Journal of Soil Science and Plant Nutrition (2025) 25:393–408
https://doi.org/10.1007/s42729-024-02140-x

REVIEW

Organic Phosphorus in the Terrestrial Environment: an Update on Current Research and Future Directions

Emileigh R. Lucas[1] · Nhiem D. Nguyen[2] · Luisella Celi[3] · Leo M. Condron[4] · Tandra D. Fraser[5] · Timothy S. George[6] · María de La Luz Mora[7] · Nelly S. Raymond[8]

Received: 29 August 2024 / Accepted: 14 November 2024 / Published online: 22 January 2025

Abstract
In 2016, a group of experts convened to set priorities for organic phosphorus (P) research, addressing global issues, methodological strengths and weaknesses, and the benefits of understanding the organic P cycle. Seven years later, scientists and students with an interest in organic P reconvened to discuss progress and new insights, and this review highlights recent major research updates. Interest in organic P research has increased since 2016, and new priorities have emerged, including the impact of climate change on organic P, the influence of geopolitical crises on P supplies, and the adoption of sustainable practices like regenerative agriculture. Climate change was a central theme in the 2023 discussions, with an increased emphasis on integrating P and especially organic P into climate change research, which has traditionally focused more on carbon (C) and nitrogen (N). The discussions highlighted disparities in accessing analytical equipment globally, and its consequent impact on research quality and scope. To address these issues, coordinated efforts involving the research community, government policies, and international cooperation are needed, much the same as we see with the climate and biodiversity crises. Promoting sustainable agricultural practices, investing in soil health, and enhancing education and extension services are crucial. Future research should focus on standardizing analytical methods, integrating nutrient balance into models, and exploring soil-microbiome-plant interactions. Regular and intedisciplinary workshops, social media engagement, and the establishment of research networks are recommended to maintain momentum in organic P research. Raising public and stakeholder awareness about the importance of organic P is essential for advancing knowledge in this area.

Keywords Organic phosphorus · Climate change · Sustainability · Planetary boundary · Soil · Agriculture

1 Purpose

In 2016, a group of experts met to set priorities for organic phosphorus (P) research. The discussion covered "global issues associated with organic P in the terrestrial environment, methodological strengths and weaknesses, benefits to be gained from understanding the organic P cycle" and presented a current state of organic P research and future research directions (George et al. 2018). Seven years later, many of this same group of experts, with the addition of new emerging experts in the field, met again to discuss the outcomes, progress and new insights for organic P research (https://opwinchile2023.cl/) with a theme of "Exploring organic P fate in soil and aquatic ecosystems under the climate change and food security scenario". The objectives of this review are to highlight major research updates since the 2016 meeting, to push for additional research in key areas, and to foster interest in organic P impacts across disciplines.

Shifts in Phosphorus Challenges?

Of the many challenges facing our changing planet, it is well established that the distribution and availability of P remains a critical concern, with potential impacts to human and environmental health (Fig. 1) (Yang et al. 2013). Phosphorus also remains beyond the planetary boundaries for sustainability (Richardson et al. 2023) a status it has held since the first analysis in the 2000's. In many regions soils are deficient in plant-available P, leading to poor crop growth and the inability to feed a growing population (Cordell et al. 2009). Simultaneously, parts of the world that have readily available P sources from animal production, P-rich residual products from urban areas, or can afford mineral P fertilizer,

Emileigh R. Lucas and Nhiem D. Nguyen equal contribution.

Extended author information available on the last page of the article

Fig. 1 Key challenges facing the future of organic phosphorus. *Figure created using Biorender.com*

have high levels of accumulated P in soils (Kleinman 2017). These P-enriched soils are known as legacy P soils and pose a risk to surface water pollution in the form of eutrophication (Lucas et al. 2023; Sharpley et al. 2013; Toor and Sims 2016). However, they also create an opportunity as a source of P for agricultural systems reducing the requirement to continually add P inputs (Doydora et al. 2020).

Along with non-uniform distribution, in both chemical form and geography, the P that exists on planet earth is a finite resource (Geissler et al. 2018; MacDonald et al. 2011). While new discoveries of phosphate deposits (e.g. Norway) (Wybrew 2023) may extend the lifespan of the P reserves in the near term, it is still a finite resource with evolving consumption rates and demands. Phosphate rock remains classified as a critical raw material (European Commission 2014), not only because it is a finite resource, but also due to the political dependency. Countries lacking P deposits are dependent on imports and are therefore vulnerable to market fluctuations and mineral fertilizer prices, creating political and economic dependence, particularly exacerbated in the current geopolitical crisis (Brownlie et al. 2023). New uses for P, such as in batteries for electric cars and other energy storage, could lead to additional competition and demand, and therefore change the trajectory of utilization and priorities for the use of the earth's P supply. Due to population growth and changes in diet as a result of rising living standards in emerging and developing countries, the agricultural demand for crop nutrients will increase and consequently their criticality (Mogollón et al. 2018).

Furthermore, when defining the "planetary boundary" of P, inorganic and organic P forms are not differentiated (Fig. 2) (Kopittke et al. 2021; Richardson et al. 2023; Steffen et al. 2015). The P boundary considers prevention of large anoxic events both in oceanic and freshwater systems, with a threshold of 11 Tg P year^{-1} influx of P from freshwater to ocean, and 6.2 Tg P year^{-1} mined and

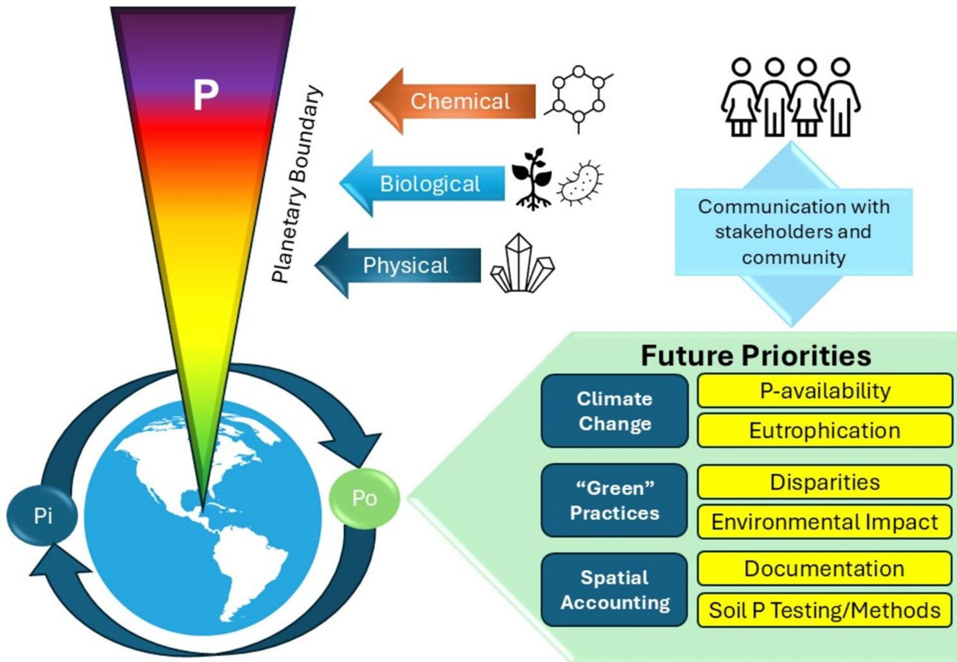

Fig. 2 The status of phosphorus as a "control variable" of planetary boundaries, redrawn viewing only P status from the list of control variables presented by Steffen et al. (2015) and Richardson et al. (2023)

applied to soils susceptible to erosion (Steffen et al. 2015). According to Steffen et al. (2015), we have passed these thresholds "beyond the zone of uncertainty."

2 The Place of Organic P

In most soils, organic P represents a substantial portion of the total P, typically ranging from 30 to 65% (Condron et al. 2005). Its transformations are therefore crucial for overall P cycling and influenced by a combination of biological, chemical, and physical factors, making this pool highly dynamic. Organic P turnover in soil is primarily driven by immobilization and mineralization rates, which are mediated by microorganisms. The transformation of organic P by soil microorganisms is often constrained by the availability of suitable C substrates (Spohn and Kuzyakov 2013; Wang et al. 2016). Organic P transformations are also dependent on abiotic interactions. For example, orthophosphate esters are almost completely ionized in most of the pH range found in soils, with their adsorption to soil minerals varying widely depending on the specific ester and soil mineralogy (Condron et al. 2005). The distinction between organic and inorganic P is challenging due to the abiotic and biotic processes occurring simultaneously. For example, inositol-P is predominantly adsorbed on soil surfaces (inorganically bound), yet its desorption or formation is largely driven by soil microorganisms, indicating a combination of chemical and biological processes (Celi and Barberis 2005; Celi et al. 2022). These dynamics are further influenced by environmental conditions such as temperature and soil water content, as well as the history and intensity of land use, including associated rates of P input and removal. Because of the particular influence of these abiotic and land management factors on the organic P pool, climate change is likely to affect the transformation dynamics. Despite the necessary importance given to understanding the C and N cycles in the context of climate change, P cycles remain under-considered. Recent works have also highlighted that increasing soil organic C storage, a key mitigation against climate change, is often limited by the amount of P available to allow the stoichiometry for C accumulation (Feng et al. 2023; Spohn 2020a). The role of organic P is yet to be clarified in this context. Given current and future global challenges, understanding the contribution of organic P to global P cycling is critical. This focus is necessary for accurately assessing the planetary boundary for P and the potential contribution to climate change mitigation and agricultural sustainability. Predicting the cycling of organic P, its availability to terrestrial and aquatic organisms, and improving methods to measure and differentiate organic P fractions will be crucial for the sustainability of P.

3 Revisiting the Priorities for Organic Phosphorus Research

The focus on organic P has increased since the 2016 meeting. Between 2017 and 2023, Web of Science Core Collection database returned 802 records (Supplementary material) for publications including keywords "organic P" and "soil". This shows a steep increase in interest considering that there are only 2045 records for "organic phosphorus" in total from 1916–2023, and therefore more than 39% of the total records have been added after 2016.

