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Opinion paper

On the history and future of soil organic phosphorus research: a critique across three generations

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Running title: On soil organic phosphorus

Summary

Soil organic phosphorus has broad agronomic and ecological significance, but remains a neglected topic of research. This opinion paper reflects a collaborative discussion between three generations of scientists who have collectively studied soil organic phosphorus for almost 50 years. We discuss personal reflections on our involvement in the field, opinions about progress and promising opportunities for future research. We debate an apparent overemphasis on analytical methodology at the expense of broader questions, and whether this has stifled progress in recent decades. We reiterate the urgent need to understand organic phosphorus cycling in the environment to address fundamental questions about phosphate supply, crop nutrition, water quality and ecosystem ecology. We also contend that we must encourage and integrate the study of organic phosphorus across all scales, from molecular chemistry to global cycling. Our discussion among three generations of researchers shows the value of a long-term perspective, emphasizes the changing nature of this field of research, and reinforces the importance of continuing to be curious about the dynamics of organic phosphorus in the environment.

Highlights

- Critical evaluation of the current state of soil organic phosphorus research
- Collective views of three researchers whose careers span 50 years
- Research is driven by analytical development, but will benefit from broader conceptual approaches
- We emphasize the value of long-term and broad-scale perspectives on this important research topic

Keywords: inositol phosphate, phytate, phosphate, ecosystem, history, microbial, analytical

Introduction

Phosphorus (P) is an important element in the soil for agriculture because it is one of the key nutrients for sustaining crop production (Haygarth *et al.*, 2013). However, it is poised precariously between sufficiency and surplus; phosphorus must be supplied to soil to maintain crop yields, but over-supply promotes leakage of phosphorus to waterways and contributes to their eutrophication with damaging effects on water quality (Schelske, 2009). There are also concerns around the longevity and geo-political location of mineral phosphate reserves, raising debate about long-term phosphorus sustainability (Cordell *et al.*, 2009; Elser & Bennett, 2011).

Soil, however, provides a key focal point and thus an opportunity for understanding and managing the phosphorus cycle. The forms and proportions of phosphorus that exist in soil vary enormously, but typically include both organic and inorganic forms. In many cases, the quantities of organic phosphorus forms in soil exceed the inorganic phosphate proportions, emphasizing the potential importance of the organic fractions to the phosphorus cycle, which account from 5 to 95% of the soil phosphorus (Harrison, 1987). Despite this, the study and utilization of organic phosphorus is neglected in relation to inorganic forms. These points were recently endorsed at the International Workshop on Organic Phosphorus in the English Lake District, September 2016 (Haygarth *et al.*, 2016). The opportunity to write this paper arose when we met together for the first time at this workshop. A comprehensive multiple author review paper from this meeting has been published by George *et al.* (2017). In contrast, our intention here is to provide a more opinion-based paper on organic phosphorus research and opportunities, approached through the collaborative discussion between three generations of soil phosphorus researchers whose collective research experience spans almost fifty years. The authors comprise a retired PhD supervisor and two generations of 'students' sharing a metaphorical academic grandfather–son–grandson relationship. This presented a unique opportunity to gain new insight from the resulting discourse across the generations. We consider the development of the subject of soil organic phosphorus and reflect on the current and future positioning of the discipline and new opportunities. It is approached initially through three separate personal narratives, which reflect our individual careers and perspectives on organic phosphorus research, followed by an attempt to integrate our discourse. This is not intended to be an exhaustive or comprehensive review of the subject, rather our collective opinion arising from discussion.

Three generations, a meeting of minds (P. M. Haygarth)

The International Organic Phosphorus Workshop provided me, as lead host, with the incentive to bring together this opinion from three generations of soil phosphorus researchers: I am sandwiched between my retired PhD supervisor and my first PhD student, now established as an independent researcher. This meeting gave us an opportunity to reflect on the historical context of our involvement in soil organic phosphorus research, to consider how it has evolved and to reflect what the new opportunities might be. I have been fascinated to see how research teams and group working can help to advance science and I wondered how the dynamics between the three generations would work and, specifically, if the interplay could provoke new insight and ideas. It also seemed a fitting opportunity to reflect on this for the special section for the 70th anniversary of the British Society of Soil Science (BSSS).

