Plant Soil (2016) 401:1–6
DOI 10.1007/s11104-016-2846-9

EDITORIAL

# Phosphorus in soils and plants – facing phosphorus scarcity

**Timothy S. George · Philippe Hinsinger · Benjamin L. Turner**

Received: 8 January 2016 / Accepted: 23 February 2016 / Published online: 3 March 2016


**Abstract**
*Introduction* Phosphorus is a fundamental nutrient for primary productivity of ecosystems and agricultural production, but its misuse impacts agricultural sustainability and has important environmental consequences. Access to global reserves of phosphate rock is politically sensitive and economically challenging. Phosphorus accumulates in agricultural soils, representing a financial loss to farmers and increasing the risk of loss to water. The challenges facing phosphorus sustainability are varied, but many solutions are to be found in the plant–soil system.
*Scope* This special issue arises from the 5th International Symposium on Phosphorus in Soils and Plants (PSP5), held in Montpellier, France. Articles highlighted here discuss ways to tackle food security, improve phosphorus sustainability by understanding the imbalanced phosphorus cycle, use technology to reduce phosphorus demand and recycle phosphorus in waste products, and consider how efforts to increase phosphorus efficiency interact with other sustainability challenges.
*Conclusions* The challenges associated with P sustainability are tackled from many different directions, including plant genetics, soil microbiology, novel imaging and modelling techniques, the development of new technologies, and an improved understanding of how these technologies interact with agronomic management. Integration of the various approaches will be necessary to deliver a truly effective solution to the challenge of attaining phosphorus sustainability.

**Keywords** Ecosystem dynamics · Environmental impact · Phosphorus acquisition · Phosphorus forms · Phosphorus cycling · Phosphorus utilization · Phosphorus signalling · Sustainable use and management

Responsible Editor: John Hammond.

T. S. George (✉)
The James Hutton Institute, Invergowrie, Dundee DD2 5DA, UK
e-mail: tim.george@hutton.ac.uk

P. Hinsinger
INRA, UMR Eco&Sols, Place Viala, 34060 Montpellier, France

B. L. Turner
Smithsonian Tropical Research Institute, Apartado 0843-03092, Balboa, Ancon, Republic of Panama

Phosphorus (P) is required for in many biochemical processes in plants and is therefore crucial to the productivity of ecosystems, including agroecosystems. However, the misuse of P in agriculture has important environmental consequences and ultimately impacts agricultural sustainability. Access to geographically discrete global reserves of phosphate rock is politically sensitive and economically challenging (Godfray et al. 2010). The use of mined rock phosphate as a principal P source for chemical fertilisers was a major contribution to the green revolution, but increased our dependence on this non-renewable P source (Elser and Bennett 2011). The biological availability of phosphate fertiliser is reduced by sorption and organic complexation in the soil, so fertiliser applications greater than the amount required by the crop are used to counteract the strong binding of the phosphate to the soil matrix (MacDonald et al. 2011). This has greatly increased the P content of managed soils, so soils in many regions of the world now contain sufficient P reserves to potentially buffer threats to food security in the coming decades. However, the accumulation of soil P also has negative consequences: it is a financial loss to the farmer, uses up a renewable resource, and has important environmental consequences, because even small amounts of the excess P leaking into watercourses can cause blooms of harmful algae and raise the trophic status of lakes for many years (Elser and Bennett 2011).

The challenges surrounding P sustainability have been addressed a number of times in the recent literature (Cordell and White 2011, 2014; Haygarth et al. 2014; Sharpley et al. 1994; Stutter et al. 2012) and in a range of international symposia, one of which led to a comprehensive declaration on the issues surrounding P sustainability (Wyant et al. 2013). In 2014, phosphate rocks were included in the list of twenty critical raw materials by the European Commission, and represent the only one which primarily concerns agriculture and food security. Declarations on P sustainability acknowledge that biological organisms need P to thrive and reproduce and that it is a limited resource. They also state that there is an **Imbalanced Cycle** caused by agricultural inputs, but that getting access to adequate P is essential for **Food Security**. To address some of these challenges, the global community needs to **Recycle and Reuse** more P, **Reduce Demand** and understand how **Interconnection with other sustainability challenges** works (Wyant et al. 2013). It is also stated that there are great opportunities to innovate in the domains of P supply, use, and cycling to deliver agricultural sustainability.