During the Organic P workshop in Pucon, Chile, participants were divided in two groups and were asked to consider the priorities of research and focus areas to be strengthened in relation to the discussions held in 2016. The discussion points from the two groups were associated with past priorities highlighted in 2016. In this section, we present the progress and some significant examples associated with the priorities set in 2016 by George et al. (2018). The significant examples were chosen based on presentations given at the OPW2023, authors knowledge of specific studies and literature search using Web of Science and Scopus with relavant key words associated to the topic (see Supplementary material). Priorities were grouped by themes and are presented in the ten boxes below.

Box 1- Analytical methodology

Priorities set for organic P in 2016:
- Link operationally-defined pools with biological processes
- Standardisation of protocols
- Development of in situ, nondestructive techniques for organic P analysis

Isotopic and sequential extraction methods

Significant progress:
The use of the stable isotope ^{18}O has become more common to investigate P cycling mediated by soil microorganisms and especially to quantify inorganic P released from enzymatic hydrolysis. Latest advances in soil–plant systems include the optimization determination of $\delta^{18}O_P$ natural abundance and in ^{18}O-water enriched soil in various P fractions (from a modified Hedley extraction (Hedley et al. 1982))
Oxygen isotope ratios in the phosphate and hydroxyl moieties of inositol phosphates has recently been measured using electrospray ionization (ESI)-based Orbitrap mass spectrometry (Hollenback and Jaisi 2024). This technological progress gives opportunities or investigating the position-specific oxygen isotopes in organophosphorus compounds
Hedley sequential extraction and its modifications have been proven to be an important tool to be
combined with other methods to better understand cycling of organic P in soils (see below examples). Recently, using various ^{33}P labelled organic P compounds in soil incubation experiments, Wasner et al. (2023) reavealed that within 24 h the pace at which phosphodiesters are hydrolyzed is set by the depolymerization step and that a considerable amount of organic P is taken up directly by microbes

Examples of key studies:
- Use of $\delta^{18}O_P$ at natural abundance and modified Hedley sequential extraction to determine how biological cycling of P contributes to P cycling during pedogenesis in a glacier chronosequence (Frkova et al. 2022) or along a climatic gradient with varying rainfall (Helfenstein et al. 2018)The latter study also combines P *K*-edge X-ray absorption spectroscopy and ^{33}P isotopes
- Combination of various methods to enhance P-cycling: ^{18}O-enriched in combination with sequential extraction, ^{33}P isotopes, K-edge X-ray absorption spectroscopy or liquid ^{31}P NMR spectroscopy—Helfenstein et al. (2018), Siegenthaler et al. (2024)

Potential future directions:
For accurate interpretation of $\delta^{18}O_P$ values, von Sperber et al. (2023) proposed a need to further
differentiate, in bulk organic P pool extracted by NaOH-EDTA, organic P that can be hydrolyzed by
enzymes (i.e., labile organic P and newly synthesized organic P such as microbial organic P) from those
that are recalcitrant (e.g., high molecular weight or those not accessible by enzymes). These authors
also stressed the importance of establishing reference standards for oxygen isotope ratios in phosphate
and proposed Ag_3PO_4 as a good candidate

Organic P speciation

Significant progress and key studies:
Liquid-state ^{31}P NMR spectroscopy is one of the main tools for organic P speciation (McLaren et al. 2019). In recent years, four main approaches have especially improved the organic P speciation identification of the unresolved phosphomonoester spectral region of soil organic P. The four approaches includes: 1) soil organic matter (SOM) fractionation followed by Liquid-state ^{31}P NMR spectroscopy for organic P speciation. It was for example shown that 47% of the unresolved phosphomonoesters are linked to the SOM fraction released by breaking ester (40%) and ether (7%) bonds, while about 30% of this unresolved organic P pool is associated with the SOM fraction closely tied to the soil mineral phase (Reusser et al. 2023); 2) treatment of NaOH-EDTA extracts by hypobromite oxidation allowed the identification of lower-order inositol phosphates (IP5 and IP4) and two isomers of myo-IP5 (Reusser et al. 2020); 3) combinaison of 1D ^{31}P NMR, 2D $^{1}H^{31}P$ NMR and $^{3}1P$ transverse relaxation (T2) investigate monoester background and molecular weight (Haddad et al. 2024); 4) improved spectral deconvolution fitting methods have also significantly increased the accuracy of myo-IP6 quantification in soil extract by avoiding overestimation
Other analytical methods, such as high-resolution liquid chromatography-mass spectrometry (LC–MS), have been shown to provide hierarchical identification of: 1) phytase-type enzymes catalyzing the hydrolysis of a mixture of organic P compounds; 2) the role of ferrihydrite in the dephosphorylation of ATP and 3) a wide range of phosphorylated organic compounds in the low molecular weight organic P pool

Examples of key studies:
- Organic P speciation refining using liquid state refined ^{31}P NMR spectroscopy methods—Reusser et al. (2020), Reusser et al. (2023), McLaren et al. (2020), Haddad et al. (2024)
- Organic P speciation using high resolution liquid chromatography – mass spectrometry (LC–MS)—Solhtalab et al. (2021), Klein et al. (2019)

Potential future directions:
With the increasing usage of liquid state ^{31}P NMR spectroscopy, standardization of protocols for spectral processing and peak identification are important. There seems to be a huge potential of using artificial intelligence (AI) to speed up this process, for example, by establishment of a platform that automates these NMR data interpretation

Organic P interaction with soil surfaces

Significant progress and key studies:

Understanding soil mineralogy and its relationship with the adsorption and precipitation of organic P is crucial for determining its availability and sequestration in the soil environment. In recent years, advancements in technologies such as atomic force microscopy (AFM), X-ray diffraction, K-edge X-ray absorption near edge structure (XANES) attenuated total reflectance-Fourier transform infrared (ATR-FTIR) spectroscopy, electrospray ionization coupled with Fourier transform ion cyclotron resonance mass spectrometry (ESI-FT-ICR MS), and solid-state ^{31}P NMR have led to significant progress in studying and understanding the interactions between organic P species and soil minerals

Examples of key studies:

- An extensive review on the organic P interactions and soil minerals—Yan et al. (2023), and references therein
- Organic P fractionation from 0.1 M NaOH-extracted sediment, driven by the adsorption on crystalline goethite and amorphous ferrihydrite at the molecular level—Jiang et al. (2024)
- Effects of pH on partitioning of P (orthophosphate and phytate) sorption on Fe oxyhydroxides and montmorillonite—Prietzel et al. (2024)
- Inorganic and organic P retention by coprecipitation during ferrous iron oxidation—Santoro et al. (2019)
- Soil minerals on organic P availability and P uptake by plants—Amadou et al. (2022)
- Reduced adsorption of arsenite and arsenate on goethite due to competition of myo-inositol hexaphosphate for the same binding sites—Balint et al. (2020)

Potential future directions:

Current research on the interaction between organic P and soil mineral interfaces remains limited. However, with the development of technologies that allow more in situ observation and analysis, future studies could focus on this area providing a direct mechanistic understanding. Two recent reviews (van der Bom et al. 2022; Vogel et al. 2016) highlight the potential of in situ methods to characterize P, although very little has been applied to organic P

Box 2—Interaction with other nutrients

Priorities set for organic P in 2016:

- Link the organic P cycle with other biogeochemical cycles
- Optimise stoichiometry between organic P and other elements for system function
- Integrate soil physics, chemistry and biology to understand organic P and how it fits with wider soil fertility

Significant progress:

Recent studies explored the impacts of various nutrient limitations on organism retention and reuse, shedding light on how nutrient availability influences microbial communities and their interactions with organic P. Investigations into the effects of SOM quality, such as particulate OM and mineral-associated OM, on C use efficiency have provided insights into the complex interplay between soil organic P and C dynamics. Integrating nutrient balance into modeling frameworks has enhanced our ability to predict nutrient dynamics and their implications for organic P cycling within soil ecosystems. Moreover, studies examining the effects of fertilizer application on organic P mobilization have highlighted agricultural practices' potential impacts on soil P availability and cycling pathways

Examples of key studies:

- Effect of various nutrient limitations on organism retention and reuse—Chen et al. (2019)
- Effect of soil organic matter quality (particulate organic matter and mineral associated organic matter) on C use efficiency—Ma et al. (2024)
- Intregration of nutrient balance into models—Yang et al. (2023)
- Effect of fertilizer addition on organic P mobilization—Spohn and Schleuss (2019)

Potential future directions:

The current work collectively underscores the multifaceted nature of organic P interactions within soil ecosystems and emphasize the need for continued research to elucidate these complex dynamics

Significant progress has been made in understanding the stoichiometry between organic P and other elements, particularly the C:N:P ratios in microbial biomass, bulk soil, and soil organic matter. This research area remains pivotal for comprehending nutrient dynamics in ecosystems, yet there is a notable scarcity of studies specifically focused on organic P, indicating a need for further investigation in this domain

Box 3—Interaction with soil microorgansims

Priorities set for organic P in 2016:

- Understand which genes and transcripts control the microbial response to organic P
- Understand microbial impacts on organic P cycles
- Understand the P limits to plants and microbes
- Produce a molecular toolkit for studying microbial structure and function

Significant progress:

Since 2016, there has been a notable increase in studies examining microbial community functional traits, particularly *phoD* and *phoC*-harboring bacteria, in relation to various land uses and soil management practices. While previous research often suggested that inoculating specific microorganisms, such as phosphate-solubilizing microorganisms (PSM), could enhance plant-available P, recent reviews have cast doubt on the ability to significantly alter soil P nutritional status at scales beneficial to plants. Additionally, research into the symbiotic relationship between arbuscular mycorrhizal fungi (AMF) and plant roots has intensified, focusing on understanding the energy costs involved and interactions with microorganisms capable of mineralizing organic P

An increasing number of publications also investigate the interaction between soil fauna and P, especially earthworms

Examples of key studies:

- Microbial communities functional traits (*phoD* and *phoC*-harboring bacteria)—Wei et al. (2019), Fraser et al. (2017), Luo et al. (2019), Wei et al. (2021)
- Effect of various nutrient limitation on organism retention and reuse—Chen et al. (2019)
- Use of microorganism inoculants as a reliable strategy to deliver P to the plant at field scale contested—Barrow (2024), O'Callaghan et al. (2022) and Raymond et al. (2021b)
- Microbial symbiosis, such as the AMF, question the energy cost (C) e.g. Andrino et al. (2021) study suggested that AM plants invest larger C amounts into their fungal partners at lower P availability. Other work involving AMF showed that AMF hyphae can serve as a transportation mean for organic P mineralizing bacteria (Jiang et al. 2021). However the question of the energy source remains a limitation for efficient organic P mineralization
- Linking soil nutrient stoichiometry and microbial interactions—Heuck et al. (2018)
- Earthworms and soil P cycling—Nahidan and Ghasemzadeh (2022), Vos et al. (2022)