Anthony 'Tony' Harrison (my PhD supervisor) published his last soil phosphorus paper in the early 1990s, but was persuaded out of retirement as Guest of Honour at the Organic Phosphorus Workshop. After some modest hesitation, Tony took on the role as 'critique extraordinaire' of the best developments 2016 had to offer. When Tony was my supervisor he was noted for his classic ‘blue book’ on *Organic Phosphorus: A Review of World Literature* (Harrison, 1987), together with core publications that led to this book (Harrison, 1975; Harrison, 1979; Harrison & Helliwell, 1979; Harrison & Pearce, 1979; Harrison, 1982; Harrison, 1985). Tony also had the benefit of being a terrestrial ecologist, with a broad, holistic and systems viewpoint. I was interested in bringing Tony out of retirement to see what he would make of the post-genomic and molecularly-focused world.

My perspective on soil organic phosphorus was somewhat different: I focused on selenium in soil for my PhD and did not become fully aware of the phosphorus story until I began to work at the Institute of Grassland and Environmental Research (now Rothamsted Research, North Wyke). At that time in the early 1990s, my brief was to study phosphorus transfer from grassland soil, to assess the magnitudes and also the forms and pathways involved (Haygarth *et al.*, 1998). I identified a notable presence of unreactive (i.e. mostly organic) phosphorus in the samples (Haygarth & Jarvis, 1997; Haygarth *et al.*, 1998). At the same time, I also noticed a prevailing interest in inorganic phosphorus in soil surface and ground waters that focused mainly on forms that reacted with molybdate, predominantly (but not exclusively) inorganic phosphorus. But why, when evidence in the literature indicated that aquatic plants could, like terrestrial plants, hydrolyse organic phosphorus compounds with root exudates in times of need?

I was confused initially when I started my research into soil phosphorus, but latterly as I gained confidence my feelings turned to irritation at the seemingly dogmatic focus by the cognoscenti on inorganic phosphate. Agronomists seemed keen to optimize plant uptake of phosphorus and used an array of agronomic soil tests, such as the now well established ‘Olsen’s P’ (Olsen *et al.*, 1954). I calculated that these agronomic phosphorus pools determined by soil tests were ostensibly inorganic and seemed to represent a modest percentage only (typically around +/-5%) of the total soil P, whereas the organic phosphorus pools in soil were often a much larger percentage. Around this time in the 1990s, the molecular and genomic revolution began and the institute that I worked in focused on the philosophy that biotechnology, genomics and plant breeding could provide solutions. Surely, I reflected, these pools must have some agronomic and ecological significance too. Can the enzymes and the organic acids help mobilize the phosphorus at times of plant need?

In 1996, Ben Turner became my first PhD student and added new momentum to my thinking from our observations of organic phosphorus in leachate (Turner & Haygarth, 1999; 2000; 2001). Ben re-discovered the Harrison 'blue book' in the library during his PhD, and as an independent researcher he took the initiative and opportunity to dig deeper into the subject with continued collaboration (Turner *et al.*, 2002). Ben has since moved on to study tropical ecology and biogeochemistry outside the United Kingdom, but he has also continued to lead in organic phosphorus.

There was a long gap between the Organic Phosphorus Workshops in Ascona 2003 (led by Emmanuel Frossard) and Panama 2013 (led by Ben Turner), and it is debatable how much had changed through this period and beyond. One interesting development during this period was the emergence of the 'peak phosphorus' scare (Cordell *et al.*, 2009), which although controversial and somewhat refuted of late, certainly helped to remind me that we need to make efficient use of the phosphorus that exists in soil, because discussions about sustainability questioned the use of phosphorus resources. These debates on phosphorus supply and security heightened the sense of opportunity for soil organic P?; surely, we should investigate this?

Most recently I undertook a collaborative research project to study organic phosphorus use in soil and this has helped us to make some new modest inroads into the complex role of organic acids and enzymes in liberating organic phosphorus in the rhizosphere (Giles *et al.*, 2016a; 2016b), but it still seems there is a long way to go. The third Organic Phosphorus Workshop resulted from the momentum developed by the project team, and crucially this brought Tony Harrison and Ben Turner together for the first time. What would Ben learn by meeting the author of the 'blue book'? What would Tony (now retired) make of the new molecular world and the modern state-of-the-art? The seeds of this opinion paper were sown…..