This special issue contains a range of papers presented at the International Symposium on Phosphorus in Soils and Plants (PSP5) held in 2014 in Montpellier, France, which address some of the themes stated in the global P challenge declaration. This meeting was the fifth international symposium of this successful series initiated in Beijing, China, in 2000 (see former special issues in Plant and Soil, volumes 237, 269 and 349) and promoted a multidisciplinary approach, gathering together 276 plant nutritionists (plant physiology, genetics and systems biology), agronomists, ecologists, biogeochemists and soil scientists from 38 countries across the world, with the aim of fostering scientific exchanges across discipline boundaries to face the challenge of P limitation in agroecosystems and terrestrial ecosystems.

## Imbalanced P cycle

The concentration of mined phosphate taken from a few small areas and applied widely onto agricultural soils in the form of soluble fertilisers has caused a geographical imbalance in P distribution in agricultural systems in comparison to natural ecosystems. While this greatly expands the capacity for food production from a given land area, it has had environmental consequences and resulted in the human-induced alteration of the biogeochemical cycle of P over the past decades (Elser and Bennett 2011; Penuelas et al. 2013). Biogeochemical P flows now exceed the planetary boundaries as defined by Steffen et al. (2015), which is of particular concern in regions of excess P fertiliser loads such as Western Europe, North America and China. To manage this imbalance sustainably we must understand what happens to the forms, availability and mobility of P after fertiliser application to soils. A number of papers in this special issue employ new techniques to examine the fate of P following application to agricultural soils. Phosphorus can be added to soils in a number of ways, including application of inorganic fertilisers or naturally from weathering of primary phosphate minerals (i.e. apatite). However, P can also be added in organic forms, including as crop residues and manures.

Rivard et al. (2016) determined the distribution and speciation of P in cultivated soils developed on a temperate calcareous loam developed in glacial till. They employed micro-X-ray fluorescence (μ-XRF) to produce maps of undisturbed samples and X-ray absorption near edge structure (XANES) spectra were collected on points of interests selected from μ-XRF maps. Results showed minor effects of cropping and fertiliser practices on P speciation in cultivated soils, suggesting that agronomic management had little impact on the forms of P in soils at the microscale.

In an attempt to assess the fate of fertiliser P in pasture systems, McLaren et al. (2016) developed a novel method for tracing fertiliser P in the field using single superphosphate granules radiolabelled with a $^{33}P$ radiotracer. The tracer was applied to the soil surface of a clover pasture and recovery of fertiliser P was determined in clover shoots, fertiliser granules and soil fractions. Recovery of fertiliser P by clover plants was up to

35 % in the year of application. Much of the fertiliser P in soil fractions was inorganic P, which highlights the importance of inorganic P forms and dynamics in soils under pasture systems, despite many of the inputs in these systems coming from organic residues.

In contrast, Foyjunnessa et al. (2016) assessed the contribution of crop residues to the soil P pool, specifically in the form of residual roots. Using a stem wick-feeding technique, $^{33}$P-labelled phosphoric acid was fed in-situ to oilseed rape (*Brassica napus*) and narrow-leaf lupin (*Lupinus angustifolius*) grown in sandy or loamy soils in sealed pots. Recovery of $^{33}$P was 93 % in the plant − soil system, and significantly more $^{33}$P was allocated below-ground than to shoots for both species. Estimated total below-ground P accumulation by both species was at least twice that of recovered root P and was a greater proportion of total plant P for narrow-leaf lupin than oilseed rape. This research suggests that a large proportion of P taken up by plants remains in the root system, which has been previously underestimated. Roots of the previous crop are therefore a potentially important source of P for subsequent crop production.