Potential future directions:

The current research places a strong emphasis on soil microorganisms; however, they are often treated as isolated entities. We propose that future research should explore the interrelationships between microorganisms and nutrient stoichiometry in cellular and community metabolism, particularly focusing on the cycling of P within the broader context of other biogeochemical cycles. This approach is critical because, depending on soil nutrient balance, microorganisms can function as either a 'net sink' or a 'net source' of available nutrients, particularly P, thereby influencing its immediate availability to plants through competition. Consequently, it is essential to consider nutrient stoichiometry and microbial interactions together in future studies to improve our understanding on ecosystem functioning. Additionally, the effects of climate change on P cycling mediated by microorganisms should be considered, as changes in soil temperature, atmospheric carbon dioxide concentrations, and N deposition are likely to impact microbial communities

Future research should also encompass various scales of interactions between organisms, such as 1) trophic interactions and food webs (e.g., nematodes, protists, and other which graze on bacteria) and 2) signaling processes between plants and the rhizosphere microbiome, as well as between AMF and the hyphosphere microbiome

Box 4 – (Co-) Precipitation and dissolution of Phosphorus with Fe

Priorities set for organic P in 2016:

- Understand organic P interaction with minerals
- Assess the fate of organic P in redox affected environments

Significant progress:

The interaction of organic P with minerals is largely known to increase its stability in soil and determine a selective enrichment of the most reactive species such as inositol-P (Celi et al. 2020) with respect to other organic P species. Recent progress has been made in understanding that, aside from adsorption and precipitation, organic P may be retained by coprecipitation processes following changes in pH, Eh and ionic strength. Coprecipitation is a complex process, involving several mechanisms as a function of the P species, porewater P/Fe ratio, and interaction with organic matter and other ionic compounds present in the soil solution. In soils experiencing reducing conditions organic P may be released into the porewater solution following microbial-driven reductive dissolution of coprecipitates and easily migrate to oxygenated zones with consequent re-precipitation. This leads to a heterogeneous organic P spatio-temporal distribution with important consequences on the microbiome-plant ecosystem

Examples of key studies:

- Organic P retention during Fe(II) oxidation—Santoro et al. (2019), Voegelin et al. (2013), Wan et al. (2016)
- Reductive dissolution of iron oxides and effects on P dynamics in redox affected soils—Wang et al. (2022), Martinengo et al. (2023)

Potential future directions:

Research is needed to understand the role of organic matter and ionic compounds in the coprecipitation processes. The impact of oxidation–reduction processes on organic P dynamics remains still underexplored as well as its implications in redox soils such as rice paddies. The influence of Fe–P coprecipitates as sources or sink of P for plants remains largely debated

Additionally, Yan et al. (2023) proposed three focus areas for organic P – mineral interactions: 1) effects of mineral compositions and structures, redox conditions (for Fe (oxyhydr)oxides) on their interaction with organic P; 2) further study on underlying mechanisms of organic P-mineral interaction at molecular scale using combination of different advanced techniques; and 3) further investigation on effects of organic P-mineral interaction on interfacial dynamics of organic matters, heavy metals, and micronutrients

Box 5—Nano-particles

Priorities set for organic P in 2016:

- Understand organic P interaction with natural and manmade nanoparticles
- Assess the utility of nanoparticles to help manage the system

Significant progress:

Natural nanoparticles and fine colloids are shown to play an important role in biogeochemical cycling of P. In forest ecosystems, these materials as dissolved organic P can make up 40–100% of P losses (Bol et al. 2016). Recent progress has been made in understanding the movement of natural colloids in soil through the development of Field Flow Fractionation coupled with an organic carbon detector and ICP-MS. This method has been applied to various soils and surface waters, revealing three distinct size classes of colloids with characteristic compositions: organic, organic matter associated with Fe- and Al-hydroxides, and layer silicates. Additionally, there have been advancements in synthesizing phosphate nanoparticles for use as fertilizers, although most studies have focused on the inorganic form of phosphorus

Examples of key studies:

- Application of Field Flow Fractionation coupled to an organic carbon detector and ICP-MS (Gottselig et al. 2017; Missong et al. 2018a, 2016, 2018b)
- Phosphate nanoparticles synthetization and evaluation for feasibility (Tosun et al. 2021), for P availability (Bollyn et al. 2019; Xiong et al. 2018), and for the effects on P use efficiency and crop productivity (Abdelmigid et al. 2022; Guzmán-Báez et al. 2021; Sakhno et al. 2022; Yaseen and Amin 2021)
- Bioavailability and engineering of the nano-fertilizer with the catalysis role of iron oxide nanoparticles in hydrolysis of several phosphate esters in water and the effect of temperature (Huang 2019)
- Maghsoodi et al. (2020) provide an review on positive and negative effects of Hydroxyapatite nanoparticles (nHAPs) as well as underlying mechanisms on plant growth and yield

Potential future directions:

We suggest to intensify the investigation of mechanistic interactions between (organic) P and nanoparticles using advanced technologies (see Box 1). This would help to clarify the influence of nanoparticles on the dynamics and bioavailability of P in soil–plant systems

Box 6—Land Management

Priorities set for organic P in 2016:
- Design tailored systems for specific managed environments that optimise use of organic P
- Optimise organic P utilisation over loss
- Improve soil P testing
- Develop a P credits system
- Utilise organic P more effectively by using what's in soil, what's added to soil and what's lost

Significant progress:
Land use and management has been linked to differences in organic P quantity, species, and fractions. Increased exploration of the microbial and land-management interface has occurred using new techniques (see "Interaction with soil microorgansims" box). Some specific land-uses, including agriculture, grassland, and forestry, have been explored in more depth across varying ecosystems around the world. Additionally, particular practices, such as liming and tillage were examined. Use of new and improved methods enhanced the quality and breadth of information related to land management (see "analytical methodology" box)

Examples of key studies:
- Impact of inorganic and organic amendments on organic P in agricultural soil—Abdala et al. (2020); Abdala et al. (2018), Boitt et al. (2018), Chen et al. (2022), Koch et al. (2018), Lu et al. (2020), Lucas et al. (2022), Luo et al. (2017), Poblete-Grant et al. (2020), van der Bom et al. (2019)
- Long term land use or changing land use impact of P cycling—Cade-Menun (2017), Gao et al. (2019), Luo et al. (2017), Maranguit et al. (2017), Nunes et al. (2020), Touhami et al. (2022)
- Impact of liming on soil P cycling—Bouray et al. (2021), Bouray et al. (2022), Simonsson et al. (2018)
- Land use impacts on organic P storage in different size fractions and colloids of soil—Missong et al. (2016), Spohn (2020b)
- Accessing organic P in soil—Darch et al. (2016), Doydora et al. (2020)
- Exploration of Po influence on P loss to surface water—Roswall et al. (2021), Sharma et al. (2017)
- Influence of land use on P solubilizing microbes and AMF (see "Interaction with soil microorgansims" box)

Potential Future Directions:
Edge-of-field studies that measure/speciate/fractionate organic P in soil and runoff/drainage and correlate the measurements with land management will lead to improved prediction and modeling of the fate of organic P in soils. A greater understanding of microbial communities and different impacts of the land management on these communities, along with how the P cycling and potential for crop availability and environmental losses are impacted by these communities will be an important future direction

Box 7—Database

Priorities set for organic P in 2016:
- Use existing datasets
- Avoid repeating experiments by being aware of past research more effectively
- Develop a minimum dataset and an accessible database

Significant progress:
In recent years, little effort has been made to collect and make datasets available, except for a plant available phosphorus map at a global scale—McDowell et al. (2023)

Potential future directions:
The expansion of global databases could be facilitated by compiling various extraction methods, such as organic P content through the ignition method and organic P in different Hedley fractions. Additionally, a database on speciation, such as ^{31}P-NMR spectra, would assist in the future identification of organic P forms in relation to location and soil physico-chemical properties. This compilation of data is likely to be strengthened in the coming years due to the increasing emphasis on open-access and free data availability. However, we call for the community to be proactive to create database

Box 8—Modelling

Priorities set for organic P in 2016:
- Model P dynamics in the environment
- Develop conceptual models of cycling at a range of scales
- Build empirical models using existing data
- Produce a life cycle analysis of organic P

Significant progress:
Efforts have been made to understand P dynamics at various scales using models. Models including P are relatively scarce and the inclusion of organic P is still more rarely considered. Agricultural systems models scale, such as the Agricultural Production Systems sIMulator (APSIM), has a P component which has been tested in more details

Examples of key studies:
- Agricultural systems models scale evaluation—Das et al. (2022) and Raymond et al. (2021a)
- Global phosphorus cycle analysis—Nesme et al. (2018)
- Integration of various organic P pool to model historical terrestrial C balance and showed to largerly improve the modelling performance—Yang et al. (2023)

Potential future directions:
Modeling soil P dynamics remain challenging due to the lack of long-term soil data on labile-P pools, making the implementation of organic P dynamics even more difficult. Models such as APSIM provide an overview of labile P pool dynamics, yet often exclude detailed representations of organic P. In these models, the organic P component is linked to the mineralization of SOM, but optimizing the models is hindered by insufficient observed data. Collecting short-term and long-term data on organic P mineralization is crucial for understanding these fluxes and improving model accuracy

Box 9—Research training

Priorities set for organic P in 2016:
- Better access to shared facilities
- Training programmes in organic P related techniques and concepts
- Interdisciplinary and long term research

Significant progress:
From the presentations at OPW2023 workshops, it seems that few activities related to those priorities have
taken place, in part due to the occurrence of the Covid-19 pandemic. Therefore, there is a lot yet
to be done with regards to training