Coming back, looking forward (A. F. Harrison)

The invitation to the Organic Phosphorus Workshop 2016 and writing this paper has resulted in me reviewing the factors that have governed the direction of my soil organic phosphorus career. I summarize these key factors, which have conditioned my activities and literature output because they could help others involved in research careers on soil organic phosphorus. The first, and perhaps one of the more important aspects, is that I was lucky to start my research on a whole ecosystem study (the Meathop Wood study in the UK) as part of the International Biological Program (IBP). This International Program ran from 1964 to 1974, with the objectives of acquiring data on the productivity, organic matter decomposition and nutrient cycling in typical ecosystems in the various biomes (e.g. forest, savanna, tundra, and so on) across the globe (Worthington, 1976; Schleper, 2017). Three key factors that arose from this experience, which had a big influence on my future research approach were: (i) working with a multidisciplinary scientific team, (ii) research of a whole ecosystem and its function and (iii) the global dimension of the overall programme. The first two factors gave rise to papers on phosphorus cycling in a whole woodland ecosystem (Harrison, 1978) and four different ecosystems (Harrison, 1985).

The other major factor that had a big influence on my research development was the appointment of John Jeffers as the Head of the Merlewood Research Station in the UK in 1970. He was a statistician who was determined that researchers at all levels should appreciate the importance of, and learn to use, statistics in environmental science studies. His in-house statistics courses on 'within' and 'between' habitat variation, temporal variation, and trends and relations between variables, covariance and canonical variation and so on had a major effect on my early soil phosphorus research in the woodlands of the English Lake District (Harrison, 1975). The marrying of the IBP global vision and the statistical analytical examination approach enabled me to investigate the global patterns of variation in soil organic P, based on analyses of data extracted from published literature, published in the Organic Phosphorus review, the 'blue book' (Harrison, 1987).

My soil phosphorus research in natural or semi-ecosystems such as woodlands, upland grasslands and moorlands made me aware of several important issues. When research spans natural ecosystems, studies encompass more extended ranges of variation in the soil variables than in heavily-managed systems; the extended ranges enable the researcher to detect better the significant differences in trends and relations between variables. Research in natural ecosystems also enables the study of basic soil phosphorus processes and functions in systems not disturbed by management practices, including, for example, the effects of tillage, applications of fertilizer and pesticides; management effects can be put into a broader perspective and better understood.

I have researched soil phosphorus at all scales from global, pedological, whole ecosystem, plant and microbe, and have tried throughout my career to gain important perspectives within and between all these levels. It is vitally important to understand the quantitative relations both within and between each of these scales to ensure that what one is studying is, and remains, relevant to soil phosphorus and its cycling in the wider environment. For example, the topic of agriculture without additional phosphorus fertilizer (one of the scenarios underpinning the Organic Phosphorus Workshop 2016) demands knowledge and data to determine how many crop cycles in each environment could be attained through mobilization of soil organic phosphorus. One would need to know the phosphorus demand of the crop and potential mobilization of the organic phosphorus present in the soil to make the basic calculations.

Gaining and keeping a perspective on phosphorus cycling across all environmental scales is vitally important for individual studies to progress into global organic phosphorus research. We must make sure that the research undertaken also addresses the effects of the broader environmental factors such as climate change, pesticide applications, atmospheric pollution, sequestering atmospheric carbon as soil organic matter and land-use changes. Understanding the effects of these broader factors could be more important to global success in managing phosphorus cycling from soil organic phosphorus than understanding the very detailed analytical chemical intricacies of soil organic phosphorus components.

It is essential, in my opinion, to understand and continually think about the role of organic phosphorus cycling at all scales from detailed soil chemistry to the global biome level. At whatever level individual researchers focus their studies, he or she should regularly reflect on the wider perspective of the big picture of phosphorus cycling, both upwards to the global level and downwards to the microbial level, to justify and appreciate the implications and importance of the research topic. I would suggest that each researcher has on the laboratory wall a large diagram showing the key processes and factors affecting organic phosphorus and its role in phosphorus cycling in the environment, and that this should be used to help formulate discussions and research projects that emphasize the importance of the big picture.

