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Editorial: Phosphorus along the soil-freshwater-ocean continuum, Volume II

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Editorial on the Research Topic
Phosphorus along the soil-freshwater-ocean continuum, Volume II

Phosphorus (P) cycling along the soil-freshwater-ocean continuum is complex. As noted for the original version of this Frontiers Research Topic (Cade-Menun et al., 2019), there is a P paradox (Lougheed, 2011), whereby P concentrations can limit growth in freshwater, oceans and soils, but may be in excess in other environments, such as heavily fertilized agricultural soils. It is widely recognized that P cycles both geochemically and biologically/biochemically, but these cycles are often studied separately and both have been limited by methodological or other constraints, such as P concentrations below instrument detection limits (Kruse et al., 2015; Cade-Menun et al., 2019; Duhamel et al., 2021). However, ensuring adequate soil P for crop production while minimizing water quality degradation requires an in-depth understanding of all aspects of P cycling, which in turn demands an international and interdisciplinary approach. This second edition of the *Phosphorus Along the Soil-Freshwater-Ocean Continuum* Research Topic aims to address knowledge gaps in P biogeochemistry along this continuum, with papers by 38 authors from Asia, Europe and North America on P research in soils, lakes, and oceans.

In many agricultural soils, P fertilization is needed to maintain or enhance crop yields. The majority of commercial chemical fertilizers are produced from mined phosphate rocks, which are a non-renewable resource (Lougheed, 2011). Agricultural intensification starting in the mid 1900's in the developed world often included high rates of P application of chemical fertilizers, leading to very high soil P concentrations in many soils globally (Withers et al., 2019). However, in most soils this residual or "legacy" P from previous fertilizer applications does not remain readily available to crops in subsequent years, but is converted to less-soluble P pools through biochemical and geochemical processes. Concerns about high legacy soil P concentrations, and their impact on the water quality of receiving watercourses, coupled with rapidly reducing rock phosphate reserves are now driving research to find alternatives to chemical P fertilization, including reducing or stopping P fertilizer applications to draw down soil legacy P, or using alternative combinations of crops or agricultural systems to make less-soluble P pools more readily available to crops (Withers et al., 2019). In calcareous soils from China without supplemental P fertilizer, Liu et al. grew maize and soybean together and separately and evaluated plant P uptake, soil P pools by sequential fractionation, soil P enzyme activities and the soil microbial community. Their results show that growing these two crops together (intercropping) enhanced plant P uptake and recovery of soil legacy P by altering geochemical and biochemical aspects of P cycling, compared to growing each crop separately. Also in China, but in acidic soils, Wang et al. studied P cycling in an integrated organic ecological farming system that combined rice production with aquaculture (fish and duck production, RDF) in the same field without P fertilization, and compared it to a rice-vegetable (pepper) production system (RVS) and conventional rice production (CRS); rice received chemical P fertilizer in the RVS and CRS systems. After four years, soil P geochemical parameters (concentrations of total, organic and soluble P) and biochemical parameters (microbial P, P enzyme activities) were greater with RDF than the other cropping systems, indicating enhanced P availability to rice without chemical P fertilization in the RDF system.

While alternative cropping systems can reduce the need for P fertilizers, P losses from high-P soils will remain a concern until soil legacy P concentrations are reduced, which can take many years depending on the crop, soil and legacy P concentrations (Withers et al., 2019). One potential solution is to interrupt P transfer from agricultural fields to nearby water bodies. In a study in the United States, Steinman et al. investigated the use of filters made from iron slag, a calcium-rich waste material from the steel industry with a high capacity to bind P, at the outflow of agricultural tile lines prior to water flow to surface waters at three sites. Bimonthly sampling showed that total P in tile drain effluent was reduced up to 76.5% by filters at all sites, while dissolved molybdate-reactive phosphate was reduced by 7.4% at one site and up to 57.9% at the other two sites, although P removal decreased over time. These results indicate that slag filters in combination with other management practices to reduce loss can play an important localized role in reducing P in watersheds.

Moving from soils to water, Wauchope-Thompson et al. studied lake sediments, Defforey et al. investigated ocean sediments, and Filella et al. investigated marine organisms. Freshwater lakes are widely used globally for recreation and drinking water, and P release from sediments can contribute to eutrophication. As such, understanding the factors controlling sediment P release is essential to manage water quality. In a chain of hardwater lakes in Canada, Wauchope-Thompson et al. used ^{31}P nuclear magnetic resonance spectroscopy (P-NMR) to identify and quantify sediment P compounds and relate them to geochemical parameters. Their results showed that geochemical factors differed among these lakes; however, P immobilized by bacteria and algae was an important sediment pool across all lakes. In samples from the North Atlantic Gyre, analyzed by P-NMR and metagenomics, the results of Defforey et al. suggest that deep sedimentary subseafloor microorganisms are using organic P and organic carbon (C) for growth in an environment depleted in P and C. This is consistent with the results of incubation experiments by Filella et al. showing that nitrogen-fixing marine organisms from depleted and moderate P ocean regions were able to use organic P as a P source and P-anhydrides (polyphosphates) as a potential energy source, although there were differences among species. These aquatic studies suggest interesting directions for future research, where P biogeochemistry is poorly understood relative to terrestrial ecosystems.

The papers assembled in this Research Topic cover the soil-freshwater-ocean continuum, providing current and interdisciplinary information to support sustainable P use in agriculture while minimizing P transfer and concomitant water quality issues, as well as novel insights into P cycling in lakes and oceans.

Author contributions

All authors listed have made a substantial, direct and intellectual contribution to the work, and have approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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