Potential future directions:
Establishing international training and exchange programs can be a potential way to promote access to
facilities between institutions. Researchers of institutions from about ten European countries stress the
importance of developing a coordinated program to train a new generation of workers with a system
thinking mindset to enable transformative P resources management as a way to address the global P
challenge (Reitzel et al. 2019). The authors also call for the formation of networks across countries. The
establishment of such training networks/programs on P can potentially be implemented by taking
advantage of existing networks such as the Global Soil Partnership with regional and national partnerships
or European Joint Program Soil. Given the global nature of P resource management challenge, we
must act globally across continents. We recommend that training programs be organized to build capacity for young researchers via which shared facilities can be accessed
Participants of OPW2023 workshop also proposed establishment of regional research hubs with a
common study site to facilitate interdisciplinary and long-term research. Those hubs will facilitate and
speed up achievements of common research goals through interdisciplinary and transdisciplinary collaboration. In addition, the data to be created are precious inputs for modelling work

Box 10—Research network

Priorities set for organic P in 2016:
- Promote discussion of organic P within the scientific community
- Better communication with stakeholders and the public on the importance of organic P
- Develop a central platform for knowledge exchange
- Understand the needs and motivations of land managers and policy makers with respect to organic P
- Emphasise educating the public in issues associated with organic P
- Understand the socio-economic factors influencing organic P dynamics
- Improve the translation of research in organic P to impactful outcomes

Significant progress and potential future directions:
OPW2023 and the next organic P workshop was/will be organized to promote exchanges of knowledge
and open up research collaboration opportunities. Priorities in communication and translation of research discussed in George et al. (2018) stay important
We further propose the creation of a Organic P Society which could have a mission of developing integrated datasets, promoting the science of organic P with stakeholders and acting as hub for organic P science (seminars, newsletters etc.)

4 New Priorities not Considered in 2016

While many topics from the 2016 OPW meeting continue to be a priority, new topics were brought to the discussion such as the impact of climate change on organic P, the impact of geopolitical crises on P supplies and interests and the adoption of more sustainable practices, including "regenerative agriculture."

4.1 Climate Change

Climate change was mentioned briefly in the previous meeting and George et al. (2018) publication; however, it was a central theme in the round table discussions of the 2023 OPW meeting. Researchers across the disciplines represented at the conference considered it as critical to future research, but few researchers presented research with direct link between P and climate change. Most of the work on climate change focuses on C and N; P remains the "forgotten" element. As an example. only 2,456 records of publications about soil P mention "climate change," compared to 22,124 soil C publications, and 10,844 soil N publications, according to a June 10, 2024 search of the Web of Science Core Collection (Appendix 1). Exclusion of P in the climate change conversation leads to an incomplete picture of the impact, as both C storage and elements of N cycling will be dependent on the availability of P in the soil. For example, investigation of the impact of stoichiometry between forms of C, N, P, and other elements in the soil have demonstrated that increasing C storage may have negative impacts on P availability (Celi et al. 2022; Spohn 2016; 2020b). There is a documented increase in discussion of P related to climate change, with records increasing nearly every year from 2000 to 2023 (Figure S1); however, only 46 records return in total considering "organic phosphorus," "soil," and "climate change" from the same Web of Science Core Collection search. Of the 46 records through June 10, 2024, approximately 87% of those have occurred in 2016 and after, indicating that interest in this topic of organic P and climate change has grown substantially since the 2016 OPW meeting. As a point of comparison, a search of "organic nitrogen," "soil," and "climate change" returned 228 records, again indicating a greater emphasis on N, while organic P is less-studied. The impact of climate change on organic P will not occur uniformly across systems, which leads to a need for fine-scale research in biogeochemical cycling along with ecosystem-level research. Two key examples of concerns linked to global climate change will be (i) the availability of organic P to plants in agricultural and natural systems where more C will be stored, (ii) the potential for increased eutrophication in systems with legacy P with the increase in precipitation intensity. The dynamic nature of P presents a challenge in quantifying both availability to crops and potential for loss, as feedback loops and fluxes exist in organic P and C pools, compounding uncertainty.

4.2 Disparities Towards the Implementation of "Green Practices" and the Facility Access Across the Globe

Associated to climate change concerns, the round tables have also addressed the issues associated with disparities in term of facility access and the implementation of "green practices" across the world.

Disparities in accessing analytical equipment in scientific research are pronounced across the world, significantly impacting the quality and scope of scientific inquiry. In developed countries, researchers may have access to advanced, high-precision analytical tools (i.e. NMR, synchrotron, mass-spectometers), which enable comprehensive analysis. Conversely, researchers in developing countries often face limitations due to inadequate funding, leading to reliance on less sophisticated equipment. This disparity hinders regional ability to conduct cutting-edge research and participate equally in the global scientific community. Furthermore, the lack of access to such equipments can limit the understanding of local soil conditions, impeding agricultural advancements and sustainable land management practices crucial for addressing current and future environmental challenges. Initiatives exist to foster collaborations at the country level (e.g. DANIDA Fellowship Centre in Denmark for developing research activities with partners in priority countries and in growth and transition countries and USDA National Institute of Food and Agriculture and Foreign Agricultural Service programs in the United States) or at the global scale with for example the UNESCO which support the access to laboratory equipment to scientists from the Global South (https://www.unesco.org/en/basic-sciences-engineering/remote-access).

Another disparity raised during the discussions was the place of P in the Green transition (e.g. the European Green Deal) and the potential disparities across the globe. This transition involves various sectors and encompasses a wide range of activities aimed at reducing environmental impact, promoting sustainable practices for more resource efficient systems, and addressing climate change. The Green transition is therefore seen as essential for counteracting climate change, preserving natural resources, and ensuring a sustainable future for coming generations. Phosphorus is highly affected when it comes to its exploitation and use. One pivotal action is the recovery of P from biowastes, producing new biobased fertilizers that can be safely and efficiently used in soil for a better circularity of agrosystems (Álvarez Salas et al. 2024; Chojnacka et al. 2020). These recycled fertilizers are complex products that contain variable concentrations of both inorganic and organic P, but also C and N that can affect P cycling. Obtaining a fertilizer product from biowaste that is efficient, has the desired nutrient content, is safe and practical to use, and free of contaminants is challenging. For example, wastewater products are often rich in P and are often stated as an alternative P source. Wastewater treatment plants are required to clean water to safe standards and generate solid waste as a byproduct without the specific goal to create fertilizer products, in most cases. Further processing of sewage sludge, such as the precipitation of heavy metals or conversion into struvite, involves processes that are expensive difficult to implement, even in developed countries (Pradel and Aissani 2019). For developed countries (which can afford mineral P and the recycling of biowaste), the shift towards "green practices" (e.g., nutrient recycling from waste-streams, organic farming) and "biological approaches" (e.g., use of microorganisms to increase plant nutrient uptake) for a more sustainable agriculture is possible and currently implemented through governmental policies. This aims to decrease the application of mineral phosphate fertilizers and its accumulation. While this can be coordinated and implemented in developed countries where P rarely limits food production, in developing countries the adoption of efficient and safe green farming practices that meet crop P requirements can be challenging due to a combination of economic, social, and infrastructural factors. Farmers in developing countries often operate on very tight budgets and may prioritize immediate needs over long-term soil health. Investing in P fertilizers can be seen as a risk when immediate returns are uncertain. In this context, P often limits crop productivity with many agricultural soils being already P-depleted. The access to affordable P fertilizers can prevent these countries from using adequate amounts and alternative source of P (e.g. using biowaste) to maintain soil fertility and achieve optimal crop yields to feed the population. The access of P fertilizer to sustain crop production for livelihood is often more a priority than transitioning towards green practices. Additionally, the lack of supportive policies and regulations for sustainable P management can exacerbate the issues.

4.3 Spatial Accounting of Organic Phosphorus

Participants of OPW 2023 also echoed the need for increased spatial accounting of organic P and creation of a map that represents the global distribution of P in soils. MacDonald et al. (2011) created a global map of P resources based on estimated agricultural inputs and outputs using various national and regional data or estimation tools. While this is a useful way to predict P flows and accumulation on a global scale, more refined information specific to organic P is necessary to predict how climate change will impact P in the soil. Historic organic P accumulation from past P management is not well-documented spatially; however, organic P is well-correlated with land-use and organic C content of soils (Stutter et al. 2015). Using soil testing data and information about land use and historical management, organic P can be spatially modeled by considering these parameters. For example, the average percentage of P in soil organic matter and the percentage of soil organic matter in different soil types could help build a database on organic P stocks. Additionally, some characteristics of parent material and soil formation may assist in prediction of organic P storage (Werner et al. 2017). Recently, McDowell et al. (2023) developed a global database of soil "plant available" P using available data and converting all to the Olsen-P equivalent. A global database of Hedley fractionation results was also published relating to natural systems (Hou et al. 2018). Such databases could be built upon or others newly developed considering additional separation of organic P and quantifying risk of loss to surface water along with potential crop availability. Proper spatial accounting of P, including differentiation of P and organic P, would lead to better allocation of resources to address issues associated with planetary boundaries.

5 How to Move Forward?

The OPW 2023 highlighted significant progress on topics identified in 2016 and set new priorities for the near future. Addressing these issues requires a coordinated effort involving the research community, government policies, international cooperation, and development. Solutions may include promoting sustainable agricultural practices, investing in soil health, and enhancing education and extension services to support efficient and environmentally friendly P use.

One major priority identified by participants is the integration of climate change into organic P research. To address climate change impacts at a fine scale, it is essential to understand the interactions between chemical and microbial transformations of soil P. This can be studied through controlled experiments simulating expected climate change impacts, such as increased temperature, extreme precipitation, drought events, elevated atmospheric CO_2, and conditions of increased flooding and saltwater intrusion (IPCC 2023). Additionally, the interactions of P with C and N should be further explored. Advanced techniques, including ^{31}P-NMR, XAS, XANES, EXAFS, LC–MS/MS, and advanced genetics and molecular techniques, have been developed and refined to address these questions (Boxes). While these advanced techniques provide valuable data on organic P, researchers must consider the limited accessibility to these methods. Traditional and updated chemical methods, such as chemical extractions and fractionations, remain highly useful and accessible. The establishment of a global infrastructure network to give access to advanced techniques may be a future opportunity to give access to advanced techniques to more scientists. The utility of these methods may also be enhanced when correlated with advanced modelling techniques, potentially through the application of artificial intelligence (AI) and machine learning in the future.

