice field outflows and infiltrated waters cause a considerable decline in soil exchangeable Ca, available S, and micronutrients. According to Sheudzhen and Bondareva (2015), a single t of PG may also supply the following rates (kg/ha) of nutrients: Ca = 265, S = 215, P_2O_5 = 20, and SiO_2 = 9.8. Rice field experiments conducted by Sheudzhen and Bondareva (2015) on meadow soil found soil N, P, and K balances and nutrient uptake to be similar for treatments receiving $N_{120}P_{80}K_{60}$ and $N_{120}K_{60}$ + 4 t PG/ha. Rice yield was even somewhat higher with PG as the source of P instead of MAP. The above-mentioned rate of PG has been considered to be optimal under these environments. Application of PG as a source of P to leached chernozem at 4 t/ha also resulted in a significant soybean and maize yield increase over a control treatment (Sheudzhen et al., 2013). Crop response to this P source was higher compared to common fertilization practices ($N_{20}P_{40}K_{20}$). Dobrydnev et al. (2014) found the optimal rate of PG for winter wheat grown on leached chernozem to be 2 t/ha.

PG has recently been studied as a multi-nutrient fertilizer in a potato-based cropping system on coarse-textured, soddy-podzolic soil (Fedotova et al., 2017). The best treatment amounted to 1.5 t PG/ha plus NPK fertilizer.

Microbiological studies indicate that PG application results in increasing numbers of soil microorganisms utilizing organic N and assimilating mineral N (Ponomareva and Belyuchenko, 2005). A low pH of nonneutralized PG favors the making of composts with biosolids, FYM, poultry manure, wood chips, distiller's grains, defecation lime, diatomite, biochar, wastes of food processing industry, and other organic wastes (Belyuchenko, 2016a; 2016b). High quality and environmentally friendly organo-mineral fertilizers can be produced using such methods. Addition of PG could improve the quality of composts by shortening time to maturity, decreasing mineralization of organic matter, reducing N losses through ammonia volatilization, enhancing microbial activity, and decreasing the number of parasitic worms.

Application of PG could provide an opportunity to remediate oil-contaminated soils. Remediation of agricultural lands exposed to moderate oil contamination (i.e., oil concentrations up to 15 to 16 L/m^2), may be done without removing the surface soil layer by applying PG and organic fertilizers (Kolesnikov et al., 2011). PG can activate processes involved in the decomposition of oil products, increase water evaporation from contaminated substrates by 3 to 4 times, and shorten the remediation period for oil-contaminated soils (Belyuchenko et al., 2008; Kalinina and Melnik, 2009).

A combined application of rock phosphate and PG has been proposed for non-chernozemic, podzolized, and leached chernozems to convert slowly available P of rock phosphate to plant-available forms (Tsurikov, 1977; Phillipova, 2006). Sulfuric acid formed after PG reaction with acid soils having high concentrations of H^+ ions may be helpful to dissolve apatite minerals. A noticeable positive effect of PG on grain yield of cereal crops grown on soddy-podzolic soils and chernozems in the forest-steppe zone has been found when it was mixed with liming materials (Recommendations …, 1977).

Phosphogypsum may contains various trace elements, depending on the chemical composition of the phosphate rock. The accumulation of trace elements in the soil should be monitored, depending on the purity of the phosphate ore. However in Russia, numerous studies did not reveal the accumulation of heavy metals (Cu, Zn, Pb, Ni, Cd, and Sr) and F^- in soils and cereal grains in quantities higher than maximum allowable concentrations after PG application

(Loktionov et al., 2015; Batukaev et al., 2017; Fedotova et al. 2017). Similarly, the concentrations of various radionuclides in PG will range widely depending on the rock used in producing soluble phosphate. The PG may become enriched with radionuclides, especially $_{238}U$ and $_{232}Th$. When PG is used properly, these elements should not pose a problem.

Phosphogypsum is widely used in parts of the world to amend subsoil acidity, such as in Brazil (Prochnow et al., 2016). In soils with excessive exchangeable aluminum (Al), application of PG facilitates movement of Ca into the subsoil and neutralization of soluble Al. The PG application results in greater root growth and crop yields in these soils. The amount of PG required to amend acid soils for improved crop growth depends on the clay content of the soil and the subsoil chemical properties.