My final comments refer back to the organic phosphorus review in the ‘blue book’ (Harrison, 1987). I have often thought that instead of producing just one publication out of this review, I should perhaps have produced several papers that covered the whole subject and had them published as a series of ‘normal’ refereed scientific journal papers. This potentially could have given me more citable references than from a single book (although it was subjected to detailed refereeing before it was published). This Organic Phosphorus Workshop 2016, and the reactions the ‘blue book’ appears to have had on those involved in it, have justified my original decision.

Identify, quantify, experiment: a contemporary perspective (B. L. Turner)

I am the academic grandson in this narrative. I began studying organic phosphorus as a graduate student with Phil Haygarth in 1996 at the Institute of Grassland and Environmental Research, North Wyke in the southwest of England (now part of Rothamsted Research). My research focused on the role of organic phosphorus and biological mechanisms that promote phosphorus leaching from agricultural grasslands (Turner & Haygarth, 2000). At the time, phosphorus leaching was considered to be unimportant in an agronomic context, because leaching losses were negligible in a mass balance at the farm scale. However, there was increasing awareness that even relatively small concentrations of phosphorus could trigger harmful algal blooms and other water quality problems in lakes and rivers (Schindler, 1977;

Tunney *et al.*, 1997). Unlike inorganic phosphate, many organic phosphorus compounds are relatively mobile in the soil and occur in sufficient concentrations to trigger algal blooms (Frossard *et al.*, 1989; Whitton *et al.*, 1991), especially at certain dynamic times of the year for the microbial biomass, which is an important pool of organic phosphorus in most soils (Brookes *et al.*, 1984).

During this time, I inevitably became interested in procedures for identifying and quantifying organic phosphorus compounds in environmental samples, both water and soil. Speciation of organic phosphorus (and complex inorganic phosphates) is a challenge for several reasons, including the wide range of compounds that can be present, the ease with which they can decompose during extraction and analysis, and the variety of techniques available for their speciation (McKelvie, 2005). In this respect, I benefitted from time with Ian McKelvie at Monash University in Melbourne, Australia, which allowed me to experiment with chromatography, ^{31}P-NMR spectroscopy and immobilized phosphatases in flow injection analysis. Ian had achieved success with the latter technique in aquatic ecosystems (Shan *et al.*, 1993; McKelvie *et al.*, 1995), but it proved more difficult to apply to soil (as do most things). However, my time at Monash University convinced me that robust analytical procedures were a prerequisite for advancing my understanding of organic phosphorus dynamics in the environment.

Subsequently, I have studied organic phosphorus in a variety of ecosystems and contexts, including the ecology of the British uplands and Florida Everglades, irrigated agriculture and animal production systems in the western USA, long-term ecosystem development in Australia and New Zealand, and now the ecology and biogeochemistry of tropical forests. Fortunately, I have had the opportunity to work with mentors who encouraged my interest in organic phosphorus, even when it was not the primary focus of the funding. In addition to my longstanding collaboration with Phil Haygarth, others included Brian Whitton (Durham University), Leo Condron (Lincoln University), Hans Lambers (University of Western Australia), Dale Westermann (USDA-ARS) and Ramesh Reddy (University of Florida). Looking back, my focus on phosphorus was an advantage because there were always opportunities for research and collaboration; it is certainly hard to imagine an ecosystem where there is nothing interesting to learn about phosphorus.

While working with Phil Haygarth, we developed a longstanding appreciation for Tony Harrison's book (Harrison, 1987), which continues to this day. The 'blue book' is always close to my desk because it provides instant insight into organic phosphorus in almost any ecosystem. How much organic phosphorus can we expect in a Florida peatland, or a tropical Oxisol? The answer is in the 'blue book'. How is soil organic phosphorus influenced by pH or texture? The 'blue book' has the answer. The main limitation of the book (or the data it reviewed), at least in my mind, was in reconciling measurements of soil organic phosphorus by ignition and extraction procedures. This problem was recognized by Tony and others because the ignition procedure overestimates organic phosphorus in strongly weathered soil (Williams & Walker, 1967; Condron *et al.*, 1990). Nevertheless, the book has been, and continues to be, a remarkable resource for anyone interested in soil organic phosphorus.