To address climate change impacts at the ecosystem level, changes in soil organic P status at the field scale due to land management and microbial-plant-fauna interactions must be assessed. Accurate sampling techniques and strategies are critical to measure these changes meaningfully. Field measurements of organic and inorganic P pools, along with other field conditions, should be correlated with edge-of-field P losses. Soil heterogeneity presents challenges in sampling and measuring P, particularly accounting for the impact of microbial communities and complex interactions within soil aggregates and organic matrices (Hall et al. 2024; Kardanpour et al. 2015; Werner et al. 2017). This may present an opportunity for AI and machine learning to aid in predicting P transformations and losses. Scaling up fine-scale observations is possible but modeling is challenging due to the many interactions at the ecosystem level compared to the relative isolation at the fine scale.

To maintain momentum in organic P research, we propose several actions: 1) Continuing organizing workshops on organic P, with the next workshop in 2026 hosted by Agrifood Canada. 2) Formalizing the activities of the organic P research community; this could be achieved by developing a Society for the field (Box 9) or most ideally establishing an Organic P working group within existing societies such as European Geosciences Union, taking advantage of available resources and facilitating exchange between Organic P community and other communities. 3) Establishing a webpage for organic P research to update research activities, sharing data, and increasing visibility within the scientific community. The establishment of a website for the organic P research community could be foster by seeking sponsorship from organizations like the United Nations Environment Program, FAO, or World Food Program. However, the maintenance of such a website over the long-term can be challenging due to financial constraints, as evidenced by the deactivation of the 'Soil Phosphorus Forum' (www.soilpforum.com). Social media can serve as an alternative platform for data and information sharing. 4) Organizing regular, possibly virtual, seminars to present and update research is crucial, especially for young researchers. 5) Addressing the funding gap for P research compared to C and N research is essential. Raising public, policy and stakeholder awareness, particularly among potential funding donors, about the importance of organic P research is crucial. Researchers often report total soil C and N because they are easier to measure, but increasing the inclusion of P, particularly organic P, in research and datasets is a priority. 6) Advocate and implement collaborations between C, N, and P research communities through joint proposal development. 7) Establish organic P research networks or hubs, either geographically or technique-based (e.g., NMR, LC–MS), to promote research exchange and train future organic P scientists internationally. Overall, the implementation of these action points requires identifying voluntary lead and supporting persons/organizations to coordinate these activities; and this can be achieved by the development of an Organic P society.

6 Impact Statement

Phosphorus is a critical element for human and environmental health. This paper highlights the importance of organic P, specifically, considering the future increased demands of climate change and population growth leading to increased P demand. Much work has been done in recent years considering P cycling, stoichiometry with N and C, impact of microbial communities, and contribution of organic P to P losses. Phosphorus, however, is still the "forgotten element" in climate change conversations dominated by C and N and understanding its role is critical to the success of climate mitigation strategies involving C accumulation in soils and reducing losses of N to the atmosphere.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-024-02140-x.

Acknowledgements The authors would like to thank Bioren-Universidad de La Frontera, Chile for hosting OPW 2023. The authors would also like to thank all the participants of the OPW 2023 for insightful presentations and discussions. Emileigh Lucas would like to thank her PhD advisor, Dr. Gurpal Toor of University of Maryland, for supporting her participation in OPW and development of this article. Nhiem Nguyen Duy would like to thank Swiss National Science Foundation for funding his participation in the OPW 2023 and Jolanda Reusser for her discussion. The contribution of Tim George is supported by funding from the Scottish Government. Nelly S. Raymond acknowledges the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No MSCA-HE-2021 No. 101064654 for supporting the participation to the workshop.

Author Contributions Conceptualization: all the authors; Writing – Original Draft Preparation: all the authors.

Funding No funding has been received for this work.

Data Availability Not applicable.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

References

Abdala DB, Moore PA, Rodrigues M, Herrera WF, Pavinato PS (2018) Long-term effects of alum-treated litter, untreated litter and NH4NO3 application on phosphorus speciation, distribution and reactivity in soils using K-edge XANES and chemical fractionation. J Environ Manage 213:206–216. https://doi.org/10.1016/j.jenvman.2018.02.007

Abdala DB, Gatiboni LC, Schmitt DE, Mumbach GL, Dall'Orsoletta DJ, Bonfada EB, Veiga M (2020) Phosphorus speciation and iron mineralogy in an oxisol after 11 years of pig slurry application. Sci Total Environ 743:140487. https://doi.org/10.1016/j.scitotenv.2020.140487

Abdelmigid HM, Morsi MM, Hussien NA, Alyamani AA, Alhuthal NA, Albukhaty S (2022) Green Synthesis of Phosphorous-Containing Hydroxyapatite Nanoparticles (nHAP) as a Novel Nano-Fertilizer: Preliminary Assessment on Pomegranate (Punica granatum L.). Nanomaterials 12:1527

Álvarez Salas M, Sica P, Rydgård M, Sitzmann TJ, Nyang'au JO, El Mahdi J, Moshkin E, de Castro e Silva HL, Chrysanthopoulos S, Kopp C, Wali K, Zireeni Y, Ural-Janssen A, El Hajj Hassan S, Kebalo LF, Chadwick D, Jensen LS (2024) Current challenges on the widespread adoption of new bio-based fertilizers: insights to move forward toward more circular food systems. Frontiers Sustain Food Syst 8. https://doi.org/10.3389/fsufs.2024.1386680

Amadou I, Faucon M-P, Houben D (2022) Role of soil minerals on organic phosphorus availability and phosphorus uptake by plants. Geoderma 428:116125. https://doi.org/10.1016/j.geoderma.2022.116125

Andrino A, Guggenberger G, Sauheitl L, Burkart S, Boy J (2021) Carbon investment into mobilization of mineral and organic phosphorus by arbuscular mycorrhiza. Biol Fertil Soils 57:47–64. https://doi.org/10.1007/s00374-020-01505-5

Balint R, Celi L, Barberis E, Prati M, Martin M (2020) Organic phosphorus affects the retention of arsenite and arsenate by goethite. J Environ Qual 49:1655–1666. https://doi.org/10.1002/jeq2.20145

Barrow NJ (2024) Phosphate solubilizing microorganisms; the modern philosopher's stone. Plant Soil. https://doi.org/10.1007/s11104-024-06785-6

Boitt G, Schmitt DE, Gatiboni LC, Wakelin SA, Black A, Sacomori W, Cassol PC, Condron LM (2018) Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil. Geoderma 321:164–172. https://doi.org/10.1016/j.geoderma.2018.02.010

Bol R, Julich D, Brödlin D, Siemens J, Kaiser K, Dippold MA, Spielvogel S, Zilla T, Mewes D, von Blanckenburg F, Puhlmann H, Holzmann S, Weiler M, Amelung W, Lang F, Kuzyakov Y, Feger K-H, Gottselig N, Klumpp E, Missong A, Winkelmann C, Uhlig D, Sohrt J, von Wilpert K, Wu B, Hagedorn F (2016)