Conclusion

The utilization of by-product PG from the phosphate fertilizer industry contributes to the sustainable use of P resources. Available technologies have allowed PG applications to improve soil properties and crop productivity in a diverse range of crop production environments with problematic soils. **BC**

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Sustainable Phosphorus Management: Defining 4R Practices

By Heidi Peterson and Tom Bruulsema

Phosphorus (P) use efficiency in the U.S. has improved dramatically since the 1980s (NuGIS, 2019), yet eutrophication and other nutrient-related water quality issues, commonly used as measurable indicators of sustainability, have persisted. Our landscapes have become more complex. For example, since the 1960s we have been experiencing an increase in the frequency of high intensity precipitation events (Melillo et al., 2014), compounded by the addition of artificial subsurface drainage networks and high residue management practices. To overcome the P challenges confronting U.S. agriculture, it is important to begin at the nutrient source.

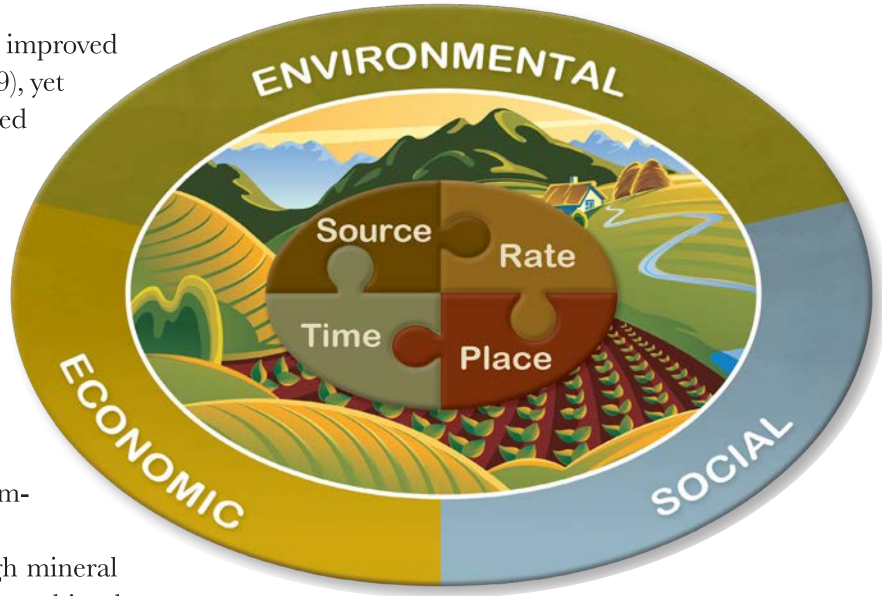

Figure 1. The 4R Nutrient Stewardship concept defines the right source, rate, time, and place for fertilizer application based on stakeholder desired economic, social, and environmental outcomes.

Phosphorus can be supplied to crops through mineral fertilizers, manures, and other organic residues (e.g., biosolids, plant residues). When P is applied to the soil, only 10 to 15% is taken up, or recovered, by the crop the first year (Roberts and Johnston, 2015). Phosphorus must be dissolved in the soil solution to be taken up by crops, typically as orthophosphate ($H_2PO_4^{2-}$ and HPO_4^{2-}) and soluble organic P compounds. The quantity of the P form supplied will vary between source with some that is: (1) readily plant available in a labile, soluble P form; (2) weakly adsorbed to mineral surfaces and slowly available; or (3) strongly adsorbed, non-labile P considered unavailable. To meet crop productivity needs, the supply of weakly bound labile-P must be maintained to continuously resupply the pool of solution P as it is being used by the crop. Organic P forms can be converted into plant-available P through mineralization. Inorganic P pools can also replenish the soil solution through soil P minerals dissolving into the soil solution or desorption of P attached to soil particles such as clay or minerals containing iron (Fe) or aluminum (Al).

Phosphorus can be transported with runoff flowing across an agricultural field or can infiltrate into the soil in the dissolved or particulate forms. Phosphorus loss is determined by complex interactions amongst physical, chemical, and biological variables. To effectively manage the pool of available P for crop production while minimizing P losses to water, P application practices should follow the 4R Nutrient Stewardship framework to ensure that the right nutrient source is applied at the right rate, at the right time, and in the right place (IPNI, 2012). "Right" is defined in terms of managing the fertilizer application to ensure alignment with economic, social, and environmental goals, resulting in a more sustainable cropping system (**Figure 1**).

Understanding that each field system is unique, 4R Nutrient Stewardship connects the management of crop nutrition to sustainable production, keeping in mind the progress toward achieving target goals on key performance metrics. These metrics may include farm productivity, P use efficiency, improved water quality, or maintaining optimum soil test levels. It integrates adaptive management as an ongoing process of developing improved practices for efficient production and resource conservation.

The Right P Source

Selection of the right source must consider the rate, time, and placement of the P application and is dependent

SUMMARY

Sustainability assurance programs seek clear definitions of 4R phosphorus practices that support continued improvement in both water quality and crop yields. Increasing phosphorus use efficiency is not enough. Site-specific practices addressing region-specific challenges are required.