## Food security

To achieve food security, farmers need access to reliable and affordable sources of fertiliser to enhance and maintain the productivity of their agricultural systems. This is particularly important for resource poor farmers in the developing world, such as in sub-Saharan Africa. In the absence of a reliable and affordable source of P fertiliser, the available crop varieties must be able to tolerate (and be productive on) P-poor soils. A number of papers in this special issue tackle the problem of identifying the genetic control of traits useful for P sustainability in crop species important for resource poor farmers in the developing world. Traits identified as having potential for delivering food security by enhancing P acquisition and utilisation efficiency and examined in this issue include mycorrhizal symbiosis, seed size and subsequent vigour and internal P use efficiency. Some of these are shown to be effective and genetically tractable, while others are not.

Leiser et al. (2016) aimed to determine whether sorghum breeding programs in West Africa should target greater colonization rates by arbuscular mycorrhizal fungi (AMF). They grew a sorghum diversity panel of 187 regional genotypes in low-P soil in a pot trial, and then grew a subset of 13 genotypes in low- and high-P fields until maturity. Significant genotypic variation was observed, although none of the genotypic groups differed significantly in AMF colonization. The groups were also unrelated to shoot-P-content and grain yield, despite contrasting in selection history and grain yield performance across multiple field trials. There were no significant genomic regions for AMF. This paper suggests that genotypic selection for AMF colonization in sorghum is not a promising approach due to low heritability and absence of positive relationship between AMF and P acquisition.

In contrast, Vandamme et al. (2016) highlight a potentially useful trait for selection of genotypes of soybean. The authors evaluated how differences in seed weight and seed P affected growth at low and high P supply for forty-two soybean genotypes in a pot trial. Correlations between seed weight and plant biomass, shoot P content and root length were stronger at low than at high P supply. At low P supply, plant growth was correlated with seed weight up to the flowering stage. This research suggests that selecting large-seeded species by seed size may be a way to improve P acquisition in crops important to food security.

In another study, Rose et al. (2016) present developments in the use of internal P use efficiency (PUE) as a basis for selecting genotypes with the ability to enhance P sustainability. They investigated various soil and hydroponic screening methods for their capacity to produce a consensus ranking of genotypes with regard to PUE. Six rice genotypes identified previously in hydroponic screening studies as being high, intermediate or low PUE were screened using hydroponic and soil-based experiments with contrasting P levels. Overall, PUE was significantly influenced by genotype and P supply, but there was no significant genotype × P supply interaction. Hence, it was concluded that screening genotypes using hydroponics at one or two P supply levels is the most cost- and time-effective way to screen large numbers of rice genotypes for PUE.

## Recycling and reuse of P

To reduce the reliance of agriculture on the use of inorganic fertilisers and the geopolitical uncertainties associated with global phosphate reserves it is important to promote technologies that attempt to recycle some of the common waste products from agricultural and human consumption systems. This requires an understanding of the ability of waste products to act as effective fertilisers and replacements for rock phosphate and the corresponding fertilisers. Several articles in this special issue assess these technologies.

Christel et al. (2016) studied the impacts of slurry acidification, separation technology and thermal processing on the availability of P in soil amended with the solid fraction of pig slurry. Following addition of various treated pig slurries to soil, P availability was determined over time using diffusive gradients in thin films (DGT). Application of separated pig slurry solids increased soil P availability initially, but this declined with time. Chars and ashes on the other hand reduced P availability initially, but availability remained constant or increased slightly with chars, eventually yielding P availability similar to biosolids. This research suggests that pig slurries treated in a number of ways are an effective replacement technology for conventional inorganic fertilisers.

In contrast, Talboys et al. (2016) demonstrate that struvite (a source of P extracted from wastewater) is utilised more effectively when used in combination with relevant plant genotypes. They examined P release from commercial fertiliser-grade struvite and its uptake from a low-P sandy soil by two different crop types, in comparison to more soluble inorganic P fertilisers (diammonium phosphate (DAP) and triple super phosphate (TSP)). Struvite solubility was enhanced greatly in the presence of organic anions, where buckwheat, which exudes a high level of organic anions, was more effective at mobilising struvite P than spring wheat, which exudes only low concentrations of organic anions. However, struvite granules placed with the seed did not provide the same rate of P supply as similarly placed DAP granules for early growth of spring wheat.