Dissolved and colloidal phosphorus fluxes in forest ecosystems—an almost blind spot in ecosystem research. J Plant Nutr Soil Sci 179:425–438. https://doi.org/10.1002/jpln.201600079
Bollyn J, Castelein L, Smolders E (2019) Fate and bioavailability of phosphorus loaded to iron oxyhydroxide nanoparticles added to weathered soils. Plant Soil 438:297–311. https://doi.org/10.1007/s11104-019-04008-x
Bouray M, Moir JL, Condron LM, Lehto NJ (2021) Lime-Induced pH Elevation Influences Phosphorus Biochemical Processes and Dynamics in the Rhizosphere of Lupinus polyphyllus and Lupinus angustifolius. J Soil Sci Plant Nutr 21:1978–1992. https://doi.org/10.1007/s42729-021-00495-z
Bouray M, Moir JL, Condron LM, Paramashivam D (2022) Early effects of surface liming on soil P biochemistry and dynamics in extensive grassland. Nutr Cycl Agroecosyst 124:173–187. https://doi.org/10.1007/s10705-021-10163-4
Brownlie WJ, Sutton MA, Cordell D, Reay DS, Heal KV, Withers PJA, Vanderbeck I, Spears BM (2023) Phosphorus price spikes: a wake-up call for phosphorus resilience. Front. Sustain Food Syst 7:1088776. https://doi.org/10.3389/fsufs.2023.1088776
Cade-Menun BJ (2017) Characterizing phosphorus forms in cropland soils with solution 31P-NMR: past studies and future research needs. Chem Biol Technol Agric 4:19. https://doi.org/10.1186/s40538-017-0098-4
Celi L, Barberis E (2005) Chapter 6 Abiotic stabilization of organic phosphorus in the environment. In: Turner BL, Frossard E, Baldwin DS (eds.) Organic Phosphorus in the Environment. CABI Publishing, Wallingford, pp 113–132
Celi L, Prati M, Magnacca G, Santoro V, Martin M (2020) Role of crystalline iron oxides on stabilization of inositol phosphates in soil. Geoderma 374:114442. https://doi.org/10.1016/j.geoderma.2020.114442
Celi L, Said-Pullicino D, Bol R, Lang F, Luster J (2022) Interconnecting soil organic matter with nitrogen and phosphorus cycling. In: Yang Y, Keiluweit M, Senesi N, Xing B (eds.) Multi-Scale Biogeochemical Processes in Soil Ecosystems. https://doi.org/10.1002/9781119480419.ch3
Chen J, Seven J, Zilla T, Dippold MA, Blagodatskaya E, Kuzyakov Y (2019) Microbial C:N: P stoichiometry and turnover depend on nutrients availability in soil: A 14C, 15N and 33P triple labelling study. Soil Biol Biochem 131:206–216. https://doi.org/10.1016/j.soilbio.2019.01.017
Chen W, Zhan Y, Zhang X, Shi X, Wang Z, Xu S, Chang Y, Ding G, Li J, Wei Y (2022) Influence of carbon-to-phosphorus ratios on phosphorus fractions transformation and bacterial community succession in phosphorus-enriched composting. Biores Technol 362:127786. https://doi.org/10.1016/j.biortech.2022.127786
Chojnacka K, Moustakas K, Witek-Krowiak A (2020) Bio-based fertilizers: A practical approach towards circular economy. Biores Technol 295:122223. https://doi.org/10.1016/j.biortech.2019.122223
Condron LM, Turner BL, Cade-Menun BJ, Sims J, Sharpley A (2005) Chemistry and dynamics of soil organic phosphorus. In: Sims JT, Sharpley AN, T WD (eds.) Phosphorus: Agriculture and the Environment, pp 87–121
Cordell D, Drangert J-O, White S (2009) The story of phosphorus: Global food security and food for thought. Glob Environ Chang 19:292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009
Darch T, Blackwell MSA, Chadwick D, Haygarth PM, Hawkins JMB, Turner BL (2016) Assessment of bioavailable organic phosphorus in tropical forest soils by organic acid extraction and phosphatase hydrolysis. Geoderma 284:93–102. https://doi.org/10.1016/j.geoderma.2016.08.018
Das BT, Schmidt S, Biggs J, Lester DW, Bourne N, Huth NI (2022) Simulating long-term phosphorus, nitrogen, and carbon dynamics to advance nutrient assessment in dryland cropping. Field Crop Res 285:108590. https://doi.org/10.1016/j.fcr.2022.108590
Doydora S, Gatiboni L, Grieger K, Hesterberg D, Jones JL, McLamore ES, Peters R, Sozzani R, Van den Broeck L, Duckworth OW (2020) Accessing legacy phosphorus in soils. Soil Systems 4(4):74
European Commission (2014) 20 critical raw materials - major challenge for EU industry. https://ec.europa.eu/commission/presscorner/detail/en/IP_14_599
Feng J, Song Y, Zhu B (2023) Ecosystem-dependent responses of soil carbon storage to phosphorus enrichment. New Phytol 238:2363–2374. https://doi.org/10.1111/nph.18907
Fraser TD, Lynch DH, Gaiero J, Khosla K, Dunfield KE (2017) Quantification of bacterial non-specific acid (phoC) and alkaline (phoD) phosphatase genes in bulk and rhizosphere soil from organically managed soybean fields. Appl Soil Ecol 111:48–56. https://doi.org/10.1016/j.apsoil.2016.11.013
Frkova Z, Pistocchi C, Vystavna Y, Capkova K, Dolezal J, Tamburini F (2022) Phosphorus dynamics during early soil development in a cold desert: insights from oxygen isotopes in phosphate. SOIL 8:1–15. https://doi.org/10.5194/soil-8-1-2022
Gao S, DeLuca TH, Cleveland CC (2019) Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. Sci Total Environ 654:463–472. https://doi.org/10.1016/j.scitotenv.2018.11.124
Geissler B, Steiner G, Mew MC (2018) Clearing the fog on phosphate rock data – Uncertainties, fuzziness, and misunderstandings. Sci Total Environ 642:250–263. https://doi.org/10.1016/j.scitotenv.2018.05.381
George TS, Giles CD, Menezes-Blackburn D, Condron LM, Gama-Rodrigues AC, Jaisi D, Lang F, Neal AL, Stutter MI, Almeida DS, Bol R, Cabugao KG, Celi L, Cotner JB, Feng G, Goll DS, Hallama M, Krueger J, Plassard C, Rosling A, Darch T, Fraser T, Giesler R, Richardson AE, Tamburini F, Shand CA, Lumsdon DG, Zhang H, Blackwell MSA, Wearing C, Mezeli MM, Almås ÅR, Audette Y, Bertrand I, Beyhaut E, Boitt G, Bradshaw N, Brearley CA, Bruulsema TW, Ciais P, Cozzolino V, Duran PC, Mora ML, de Menezes AB, Dodd RJ, Dunfield K, Engl C, Frazão JJ, Garland G, González Jiménez JL, Graca J, Granger SJ, Harrison AF, Heuck C, Hou EQ, Johnes PJ, Kaiser K, Kjær HA, Klumpp E, Lamb AL, Macintosh KA, Mackay EB, McGrath J, McIntyre C, McLaren T, Mészáros E, Missong A, Mooshammer M, Negrón CP, Nelson LA, Pfahler V, Poblete-Grant P, Randall M, Seguel A, Seth K, Smith AC, Smits MM, Sobarzo JA, Spohn M, Tawaraya K, Tibbett M, Voroney P, Wallander H, Wang L, Wasaki J, Haygarth PM (2018) Organic phosphorus in the terrestrial environment: a perspective on the state of the art and future priorities. Plant Soil 427:191–208. https://doi.org/10.1007/s11104-017-3391-x
Gottselig N, Amelung W, Kirchner JW, Bol R, Eugster W, Granger SJ, Hernández-Crespo C, Herrmann F, Keizer JJ, Korkiakoski M, Laudon H, Lehner I, Löfgren S, Lohila A, Macleod CJA, Mölder M, Müller C, Nasta P, Nischwitz V, Paul-Limoges E, Pierret MC, Pilegaard K, Romano N, Sebastià MT, Stähli M, Voltz M, Vereecken H, Siemens J, Klumpp E (2017) Elemental composition of natural nanoparticles and fine colloids in european forest stream waters and their role as phosphorus carriers. Global Biogeochemical Cycles 31:1592–1607. https://doi.org/10.1002/2017GB005657
Guzmán-Báez GA, Trejo-Téllez LI, Ramírez-Olvera SM, Salinas-Ruíz J, Bello-Bello JJ, Alcántar-González G, Hidalgo-Contreras JV, Gómez-Merino FC (2021) Silver nanoparticles increase nitrogen,

phosphorus, and potassium concentrations in leaves and stimulate root length and number of roots in tomato seedlings in a hormetic manner. Dose-Response 19(4). https://doi.org/10.1177/15593258211044576
Haddad L, Vincent AG, Giesler R, Schleucher J (2024) Small molecules dominate organic phosphorus in NaOH-EDTA extracts of soils as determined by 31P NMR. Sci Total Environ 931:172496. https://doi.org/10.1016/j.scitotenv.2024.172496
Hall RL, de Santana FB, Grunsky EC, Browne MA, Lowe V, Fitzsimons M, Higgins S, Gallagher V, Daly K (2024) A machine learning approach to predicting plant available phosphorus that accounts for soil heterogeneity and regional variability. J Soils Sediments 24:390–401. https://doi.org/10.1007/s11368-023-03648-y
Hedley MJ, Stewart J, Chauhan B (1982) Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations 1. Soil Sci Soc Am J 46:970–976
Helfenstein J, Tamburini F, von Sperber C, Massey MS, Pistocchi C, Chadwick OA, Vitousek PM, Kretzschmar R, Frossard E (2018) Combining spectroscopic and isotopic techniques gives a dynamic view of phosphorus cycling in soil. Nat Commun 9:3226. https://doi.org/10.1038/s41467-018-05731-2
Heuck C, Weig A, Spohn M (2018) Corrigendum to Heuck et al "Soil microbial biomass C:N: P stoichiometry and microbial use of organic phosphorus", Soil Biology & Biochemistry 85, 119–129. Soil Biol Biochem 127:329–330. https://doi.org/10.1016/j.soilbio.2018.09.011
Hollenback AJ, Jaisi DP (2024) Position-Specific Oxygen Isotope Analysis in Inositol Phosphates by Using Electrospray Ionization-Quadrupole-Orbitrap Mass Spectrometry. J Am Soc Mass Spectrom 35(9):2176–1286
Hou E, Tan X, Heenan M, Wen D (2018) A global dataset of plant available and unavailable phosphorus in natural soils derived by Hedley method. Sci Data 5:180166. https://doi.org/10.1038/sdata.2018.166
Huang X-L (2019) Iron oxide nanoparticles: an inorganic phosphatase. In: Sinha I, Shukla M (eds.) Nanocatalysts. IntechOpen, London, pp 97–124
IPCC (2023) Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.
Jiang Y, Guo M, Shao Y, Du Y, Wang J, Huang Z, Li J, Wang Y, Liu G (2024) Molecular characterization on the fractionation of organic phosphorus induced by iron oxide adsorption using ESI-FT-ICR MS. Ecotoxicol Environ Saf 284:116910. https://doi.org/10.1016/j.ecoenv.2024.116910
Jiang F, Zhang L, Zhou J, George TS, Feng G (2021) Arbuscular mycorrhizal fungi enhance mineralisation of organic phosphorus by carrying bacteria along their extraradical hyphae. New Phytol 230:304–315. https://doi.org/10.1111/nph.17081
Kardanpour Z, Jacobsen OS, Esbensen KH (2015) Local versus field scale soil heterogeneity characterization – a challenge for representative sampling in pollution studies. SOIL 1:695–705. https://doi.org/10.5194/soil-1-695-2015
Klein AR, Bone SE, Bakker E, Chang Z, Aristilde L (2019) Abiotic phosphorus recycling from adsorbed ribonucleotides on a ferrihydrite-type mineral: Probing solution and surface species. J Colloid Interface Sci 547:171–182. https://doi.org/10.1016/j.jcis.2019.03.086
Kleinman PJA (2017) The Persistent Environmental Relevance of Soil Phosphorus Sorption Saturation. Curr Pollut Rep 3:141–150. https://doi.org/10.1007/s40726-017-0058-4
Koch M, Kruse J, Eichler-Löbermann B, Zimmer D, Willbold S, Leinweber P, Siebers N (2018) Phosphorus stocks and speciation in soil profiles of a long-term fertilizer experiment: Evidence from sequential fractionation, P K-edge XANES, and 31P NMR spectroscopy. Geoderma 316:115–126. https://doi.org/10.1016/j.geoderma.2017.12.003
Kopittke PM, Menzies NW, Dalal RC, McKenna BA, Husted S, Wang P, Lombi E (2021) The role of soil in defining planetary boundaries and the safe operating space for humanity. Environ Int 146:106245. https://doi.org/10.1016/j.envint.2020.106245
Lu Y, Silveira ML, O'Connor GA, Vendramini JMB, Erickson JE, Li YC, Cavigelli M (2020) Biochar impacts on nutrient dynamics in a subtropical grassland soil: 1. Nitrogen Phosphorus Leaching 49:1408–1420. https://doi.org/10.1002/jeq2.20139
Lucas E, Mosesso L, Roswall T, Yang Y-Y, Scheckel K, Shober A, Toor GS (2022) X-ray absorption near edge structure spectroscopy reveals phosphate minerals at surface and agronomic sampling depths in agricultural Ultisols saturated with legacy phosphorus. Chemosphere 308:136288. https://doi.org/10.1016/j.chemosphere.2022.136288
Lucas E, Kennedy B, Roswall T, Burgis C, Toor GS (2023) Climate Change Effects on Phosphorus Loss from Agricultural Land to Water: A Review. Curr Pollut Rep 9:623–645. https://doi.org/10.1007/s40726-023-00282-7
Luo G, Ling N, Nannipieri P, Chen H, Raza W, Wang M, Guo S, Shen Q (2017) Long-term fertilisation regimes affect the composition of the alkaline phosphomonoesterase encoding microbial community of a vertisol and its derivative soil fractions. Biol Fertil Soils 53:375–388. https://doi.org/10.1007/s00374-017-1183-3
Luo G, Sun B, Li L, Li M, Liu M, Zhu Y, Guo S, Ling N, Shen Q (2019) Understanding how long-term organic amendments increase soil phosphatase activities: Insight into phoD- and phoC-harboring functional microbial populations. Soil Biol Biochem 139:107632. https://doi.org/10.1016/j.soilbio.2019.107632
Ma L, Zhu E, Jia J, Wang Y, Kang E, Yi W, Jiang Z, Dai G, Feng X (2024) Does microbial carbon use efficiency differ between particulate and mineral-associated organic matter? Funct Ecol 38:1510–1522. https://doi.org/10.1111/1365-2435.14569
MacDonald GK, Bennett EM, Potter PA, Ramankutty N (2011) Agronomic phosphorus imbalances across the world's croplands. Proc Natl Acad Sci USA 108(7):3086–3091
Maghsoodi MR, Ghodszad L, Asgari Lajayer B (2020) Dilemma of hydroxyapatite nanoparticles as phosphorus fertilizer: Potentials, challenges and effects on plants. Environ Technol Innov 19:100869. https://doi.org/10.1016/j.eti.2020.100869
Maranguit D, Guillaume T, Kuzyakov Y (2017) Effects of flooding on phosphorus and iron mobilization in highly weathered soils under different land-use types: Short-term effects and mechanisms. CATENA 158:161–170. https://doi.org/10.1016/j.catena.2017.06.023
Martinengo S, Schiavon M, Santoro V, Said-Pullicino D, Romani M, Miniotti EF, Celi L, Martin M (2023) Assessing phosphorus availability in paddy soils: the importance of integrating soil tests and plant responses. Biol Fertil Soils 59:391–405. https://doi.org/10.1007/s00374-023-01714-8
McDowell RW, Noble A, Pletnyakov P, Haygarth PM (2023) A Global Database of Soil Plant Available Phosphorus. Sci Data 10:125. https://doi.org/10.1038/s41597-023-02022-4
McLaren TI, Verel R, Frossard E (2019) The structural composition of soil phosphomonoesters as determined by solution 31P NMR spectroscopy and transverse relaxation (T2) experiments. Geoderma 345:31–37. https://doi.org/10.1016/j.geoderma.2019.03.015
McLaren TI, Smernik RJ, McLaughlin MJ, Doolette AL, Richardson AE, Frossard E (2020) Chapter Two - The chemical nature of soil organic phosphorus: a critical review and global compilation of quantitative data. In: Sparks DL (ed) Advances in Agronomy. Academic Press. https://doi.org/10.1016/bs.agron.2019.10.001
Missong A, Bol R, Willbold S, Siemens J, Klumpp E (2016) Phosphorus forms in forest soil colloids as revealed by liquid-state