KEYWORDS:

4R Nutrient Stewardship; adaptive management; use efficiency

ABBREVIATIONS AND NOTES:

P = phosphorus; N = nitrogen; K = potassium

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R. Derickson

Drainage ditch with water discharge from network of in-field, subsurface tile drainage lines.

upon the nutrient content, its solubility, and whether it is regionally available. Most mineral fertilizers are highly soluble and can contain different quantities of P, in addition to N, K, and other essential crop nutrients. Manure is an organic P source, which tends to be less soluble and much less concentrated than the P found in mineral fertilizers. When applied to the soil, organic nutrients mineralize over time, releasing nutrients that may be susceptible to loss through runoff; however, its variability in P content and interaction with other nutrients, such as Al, Fe, or calcium (Ca), can make it more difficult to manage than mineral fertilizers (Sharpley et al., 2004).

Since P is most often supplied in blends or with other nutrient sources, nutrient interactions must also be considered. Synergisms with other nutrients and sources is also important to maintain balanced nutrition. The crop's efficiency to recover P will depend upon whether the selected source adequately provides the necessary soil P supply, balanced together with N and K. For instance, results from a 50-yr irrigated continuous corn field experiment conducted in Kansas demonstrated a strong positive interaction between N and P. Application of N at the economic optimum rate of 172 kg N/ha increased P fertilizer recovery when applied at 20 kg P/ha, from 20% without N to 63% with N (Schlegel and Havlin, 2017).

The Right P Rate

Applying the right rate of P fertilizer begins with understanding the plant needs and ensuring that adequate methods are used to assess the soil nutrient supply. The spatial variability in soil nutrient concentrations and yield potential within a field due to soil texture, soil pH, past management activities, and topography must be acknowledged. Variable rate application technology, which varies the nutrient application rate according to the location within the field using geographic information systems (GIS) and global positioning systems (GPS), can improve P use efficiency and decrease the risk for runoff and leachate losses.

Crops take up nutrients in proportion to yield. Under or over applying P may result in negative production, economic, and environmental implications. The right application rate for P is often based on soil sample collection and testing, which provides an index of nutrient availability. Soil testing provides a probability of response to P inputs and guidance on the amount of fertilizer needed to maximize economic return by maintaining an optimum soil test level. Over applying P can increase the risk of loss to surface runoff and leachate, whereas drawing down soil P concentrations by harvesting biomass P at a rate that exceeds P input may result in a decline in both soil fertility and yield potential (Dodd and Mallarino, 2005). Inputs from manure, composts, and other bioproducts all contribute to the distribution of P in soils and should be properly credited to avoid over application (Pagliari et al., 2018).

The Right P Timing

Seasonal crop demand and nutrient uptake patterns should be considered when determining the right time to apply P fertilizer. Although it is often driven by the management capabilities and logistics of the producer, timing surface application of organic and inorganic P sources must be balanced with crop needs and discharge-producing precipitation events to minimize runoff and leaching loss (King et al., 2018). Edge-of-field water quality monitoring indicates that the time between P application and the first precipitation event is negatively correlated to surface runoff and

TAKE IT TO THE FIELD

Cropping systems are dynamic and require an adaptive approach to P management, which focuses on the 4Rs to optimize recovery and minimize losses.

subsurface tile P concentrations (Smith et al. 2016).

The primary concern is to avoid surface application on frozen soils and prior to precipitation events to reduce runoff and leaching loss. Although crops take up nutrients at different rates throughout the growing season, in soils with low soil test P (STP) applying a starter fertilizer at a high rate may optimize productivity (Mallarino and Bundy, 2008). Since P is essential to early plant root growth and development, application at or near planting is most effective, particularly on highly acidic or alkaline soils that have very high P fixation capacity. Although P remains in the soil, in these acidic and alkaline soils, annual applications may be necessary to adequately supply the crop needs.

The Right P Placement

The right placement of P fertilizer near the roots increases the availability to the plant since P is less mobile than N and K. This is especially important in soils with a very high P fixation capacity. Seed placement or banding P fertilizer near the root zone at lower rates in soils with low STP can maximize corn response and result in higher efficiency, although soil type and moisture conditions may impact results (Mallarino et al., 1999; Mallarino and Bundy, 2008). Subsurface placement techniques improve soil-fertilizer contact while reducing surface disturbance and reducing P runoff and leachate losses (Williams et al., 2018). Unincorporated broadcast applications may initially save time and money, especially in no-till systems, but P stratification may also occur (Baker et al., 2017). Stratification limits deeper root growth and development and increases the risk for loss through surface runoff and subsurface tile drainage. However, there is insufficient literature suggesting stratification impacts yields. Uptake of P is also influenced by soil moisture, and subsurface P placement can improve plant uptake during drought conditions by inducing deeper plant root growth, ultimately improving the plant resiliency (Hansel et al., 2017).