## Reduced demand for P

Phosphorus sustainability can be improved by reducing P demand in agricultural systems. This can be achieved in a number of ways, including improvements in the efficiency of P use by crops and the enhanced use of P that has accumulated in soils following decades of inorganic P additions. The special issue contains several articles that help understand (1) the efficiency with which plants access fertiliser P in soils and (2) the rhizosphere environment with respect to its ability to enhance access to organic forms.

Ahmed et al. (2016) investigated how plant roots interact with fertiliser granules in three-dimensional space and with time. This understanding will help more effectively utilise inorganic P fertilisers added to soils and therefore reduce demand for mineral P fertiliser. They used in-vivo, time resolved, microfocus X-ray CT imaging (μCT) in three dimensions to visualise, quantify and assess root–fertiliser interactions of wheat plants in an agricultural soil during the entire plant life cycle. Two contrasting fertilisers – triple superphosphate and struvite – were applied to the soil mesocosms. Lateral roots tended to pass within a few millimetres of the P source and could therefore access the P diffusing from the granule. The authors also showed that rooting density was positively correlated with granule volume-loss for a slow release struvite fertiliser.

In a complementary study, Heppell et al. (2016) developed a model to assess a range of P fertiliser and soil management strategies for a cereal crop, to maximise plant P uptake under different climate conditions. The model was able to fit data from two barley field trials with regard to P uptake by the crop, although the model fits were better for early compared to late growth stages. Refinement of such models will allow more effective, site-specific recommendations for use of P fertilisers, thus reducing the demand for mineral P.

In a completely different approach, Sanguin et al. (2016) investigated the potential for rhizosphere microorganisms to reduce demand for mineral P by enhancing the use of phytate (salts of *myo*-inositol hexakisphosphate), which can constitute a considerable proportion of the organic P in agricultural soils. In this study, the phytate-hydrolysing bacterial community was characterized in the rhizosphere of plants cultivated in the presence or absence of phytate supplementation. Major changes in the bacterial community structure were observed with both culture-dependent and culture-independent methods, including the predominance of Proteobacteria and Actinobacteria in phytate-treated soils. Phytase activity was detected for a range of rhizobacterial isolates and β-propeller phytases were detected in both isolates and soils. It is clear that a range of soil microorganisms are endemic to the rhizosphere which, if harnessed correctly, could enhance P sustainability and reduce demand for added P.

## Interconnection with global sustainability challenges

In addition to P sustainability, there are a number of other sustainability challenges facing global agriculture. These include (1) the sustainable use of water and other nutrients (specifically nitrogen), (2) the ability to provide adequate nutritious food, particularly with reference to zinc, iron and iodine nutrition, (3) the ability to mitigate global environmental change (specifically carbon sequestration), and (4) the loss of biodiversity due the degradation of natural ecosystems. If we consider the sustainability of P in the absence of these other concerns, it is unlikely that any technology for improving food security will be effectively deployed. This special issue contains two articles that look at how land-use change and management can impact the cycling of P in association with some other nutrients inherent in global sustainability issues.

Somaweera et al. (2016) examined the impact of water saving management for rice production on the effective utilisation of both P and nitrogen. Rice was grown in soil columns under four water management treatments. Moisture limitation substantially reduced tissue P content and retranslocation of P to panicles, but nitrogen nutrition was little affected. This research demonstrates that when managing crops with other sustainability issues in mind there are significant impacts on the ability of the crops to utilise nutrients, including P. Management packages that account for all the various demands on the system should be considered.