31P-NMR. J Plant Nutr Soil Sci 179:159–167. https://doi.org/10.1002/jpln.201500119
Missong A, Bol R, Nischwitz V, Krüger J, Lang F, Siemens J, Klumpp E (2018) Phosphorus in water dispersible-colloids of forest soil profiles. Plant Soil 427:71–86. https://doi.org/10.1007/s11104-017-3430-7
Missong A, Holzmann S, Bol R, Nischwitz V, Puhlmann H, Wilpert vK, Siemens J, Klumpp E (2018) Leaching of natural colloids from forest topsoils and their relevance for phosphorus mobility. Sci Total Environ 634:305–315. https://doi.org/10.1016/j.scitotenv.2018.03.265
Mogollón JM, Beusen AHW, van Grinsven HJM, Westhoek H, Bouwman AF (2018) Future agricultural phosphorus demand according to the shared socioeconomic pathways. Glob Environ Chang 50:149–163. https://doi.org/10.1016/j.gloenvcha.2018.03.007
Nahidan S, Ghasemzadeh M (2022) Biochemical phosphorus transformations in a calcareous soil as affected by earthworm, cow manure and its biochar additions. Appl Soil Ecol 170:104310. https://doi.org/10.1016/j.apsoil.2021.104310
Nesme T, Metson GS, Bennett EM (2018) Global phosphorus flows through agricultural trade. Glob Environ Chang 50:133–141. https://doi.org/10.1016/j.gloenvcha.2018.04.004
Nunes RdS, de Sousa DMG, Goedert WJ, de Oliveira LEZ, Pavinato PS, Pinheiro TD (2020) Distribution of soil phosphorus fractions as a function of long-term soil tillage and phosphate fertilization management. Front Earth Sci 8. https://doi.org/10.3389/feart.2020.00350
O'Callaghan M, Ballard RA, Wright D (2022) Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. Soil Use Manag 38(3):1340–1369
Poblete-Grant P, Suazo-Hernández J, Condron L, Rumpel C, Demanet R, Malone SL, Mora MdLL (2020) Soil available P, soil organic carbon and aggregation as affected by long-term poultry manure application to Andisols under pastures in Southern Chile. Geoderma Reg 21:e00271. https://doi.org/10.1016/j.geodrs.2020.e00271
Pradel M, Aissani L (2019) Environmental impacts of phosphorus recovery from a "product" Life Cycle Assessment perspective: Allocating burdens of wastewater treatment in the production of sludge-based phosphate fertilizers. Sci Total Environ 656:55–69. https://doi.org/10.1016/j.scitotenv.2018.11.356
Prietzel J, Harrington G, Hiesch S, Klysubun W (2024) XANES spectroscopy proofs pH-dependent P sorption partitioning to Fe oxyhydroxides versus montmorillonite in acidic soils. J Plant Nutr Soil Sci :1–14. https://doi.org/10.1002/jpln.202400258
Raymond N, Kopittke PM, Wang E, Lester D, Bell MJ (2021a) Does the APSIM model capture soil phosphorus dynamics? A case study with Vertisols. Field Crop Res 273:108302. https://doi.org/10.1016/j.fcr.2021.108302
Raymond NS, Gómez-Muñoz B, van der Bom FJT, Nybroe O, Jensen LS, Müller-Stöver DS, Oberson A, Richardson AE (2021b) Phosphate-solubilising microorganisms for improved crop productivity: a critical assessment. New Phytol 229:1268–1277. https://doi.org/10.1111/nph.16924
Reitzel K, Bennett WW, Berger N, Brownlie WJ, Bruun S, Christensen ML, Cordell D, van Dijk K, Egemose S, Eigner H, Glud RN, Grönfors O, Hermann L, Houot S, Hupfer M, Jacobs B, Korving L, Kjærgaard C, Liimatainen H, Van Loosdrecht MCM, Macintosh KA, Magid J, Maia F, Martin-Ortega J, McGrath J, Meulepas R, Murry M, Neset T-S, Neumann G, Nielsen UG, Nielsen PH, O'Flaherty V, Qu H, Santner J, Seufert V, Spears B, Stringer LC, Stutter M, Verburg PH, Wilfert P, Williams PN, Metson GS (2019) New Training to Meet the Global Phosphorus Challenge. Environ Sci Technol 53:8479–8481. https://doi.org/10.1021/acs.est.9b03519
Reusser JE, Verel R, Zindel D, Frossard E, McLaren TI (2020) Identification of lower-order inositol phosphates (IP5 and IP4) in soil extracts as determined by hypobromite oxidation and solution 31P NMR spectroscopy. Biogeosciences 17:5079–5095. https://doi.org/10.5194/bg-17-5079-2020
Reusser JE, Piccolo A, Vinci G, Savarese C, Cangemi S, Cozzolino V, Verel R, Frossard E, McLaren TI (2023) Phosphorus species in sequentially extracted soil organic matter fractions. Geoderma 429:116227. https://doi.org/10.1016/j.geoderma.2022.116227
Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D, Petri S, Porkka M, Rahmstorf S, Schaphoff S, Thonicke K, Tobian A, Virkki V, Wang-Erlandsson L, Weber L, Rockström J (2023) Earth beyond six of nine planetary boundaries. Sci Adv 9:eadh2458. https://doi.org/10.1126/sciadv.adh2458
Roswall T, Lucas E, Yang Y-Y, Burgis C, Scott ISPC, Toor GS (2021) Hotspots of legacy phosphorus in agricultural landscapes: revisiting water-extractable phosphorus pools in soils. Water 13:1006
Sakhno Y, Miletto I, Paul G, Jaisi DP (2022) A novel route to enhance the dissolution of apatite: Structural incorporation of hydrogen phosphate. NanoImpact 28:100422. https://doi.org/10.1016/j.impact.2022.100422
Santoro V, Martin M, Persson P, Lerda C, Said-Pullicino D, Magnacca G, Celi L (2019) Inorganic and organic P retention by coprecipitation during ferrous iron oxidation. Geoderma 348:168–180. https://doi.org/10.1016/j.geoderma.2019.04.004
Sharma R, Bell RW, Wong MTF (2017) Dissolved reactive phosphorus played a limited role in phosphorus transport via runoff, throughflow and leaching on contrasting cropping soils from southwest Australia. Sci Total Environ 577:33–44. https://doi.org/10.1016/j.scitotenv.2016.09.182
Sharpley A, Jarvie HP, Buda A, May L, Spears B, Kleinman P (2013) Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment. J Environ Qual 42:1308–1326. https://doi.org/10.2134/jeq2013.03.0098
Siegenthaler MB, McLaren TI, Frossard E, Tamburini F (2024) Dual isotopic (33P and 18O) tracing and solution 31P NMR spectroscopy to reveal organic phosphorus synthesis in organic soil horizons. Soil Biol Biochem 197:109519. https://doi.org/10.1016/j.soilbio.2024.109519
Simonsson M, Östlund A, Renfjäll L, Sigtryggsson C, Börjesson G, Kätterer T (2018) Pools and solubility of soil phosphorus as affected by liming in long-term agricultural field experiments. Geoderma 315:208–219. https://doi.org/10.1016/j.geoderma.2017.11.019
Solhtalab M, Klein AR, Aristilde L (2021) Hierarchical reactivity of enzyme-mediated phosphorus recycling from organic mixtures by aspergillus niger phytase. J Agric Food Chem 69:2295–2305. https://doi.org/10.1021/acs.jafc.0c05924
Spohn M (2016) Element cycling as driven by stoichiometric homeostasis of soil microorganisms. Basic Appl Ecol 17:471–478. https://doi.org/10.1016/j.baae.2016.05.003
Spohn M (2020a) Increasing the organic carbon stocks in mineral soils sequesters large amounts of phosphorus. Glob Change Biol 26(8):4169–4177