A Holistic Approach

Cropping systems are dynamic, and when climatic and hydrologic factors are integrated into these management decisions, it is important that the choices made evolve with the current science and technology, but also consider economic factors. The site-specific nature of 4R practices limits the degree of detail with which they can be described across large regional cropping systems. Therefore, the development of a regionally based 4R P guidance requires collaboration between agricultural scientists and stakeholders with an awareness of local farm-based implementation to ensure that the practices are both efficient and economically feasible. As new resources and tools are developed, integrating adaptive P fertilizer management into farm-level decisions will encourage the use of relevant, site-specific information to determine the right source, rate, time, and place for efficient and effective fertilizer management. **BC**

H. Peterson/IPNI

Conservation tillage and cover crops control P losses in the particulate form, but control of the dissolved form requires attention to placement and timing.

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The Future of Phosphorus Use in Agriculture

By Michael J. McLaughlin

Given the well-known fact that P is an essential component of many biomolecules in our body, and the fact that the human population will continue to grow, at least for the next five decades (United Nations, 2017), the future use of P in agriculture will continue to increase for some time. Most agricultural systems are, by definition, not closed systems due to the export of P in produce to feed this growing population, and hence there will always be a need to replace that exported P with P in farm inputs, as rates of soil weathering are too slow to match agricultural rates of P removal (Chadwick et al., 1999).

Perhaps a bigger change in the future might be the source of P used in agriculture in some countries—the source of the P used as farm inputs in agriculture has changed over the last 5,000 years (Ashley et al., 2011)—from the exclusive use of human and animal manures (which is essentially horizontal transfer of P in the biosphere), to the processing and use of igneous and sedimentary rock phosphates, which is essentially a vertical and horizontal movement of P from the geosphere to the biosphere. Now, at least in some developed countries, we have seen a move back to the recovery and use of P from human and animal waste streams for reuse in agriculture (Desmidt et al., 2015). Large-scale adoption of these technologies has been slow however, as the cost per unit P is still higher than mined P. Cost alone however does

SUMMARY

Securing the nutritional needs for our increasing population will continue to drive a healthy demand for P. Innovation will continue to broaden our viable choices for P, which combined with social drivers, will continue to generate momentum towards a more closed P cycle. Further advances in plant breeding, agronomy, and fertilizer technology are required for today's agricultural systems on soils with high P sorption capacity.

KEYWORDS:

food security; recycling; recovery; use efficiency; fertilizer technology; cycling

ABBREVIATIONS AND NOTES:

P = phosphorus; N = nitrogen

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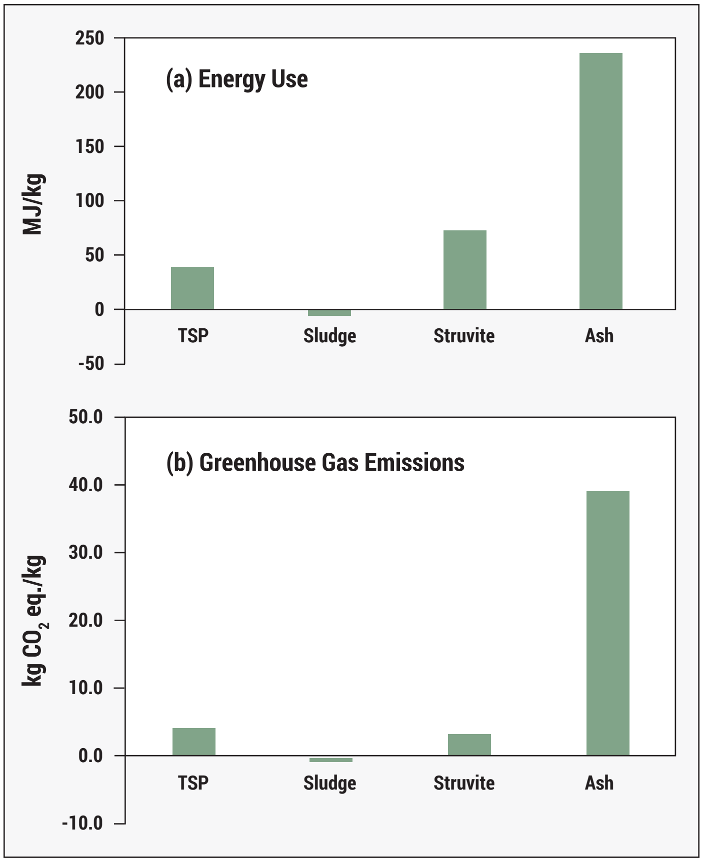