Likewise the impact of land-use change can have profound effects on the sustainability of use of P and other nutrients. This is highlighted by Spohn et al. (2016), who quantified changes in soil total P, nitrogen, and carbon during secondary succession after abandonment of vineyards on calcareous soils. Soil carbon and organic P concentrations increased after vineyard abandonment in two chronosequences covering 200 years and differing in aspect and slope, while P availability determined by bicarbonate extraction diminished during the first 50 years after abandonment. The study demonstrates that the legacy of former cultivation persists for more than a century under these conditions, indicating that our efforts to improve P sustainability in agricultural systems are unlikely to be short term solutions but rather long term effort to develop systems that are truly sustainable.

## Conclusions

It is apparent from the information contained in this special issue that the challenges associated with P sustainability are being tackled in a variety of ways, including crop genetics, soil microbiology, novel imaging and modelling techniques, technology development, and an understanding of how new technologies interact with the management environment. Obviously, additional solutions can be provided in the fields of crop physiology, agronomy, landscape management, to name but a few. While it is clear that progress in being made, integration of the range of approaches will be necessary to deliver a truly effective solution to the challenge set out by P sustainability. Indeed, the life cycle of mined P, which is now considered as a critical raw material for society, demonstrates that major losses occur along the entire production/consumption chain, from the phosphate rock mine to the consumer's plate and beyond. Facing P scarcity is a major challenge ahead of us, and will require the identification of multiple solutions to reduce these losses and use P more efficiently. Many of these solutions pertain to plants and soils, as major losses occur in agroecosystems of regions that can afford substantial application of P fertilisers. However, many regions of the developing world have limited access to P fertilisers, which are becoming increasingly more expensive. In these regions, facing P scarcity is a major challenge, and major research efforts in plant and soil sciences are needed to solve this issue, which also poses the question of global P stewardship. We anticipate that the sixth International Symposium on Phosphorus in Soils and Plants (PSP6) to be held in Leuven, Belgium in 2018, will shed new light on the various solutions to improve P sustainability atlocal, regional, and global scales.

**Acknowledgments** This work was supported by the Rural and Environment Science and Analytical Services Division (RESAS) of the Scottish Government, and by Agropolis Fondation (PHOSPHORUS 2014 project) under the reference ID 1202-019 through the « Investissements d'avenir » programme (Labex Agro:ANR-10-LABX-0001-01).

## References

Ahmed S, Klassen TN, Keyes S, Daly M, Jones DL, Mavrogordato M, Sinclair I, Roose T (2016) Imaging the interaction of roots and phosphate fertiliser granules using 4D X-ray tomography. Plant Soil. doi:10.1007/s11104-015-2425-5 (this Issue)

Christel W, Bruun S, Magid J, Kwapinski W, Jensen LS (2016) Pig slurry acidification, separation technology and thermal conversion affect phosphorus availability in soil amended with the derived solid fractions, chars or ashes. Plant Soil. doi:10.1007/s11104-015-2519-0 (this issue)

Cordell D, White S (2011) Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability 3:2027–2049

Cordell D, White S (2014) Life's bottleneck: sustaining the world's phosphorus for a food secure future. Ann Rev Environ Res 39:161–188

Elser J, Bennett EM (2011) A broken biogeochemical cycle. Nature 478:29–31

Foyjunnessa, McNeill A, Doolette A, Mason S, McLaughlin, MJ (2016) Quantifying total phosphorus accumulation below-ground by canola and lupin plants using 33P-labelling. Plant Soil. doi:10.1007/s11104-015-2545-y (this Issue)

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–881

Haygarth PM, Jarvie HP, Powers SM, Sharpley AN, Elser JJ, Shen J, Peterson HM, Chan NL, Howden NJK, Burt T, Worrall F, Zhang F, Liu X (2014) Sustainable Phosphorus Management and the need for a long-term perspective: the legacy hypothesis. Environ Sci Technol 48:8417–8419

Heppell J, Payvandi S, Talboys P, Zygalakis KC, Fliege J, Landton D, Sylvester-Bradley R, Walker R, Jones DL, Roose, T (2016) Modelling the optimal phosphate fertiliser and soil management strategy for crops. Plant Soil. doi:10.1007/s11104-015-2543-0 (this Issue)