Spohn M (2020b) Phosphorus and carbon in soil particle size fractions: A synthesis. Biogeochemistry 147:225–242. https://doi.org/10.1007/s10533-019-00633-x

Spohn M, Kuzyakov Y (2013) Phosphorus mineralization can be driven by microbial need for carbon. Soil Biol Biochem 61:69–75. https://doi.org/10.1016/j.soilbio.2013.02.013

Spohn M, Schleuss P-M (2019) Addition of inorganic phosphorus to soil leads to desorption of organic compounds and thus to increased soil respiration. Soil Biol Biochem 130:220–226. https://doi.org/10.1016/j.soilbio.2018.12.018

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: 1259855. https://doi.org/10.1126/science.1259855

Stutter MI, Shand CA, George TS, Blackwell MSA, Dixon L, Bol R, MacKay RL, Richardson AE, Condron LM, Haygarth PM (2015) Land use and soil factors affecting accumulation of phosphorus species in temperate soils. Geoderma 257–258:29–39. https://doi.org/10.1016/j.geoderma.2015.03.020

Toor GS, Sims JT (2016) Managing legacy and new sources of phosphorus to reduce leaching in Mid-Atlantic soils. Crops Soils 49(5):40–47

Tosun G, Sakhno Y, Jaisi DP (2021) Synthesis of Hydroxyapatite Nanoparticles from Phosphorus Recovered from Animal Wastes. ACS Sustain Chem Eng 9:15117–15126. https://doi.org/10.1021/acssuschemeng.1c01006

Touhami D, McDowell RW, Condron LM, Bouray M (2022) Nitrogen fertilization effects on soil phosphorus dynamics under a grass-pasture system. Nutr Cycl Agroecosyst 124:227–246. https://doi.org/10.1007/s10705-021-10191-0

van der Bom FJT, McLaren TI, Doolette AL, Magid J, Frossard E, Oberson A, Jensen LS (2019) Influence of long-term phosphorus fertilisation history on the availability and chemical nature of soil phosphorus. Geoderma 355:113909. https://doi.org/10.1016/j.geoderma.2019.113909

van der Bom FJT, Kopittke PM, Raymond NS, Sekine R, Lombi E, Mueller CW, Doolette CL (2022) Methods for assessing laterally-resolved distribution, speciation and bioavailability of phosphorus in soils. Rev Environ Sci Bio/technol 21:53–74. https://doi.org/10.1007/s11157-021-09602-z

Voegelin A, Senn A-C, Kaegi R, Hug SJ, Mangold S (2013) Dynamic Fe-precipitate formation induced by Fe(II) oxidation in aerated phosphate-containing water. Geochim Cosmochim Acta 117:216–231. https://doi.org/10.1016/j.gca.2013.04.022

Vogel C, Rivard C, Tanabe I, Adam C (2016) Microspectroscopy – Promising Techniques to Characterize Phosphorus in Soil. Commun Soil Sci Plant Anal 47:2088–2102. https://doi.org/10.1080/00103624.2016.1228942

von Sperber C, Pistocchi C, Weiler M, Tamburini F (2023) Oxygen isotope ratios of phosphates in the soil-plant system: Limitations and future developments. Eur J Soil Sci 74(6):e13434

Vos HMJ, Hiemstra T, Prado Lopez M, van Groenigen JW, Voegelin A, Mangold S, Koopmans GF (2022) Earthworms affect reactive surface area and thereby phosphate solubility in iron-(hydr)oxide dominated soils. Geoderma 428:116212. https://doi.org/10.1016/j.geoderma.2022.116212

Wan B, Yan Y, Liu F, Tan W, He J, Feng X (2016) Surface speciation of myo-inositol hexakisphosphate adsorbed on TiO2 nanoparticles and its impact on their colloidal stability in aqueous suspension: A comparative study with orthophosphate. Sci Total Environ 544:134–142. https://doi.org/10.1016/j.scitotenv.2015.11.157

Wang J, Wu Y, Zhou J, Bing H, Sun H (2016) Carbon demand drives microbial mineralization of organic phosphorus during the early stage of soil development. Biol Fertil Soils 52:825–839. https://doi.org/10.1007/s00374-016-1123-7

Wang C, Thielemann L, Dippold MA, Guggenberger G, Kuzyakov Y, Banfield CC, Ge T, Guenther S, Bork P, Horn MA, Dorodnikov M (2022) Can the reductive dissolution of ferric iron in paddy soils compensate phosphorus limitation of rice plants and microorganisms? Soil Biol Biochem 168:108653. https://doi.org/10.1016/j.soilbio.2022.108653

Wasner D, Prommer J, Zezula D, Mooshammer M, Hu Y, Wanek W (2023) Tracing 33P-labelled organic phosphorus compounds in two soils: New insights into decomposition dynamics and direct use by microbes. Front Soil Sci 3. https://doi.org/10.3389/fsoil.2023.1097965

Wei X, Hu Y, Razavi BS, Zhou J, Shen J, Nannipieri P, Wu J, Ge T (2019) Rare taxa of alkaline phosphomonoesterase-harboring microorganisms mediate soil phosphorus mineralization. Soil Biol Biochem 131:62–70. https://doi.org/10.1016/j.soilbio.2018.12.025

Wei X, Hu Y, Cai G, Yao H, Ye J, Sun Q, Veresoglou SD, Li Y, Zhu Z, Guggenberger G, Chen X, Su Y, Li Y, Wu J, Ge T (2021) Organic phosphorus availability shapes the diversity of phoD-harboring bacteria in agricultural soil. Soil Biol Biochem 161:108364. https://doi.org/10.1016/j.soilbio.2021.108364

Werner F, Mueller CW, Thieme J, Gianoncelli A, Rivard C, Höschen C, Prietzel J (2017) Micro-scale heterogeneity of soil phosphorus depends on soil substrate and depth. Sci Rep 7:3203. https://doi.org/10.1038/s41598-017-03537-8

Wybrew A (2023) Huge mineral discovery in Norway could supply battery and solar panels for the next 50 years. Euronews. Euronews, https://www.euronews.com/green/2023/07/10/huge-mineral-discovery-in-norway-could-supply-battery-and-solar-panels-for-the-next-100-ye.

Xiong L, Wang P, Kopittke PM (2018) Tailoring hydroxyapatite nanoparticles to increase their efficiency as phosphorus fertilisers in soils. Geoderma 323:116–125. https://doi.org/10.1016/j.geoderma.2018.03.002

Yan Y, Wan B, Jiang R, Wang X, Wang H, Lan S, Zhang Q, Feng X (2023) Interactions of organic phosphorus with soil minerals and the associated environmental impacts: A review. Pedosphere 33:74–92. https://doi.org/10.1016/j.pedsph.2022.08.001

Yang X, Post WM, Thornton PE, Jain A (2013) The distribution of soil phosphorus for global biogeochemical modeling. Biogeosciences 10:2525–2537. https://doi.org/10.5194/bg-10-2525-2013

Yang X, Thornton P, Ricciuto D, Wang Y, Hoffman F (2023) Global evaluation of terrestrial biogeochemistry in the Energy Exascale Earth System Model (E3SM) and the role of the phosphorus cycle in the historical terrestrial carbon balance. Biogeosciences 20:2813–2836. https://doi.org/10.5194/bg-20-2813-2023

Yaseen R, Amin BH (2021) The use of phosphorus nanoparticles synthesized by rhizospheric fungus Aspergillius fumigatus as a nanofertilizer for flax plant. Malays J Microbiol 17(3). https://doi.org/10.21161/mjm.200852

Authors and Affiliations

Emileigh R. Lucas[1] · **Nhiem D. Nguyen**[2] · **Luisella Celi**[3] · **Leo M. Condron**[4] · **Tandra D. Fraser**[5] · **Timothy S. George**[6] · **María de La Luz Mora**[7] · **Nelly S. Raymond**[8]

✉ Timothy S. George
tim.george@hutton.ac.uk

✉ Nelly S. Raymond
nr@ign.ku.dk

Emileigh R. Lucas
erosso@umd.edu

Nhiem D. Nguyen
nhiem.nguyenduy@usys.ethz.ch

Luisella Celi
luisella.celi@unito.it

Leo M. Condron
leo.condron@lincoln.ac.nz

Tandra D. Fraser
tandra.fraser@agr.gc.ca

María de La Luz Mora
mariluz.mora@ufrontera.cl

1 Department of Environmental Science and Technology, University of Maryland, College Park, MD 21043, USA

2 Department of Environmental Systems Science, ETH Zürich, CH-8315 Lindau, Switzerland

3 Department of Agricultural, Forest and Food Sciences, Turin University, 10095 Grugliasco, Italy

4 Faculty of Agriculture and Life Sciences, Lincoln University, Christchurch 7647, New Zealand

5 Agriculture and Agri-Food Canada, Charlottetown, PE C1A4N6, Canada

6 The James Hutton Institute, Invergowrie, Dundee DD2 5DA, UK

7 Center of Plant Soil Interaction and Natural Resources Biotechnology, Scientific and Technological Bioresource Nucleus (BIOREN-UFRO), Universidad de La Frontera, P.O. Box 54-D, 4811230 Temuco, Chile

8 Department of Geosciences and Natural Resource Management, Geograhy, People and Processes,, University of Copenhagen, Øster Voldgade 10, 1350, Copenhagen, Denmark