Tony had the privilege of working in what I consider to be the golden age of organic phosphorus research. In the early 1970s, pioneers like Dennis Cosgrove in Australia, George Anderson in Scotland, Vernon Cole in the USA, John Stewart in Canada and Thomas Walker in New Zealand were generating fundamental analytical and conceptual insights into soil organic phosphorus (Cosgrove, 1962; Cosgrove & Tate, 1963; Walker, 1965; Anderson *et al.*, 1974; Walker & Syers, 1976; Cole *et al.*, 1977; Anderson, 1980). This was followed in the early 1980s by the development of a remarkable set of new procedures: methods to measure soil microbial phosphorus (Brookes *et al.*, 1982; Hedley *et al.*, 1982), a widely-adopted fractionation procedure (Hedley *et al.*, 1982) and a ^{31}P NMR spectroscopy procedure to identify and quantify organic phosphorus in soil extracts (Newman & Tate, 1980). During these exciting times, Tony was conducting his own detailed studies of organic phosphorus and phosphatase in UK woodlands, producing publications that were a vital resource for me and that contain results that are still relevant today (Harrison & Pearce, 1979; Harrison, 1982; 1983). At a time when considerable effort was being expended on identifying organic phosphorus compounds, Tony recognized the importance of obtaining information on rates of turnover of organic phosphorus to generate ecologically meaningful insight; his ^{32}P-labelled RNA procedure (Harrison, 1982) provided some of the only information on this for forested soil.

The 1980s also witnessed the recognition that phosphorus is a pollutant, leading to a shift in emphasis towards quantifying and mitigating phosphorus transfer in runoff from agricultural land to watercourses (Sharpley *et al.*, 1994; Tunney *et al.*, 1997; Carpenter *et al.*, 1998). Research then focused on inorganic and particulate phosphorus transfer, the predominant forms of phosphorus leaving intensively managed farmland (Haygarth *et al.*, 1998). Consequently, by the time I started my graduate studies, research into organic phosphorus in the environment was dwarfed by the study of inorganic and particulate phosphorus transfer, at least in Europe and North America.

The first organic phosphorus meeting was held at Monte Verita, in Ascona, Switzerland, in 2003. The idea for the meeting arose from frustration at the marginalization of organic phosphorus at academic meetings. Together with Emmanuel Frossard at ETH Zurich and Darren Baldwin at CSIRO in Australia, we brought together an interdisciplinary community of scientists working on organic phosphorus to discuss techniques and processes, and to provide a foundation for future research and collaboration with a book of review chapters outlining the current state of the field, analytically, mechanistically and conceptually (Turner *et al.*, 2005).

We have now had three organic phosphorus meetings, and each has been remarkably productive, not only in terms of published outputs (Turner *et al*. 2005; Turner *et al*. 2015; Haygarth *et al*. 2016), but also in terms of developing and nurturing long-term scientific interactions and collaboration, in ways that are difficult to develop without this kind of cross-disciplinary format. The organic phosphorus meetings have united a diverse group of terrestrial and aquatic scientists who have focused on a single topic that transcends disciplinary boundaries. The group is united analytically and mechanistically, which produced a dynamic meeting that generates novel interactions and long-lasting collaborations. I am already looking forward to the next one planned for Sweden in 2019.

Tony Harrison's comments earlier in this narrative imply that he felt the modern cognoscenti were failing to see the broader picture, focusing on analytical details at the expense of wider and perhaps more challenging research questions. Tony was no doubt surprised during the meeting in The Lake District to see how little has changed since he worked on organic phosphorus decades ago. It is certainly arguable that in some ways our understanding of the topic has not advanced much in 100 years. For example, the organic phosphorus composition of soil was largely understood in the first half of the 20th Century (Aso, 1904; Shorey, 1913; Potter & Benton, 1916; Dyer *et al.*, 1940; Wrenshall & Dyer, 1941). However, while recognizing the importance of thinking broadly, I disagree with Tony about the analytical emphasis. One of the most important limitations on organic phosphorus research, which discourages research and stifles progress, is the difficulty in identifying and quantifying the myriad of organic phosphorus compounds cycling in the environment. I discovered quickly as a graduate student that it is difficult to study things when you have no idea what they are.