Leiser WL, Olatoye MO, Frederick H, Rattunde W, Neumann G, Weltzen E, Haussmann BIG (2016) No need to breed for enhanced colonization by arbuscular mycorrhizal fungi to improve low-P adaptation of West African sorghums. Plant Soil. doi:10.1007/s11104-015-2437-1 (this issue)

MacDonald GK, Bennett EM, Potter PA, Ramankutty N (2011) Agronomic phosphorus imbalances across the world's croplands. Proc Natl Acad Sci U S A 108:3086–3091

Mclaren TI, McLaughlin MJ, McBeath TM, Simpson RJ, Smernik RJ, Guppy CN, Richardson AE (2016) The fate of fertiliser P in soil under pasture and uptake by subterraneum clover – a field study using 33P-labelled single superphosphate. Plant Soil. doi:10.1007/s11104-015-2610-6 (this issue)

Penuelas J, Poulter B, Sardans J, Ciais P, van der Velde M, Bopp L, Boucher O, Godderis Y, Hinsinger P, Llusia J, Nardin E, Vicca S, Obersteiner M, Janssens IA (2013) Human-induced nitrogen-phosphorus imbalances alter natural and managed ecosystems across the globe. Nature Comm 4:2934

Rivard C, Lanson B, Cotte M (2016) Phosphorus speciation and micro-scale spatial distribution in North-American temperate agricultural soils from micro X-ray fluorescence and X-ray absorption near-edge spectroscopy. Plant Soil. doi:10.1007/s11104-015-2494-5 (this Issue)

Rose TJ, Mori A, Julia CC, Wissuwa M (2016) Screening for internal phosphorus utilisation efficiency: comparison of genotypes at equal shoot P content is critical. Plant Soil. doi:10.1007/s11104-015-2565-7 (this Issue)

Sanguin H, Wilson, NL, Kertesz MA (2016) Assessment of functional diversity and structure of phytate hydrolysing bacterial community in *Lolium perenne* rhizosphere. Plant Soil. doi:10.1007/s11104-015-2512-7 (this Issue)

Sharpley AN, Chapra SC, Wedepohl R, Sims JT, Daniel TC, Reddy KR (1994) Managing agricultural phosphorus for protection of surface waters: issues and options. J Environ Qual 23:437–451

Somaweera KATN, Suriyagoda LDB, Sirisena DN, De Costa WAJM (2016) Accumulation and partitioning of biomass, nitrogen, phosphorus and potassium among different tissues during the life cycle of rice grown under different water management regimes. Plant Soil. doi:10.1007/s11104-015-2541-2 (this Issue)

Spohn M, Novak, TJ, Incze J, Giani L (2016) Dynamics of soil carbon, nitrogen, and phosphorus in calcareous soils after land-use abandonment – A chronosequence study. Plant Soil. doi:10.1007/s11104-015-2513-6 (this Issue)

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, de Vries W, de Wit CA, Folke C, Gerten D, Heinke J, Mace GM, Persson LM, Ramanathan V, Reyers B, Sörlin S (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:736–746. doi:10.1126/science.1259855

Stutter MI, Shand CA, George TS, Blackwell MSA, Bol R, Mackay RL, Richardson AE, Condron LM, Turner BL, Haygarth PM (2012) Recovering phosphorus from soil: A root solution. Environ Sci Technol 46:1977–1978

Talboys PJ, Heppell J, Roose T, Healey JR, Jones DL, Withers PJA (2016) Struvite: a slow-release fertiliser for sustainable phosphorus management? Plant Soil. doi:10.1007/s11104-015-2747-3 (this Issue)

Vandamme E, Pypers P, Smolders E, Merckx R (2016) Seed weight affects shoot and root growth among and within soybean genotypes beyond the seedling stage: implications for low P tolerance screening. Plant Soil. doi:10.1007/s11104-015-2564-8 (this issue)

Wyant KA, Corman JR, Elser JJ (2013) Phosphorus, food and our future. Oxford University Press, New York