Figure 1. Energy use (a) and emissions of greenhouse gases (b) per kg P for four sources of P used in Swedish agriculture [redrawn from Linderholm et al. (2012)]. The negative values for sludge are due to credits for the N content in the material.

not take into account the externalities of energy consumption and greenhouse gas (GHG) emissions during manufacture and transport. A complete life-cycle comparison of use of P from triple superphosphate (TSP), struvite, sewage sludge and P recovered from sewage ash found that P use from sewage sludge application to farmland had the least energy consumption and lowest emissions of GHGs, but is compromised by the co-contaminants in the material (e.g., cadmium or persistent organic chemicals; Linderholm et al., 2012). Use of P recovered from sewage ash had higher energy requirements and emissions of GHGs than use of mined P (TSP) and struvite, with mined P having the lowest energy requirements (**Figure 1**). Furthermore, an important point to note with use of technologies to recover P from wastes is that the efficiency of recovery will seldom be close to 100% (Linderholm et al., 2012). Hence, there will always be some "leakage" of P to the environment (predominantly to fresh and marine waters and sediments; White, 1980).

Closing the P cycle is an aspirational goal and there is certainly room for improvement in the efficiency of use of mined P. The efficiency of P use in agriculture, and the efficiency of P transfer and capture through mined material to food to wastes has been the subject of much study and debate, as discussed earlier in this edition (Scholz and Wellmer, 2019). However, until the economic, legislative, and social drivers are aligned and favorable, global use of recycled P in agriculture will remain a small percentage of the total P use (Linderholm et al., 2012). The efficiency of P use in agriculture is also often erroneously stated to be low, when this is not the case once soil P fertility has been built up and retention or "fixation" of P is saturated; then rates of P used by farmers reduce to "maintenance" levels and the P balance efficiency nears 100% (Syers et al., 2008; Barrow et al., 2018). In those soils where the soil P status is low and P retention still strong, or where P retention mechanisms are not saturable (e.g., calcareous soils), efficiency of P use is low and it is for these situations that improvements in P use efficiency are needed through plant breeding, agronomic means, or new fertilizer formulations (McLaughlin et al., 2011). Bringing soils closer to a P balance efficiency of 100% at a lower total loading of "legacy" P is the goal, as this has both agronomic and environmental benefits (Sharpley et al., 2018).

Concluding Thoughts

While the history of P according to mankind started 350 years ago, the geochemical history of P started billions of years ago. Indeed, the origin of P on Earth has recently been questioned with a suggestion that P oxoacids were first synthesized from interstellar phosphine and delivered to the Earth on meteorites or comets (Turner et al., 2018). No matter the origin of P on Earth, mankind has been blessed that this essential element is abundant in the Earth's crust now. It is critical we use this resource wisely, to maximize crop production and quality, and minimize the environmental consequences of inefficiencies in the P cycle. **BC**

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Follow the Yellow Brick Road

Perhaps you've heard that IPNI is being restructured. Key scientific resources are moving to the industry's trade associations to strengthen their 4R and other agronomic initiatives, and to provide direct scientific support for engagement with their stakeholders. This transition marks the end of era.

Many of us at IPNI feel like Dorothy in the Wizard of Oz as we embark on the yellow brick road in search of Emerald City. We are a little uncertain and the road ahead is not entirely straight. As seen in the movie, the road has graceful curves as it travels over the rich grassy land; it has areas where the bricks are polished and smooth and clearly marked. It also has areas where the bricks are broken or uprooted, or missing altogether like in the dark abandoned forests of Oz. The road ahead is uncertain and even frightening … change always is.

But change is also exciting and reinvigorating. It causes us to adapt and to improve, and it strengthens us. IPNI has always attracted talented and highly capable scientists … scientists dedicated to improving nutrient management and nutrient use efficiency, to improving food production and farmer's livelihoods, and to protecting our environment. That dedication and service to global agriculture will not change; it will continue albeit in a different setting as our staff move on to other opportunities and challenges.

IPNI is leaving a great legacy. *Better Crops* is part of that legacy. It's been an honor to have worked in this amazing Institute and in partnership with all of you. On behalf of everyone at IPNI, we thank you for your support over many years. We wish you well and hope our paths will cross again as we begin our journey down the yellow brick road in search of our "Emerald City."

Terry L. Roberts
IPNI President

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