Tony's point about maintaining a broad perspective is well taken: we must always think broadly, even when working on detailed questions. However, there is value in detail. It brings deeper insight, reveals mechanisms and processes, and by providing tractable questions it inevitably forms the focus of much of our research. As a scientific community we are at different stages in our careers, and we must all start somewhere. Not everyone can study the big picture, and there is immense value in precise studies of individual processes and mechanisms. Most of the time science advances incrementally, and the study of soil organic phosphorus is no different. Conceptual advances in the earth sciences are typically preceded and galvanized by analytical development, when major progress in a field is triggered by a key technological advance. This can be confirmed by a cursory look through the list of Nobel prizes in Chemistry and Physics, many of which celebrate transformative advances in analytical methodology.

The development of solution ^{31}P NMR spectroscopy for application to soil in the early 1980s was in some ways a double-edged sword. It undoubtedly led to important new information such as the presence of phosphonates in soil, but it stifled other avenues of research, particularly the use of selective analytical procedures and the study of individual groups of organic phosphorus compounds. For example, the inositol phosphates became included in a general monoester pool and have been largely ignored in soil research since 1980, even though we still do not understand the origin or function of three of the four stereoisomeric forms that can constitute such a quantitatively important component of soil organic phosphorus (Turner, 2007).

Techniques for organic phosphorus speciation are now relatively well-standardized and we have a much clearer understanding of their application and limitations. Solution ^{31}P NMR spectroscopy is the established method of choice for quantifying the overall organic phosphorus composition of soil and sediments (Cade-Menun, 2005). In contrast, the phosphatase hydrolysis procedure provides information on functional phosphorus groups and their potential hydrolysis of organic phosphorus in soil extracts and waters (Bunemann, 2008). Combining these with other treatments, such as hypobromite oxidation for selective identification of inositol phosphates (Turner *et al.*, 2012), provides an analytical framework for addressing questions on organic phosphorus in the environment.

So where do we stand as a community? In my opinion, the need to understand organic phosphorus cycling seems more urgent than ever. It is central to some of the key issues of our time, and technological advances are opening new avenues to further our understanding. It was clear from the Organic Phosphorus Workshop 2016 that there is renewed emphasis on organic phosphorus to reduce reliance on mineral fertilizers. This depends in part on improving the ability of plants to exploit organic phosphorus in the soil, and on promoting the efficient cycling of phosphorus through organic pools in the soil (Stutter *et al.*, 2012). From my own research, organic phosphorus is central to addressing key questions in ecosystem ecology. Differences in the ability of plant and microbial species to exploit organic phosphorus affect the distribution and productivity of natural plant communities (Zalamea *et al.*, 2016), and can promote or maintain diversity through resource partitioning (Turner, 2008). The extent to which ecosystems worldwide can respond to increasing atmospheric carbon dioxide concentrations will depend in part on the extent to which the soil can supply phosphorus to support increased plant growth (Cernusak *et al.*, 2013), which in turn depends inevitably on the turnover and acquisition of soil organic phosphorus. Finally, sequencing technology provides novel ways to identify and study the genetic basis of organic phosphorus acquisition by plants and soil microbial communities in ways that were not possible when we first convened the community in 2003 (e.g. Fraser *et al.*, 2015a; Morrison *et al.*, 2016). This certainly promises to yield some of the most transformative insight in the coming years.

Some collective reflections

Clearly, the strategic context and policy required to understand organic phosphorus cycling seems more urgent than ever because there remains a strong need to understand organic phosphorus availability, mobility and general cycling. Contemporary discussions on these topics and on the supply of phosphorus heighten the sense of opportunity presented to us today. We must continue to encourage the study of organic phosphorus across all scales, from molecular advances, through detailed soil chemistry, to cycling at the global scale. However, from a research perspective, we make several collective observations:

Technologies and techniques

In Table 1 we present a chronology of what we consider significant developments in soil organic phosphorus research since 1900. Interestingly, this seems to be mostly (but not exclusively) populated with technological advances that opened new avenues to further our understanding. Most recently, there have been developments around molecular sequencing technology, which shows potential in providing novel ways to identify and study the genetic basis of organic phosphorus acquisition in plants and soil microbial communities in ways that were not possible even 15 years ago. For example, since the first characterization of the phosphate (pho) regulon in *Escherichia coli* (Wanner & Chang, 1987) there have been developments that have culminated in the exciting determination of phosphatase genes in soil (Fraser *et al.*, 2015a; Fraser *et al.*, 2015b; Morrison *et al.*, 2016; Fraser *et al.*, 2017) and more recently assessment of the relation between land use with phosphatase gene diversity in soil (Neal *et al.*, 2017). These are exciting and certainly have the potential to yield some of the most transformative insight in the coming years.

As aforementioned, Table 1 seems to be dominated with new tools and techniques, which, whilst they have irrefutably contributed much to the discipline, also deserve a note of caution. Such tools have a tendency for "I have a technique so what can I measure?" syndrome, at the expense of asking some new questions of the processes, dynamics and biogeochemistry. This issue is discussed further below.

What has changed in 30 years?

The advantage of participating in the discussion across three generations is that we could ask critical questions of one another about what has really changed. One of the uncomfortable conclusions that we all agreed on was that, whilst there have been new advances in the development of tools and technologies, things have not advanced much in thirty years. Similar questions are being asked today as in the past, albeit with new reductionist detail but little broader conceptual advance. Tony Harrison, especially, brought a longevity that offered a unique perspective into the meeting of the cognosenti after some years away. The most striking thing for him was how little had changed; similar things are being done now but in a more sophisticated way with modern tools. In our dialogue that followed our meeting Tony reported:

"I was rather disappointed about the lack of scientific cover of the broader aspects of the organic phosphorus science."

Furthermore, during his final closing speech at the Organic Phosphorus Workshop 2016, Tony Harrison reported, verbatim:

"You all now have access to newer more sophisticated methods to analyse organic phosphorus (e.g. ^{31}P NMR, HPLC, LC-HRMS). You have many automated instruments for these analyses making them easier to perform and with potentially better quality control. Computing has developed enormous potential giving you easy access to data base programs, Excel, SAS or other statistical packages and Web of Science to get almost instantly the information you need. With this increased technological development and 30 years of more research, you have access to more data and results. With these much-improved facilities, you all should have made lots of real research advances. So you now need to ask yourselves: How has the science progressed over the last 30 years? What have been the key new developments? And above all, where has the science been going, and where does it need to go?"

In this Tony was reflecting on and emphasizing the great technological advances of the last 30 years. However, he went on to be rather critical of where the future research is going:

"I feel strongly there is a need to broaden the perspective of the current research. I feel there is a big missing dimension. Imagine there is a big box of knowledge labelled "Research on Soil Organic Phosphorus". From what I have seen in the Organic Phosphorus Workshop

2016, most if not all of your research topics seem to start off inside this box. Most projects seem to get ever deeper into this box looking at details of increasing complexity. Other research projects also start off inside the box, but try to look outwards towards trends with external factors, such as across ecosystems, plant successions or pedogenetic developments. I think that at least some of you should start your projects off from outside the box and look in. What do I mean? Some of you should start, for example, by addressing the important environmental issues of our time."

Perhaps, in the words of the Lake District poet William Wordsworth, who was cited during the Organic Phosphorus Workshop 2016 as a means of inspiration, we should stop worrying about the fine techniques and "let nature be your teacher".

Are we asking the right questions?

So, we believe that whilst the techniques have become more sophisticated, we have not been successful at applying the new techniques to the wider soil and environmental questions, although some recent papers are encouraging, with one example identifiying sorption processes of inositol phosphorus in soil Ruyter-Hooley *et al.* (2016). Although we advocate the development of new techniques, we need to encourage and balance this with more 'out of the box' integration and thinking at the large scale to develop organic phosphorus research in the context of larger global issues such as climate change and food security. Put another way, we must strive for a better balance between reductionism, which is thriving, and 'big thinking', which is lacking. The latter should be more feasible than ever now that we are in the era of 'big data'.

What do the above mean for the organic phosphorus and soil community, and are we asking the wrong, or perhaps intractable, questions? Is it productive to go in circles using apparently more sophisticated techniques each time? And have these technologies really advanced the science, or merely given researchers more things to play with? It is our opinion that it is time for the organic phosphorus community to take stock of where we are going and how we should get there. For example, the possibility of promoting plant use of organic phosphorus, or taking advantage of organic phosphorus cycling in agriculture, has been mooted for decades, but we are still struggling to achieve it; is this an example of an intractable question? Where precisely do we want organic phosphorus research to lead us, what is the goal and is it feasible? We cannot answer these questions here, but they should remain at the forefront of our minds as we proceed to develop new research projects to further our understanding of phosphorus and soil science.

Wider reflection—the benefit of three generations

Working together in the collaborative partnership of the three generations, with our diverse insights and varying experiences, has enabled us to see much further than possible individually. Writing this commentary has been a positive experience for the three authors and we hope that the dynamic of the interaction has helped us to produce meaningful reflections that can help guide and focus discussion in the future. In our opinion, the need to understand the cycling of organic phosphorus seems more urgent than ever, as contemporary discussions on phosphorus supply and security heighten the sense of opportunity presented today. There has never been a more pertinent time to research organic phosphorus and there remain many challenges to understand and characterize the large pools of organic phosphorus that exist in the soil throughout the world.

Finally, at the personal level, this exercise has shown that across the three generations, we still share a common and persistent fascination for organic phosphorus and its cycling where, remarkably, many of the core issues remain. Through mutual respect and dialogue, this meeting of minds has helped to sharpen our reflections, which we hope have helped to indicate the way forward.

"Come forth into the light of things, let nature be your teacher" (William Wordsworth, The Tables Turned)

Supporting information

1. A meeting of minds – (left to right) P.M. Haygarth, A.F. Harrison and B.L. Turner meet for the first time in September 2016 at the Organic Phosphorus Workshop 2016 in Ambleside, The Lake District, UK. https://www.dropbox.com/s/2tcmlaxs1s03yl7/Plate1.jpg?dl=0
2. A video of AF Harrison's post-meeting speech at Organic Phosphorus Workshop 2016 can be viewed at https://www.youtube.com/watch?v=RNUSgY2NbFM&t=37s and Prof Simon Bainbridge reads an excerpt from William Wordsworth's *The Tables Turned* at Organic Phosphorus Workshop 2016: https://www.youtube.com/watch?v=iwkbMWyu4rk
3. The proceedings of the OP2016 Workshop are available here https://www.dropbox.com/s/d3xfgfrv063gv8p/op2016-abstract-book.pdf?dl=0

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Table 1. Chronology of significant developments in soil organic phosphorus research.

1904–1918: First papers on soil organic phosphorus, at least in English, demonstrating an early appreciation for the chemical nature of the compounds (Aso, 1904; Stoklasa, 1911; Shorey, 1913; Potter & Benton, 1916).

1940: Isolation of inositol phosphate from soil (Dyer *et al.*, 1940; Wrenshall & Dyer, 1941).

1954: Development of a simple procedure to fractionate soil organic phosphorus (Mehta *et al.*, 1954).

1962: Identification of the inositol hexakisphosphate stereoisomers in soils (Cosgrove, 1962; 1963).

1969: Development of a simple colorimetric assay for soil phosphatase activity (Tabatabai & Bremner, 1969).

1976: Development of a conceptual model of phosphorus transformations during pedogenesis (Walker & Syers, 1976).

1977, 1978: Explicit recognition by model development and testing of the importance of organic phosphorus turnover in ecosystem nutrition (Cole *et al.*, 1977; Harrison, 1978).

1980: First use of solution ^{31}P NMR spectroscopy to characterize soil organic phosphorus (Newman & Tate, 1980).

1981: Conceptual distinction between biochemical and biological mineralization of phosphorus in soil organic matter (McGill & Cole, 1981).

1982: Development of methods to measure soil microbial phosphorus (Brookes *et al.*, 1982; Hedley & Stewart, 1982).

1982: Development of a widely used sequential fractionation scheme (Hedley *et al.*, 1982).

1987: Compilation of literature defining the state of knowledge on soil organic phosphorus – the 'blue book' (Harrison, 1987).

1993: Development of NaOH–EDTA procedure for soil organic phosphorus extraction (Bowman & Moir, 1993; Cade-Menun & Preston, 1996).

2001: Development of transgenic plants expressing a fungal phytase (Richardson *et al.*, 2001).

2005: Overview of the state-of-the-art in organic phosphorus in the environment after a century of research (Turner *et al.*, 2005).

2015: Quantification of the abundance of phosphatase genes in soil (Fraser *et al.*, 2015a,b).

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