



Recognizing the role of soil organic phosphorus in soil fertility and water quality



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ABSTRACT

Despite the large scale implementation of conservation schemes aimed at reducing phosphorus (P) loss from agricultural lands, significant improvements in water quality at the watershed scale remain elusive. Changes in land management influence the speciation and cycling of P within soils and recent promotion of conservation practices to improve soil health revolve around increasing soil carbon stores, thereby increasing the pool of soil organic P. Adopting conservation tillage, use of cover crops, strategic crop rotations, and use of manures can increase organic P by 3–180% and microbial biomass pool of P by 30–240%. The role of organic P in soil fertility has been largely ignored in current soil testing methods, which in many cases may explain the lack of crop response to recommended fertilizer inputs in a growing number of trials. Conversely, soil organic P is gaining recognition as a potential source of P to runoff. This review explores the impact of adopting widely promoted “soil health” conservation practices on the speciation and cycling of soil P, with particular focus on the organic pool and the biotic processes regulating its accumulation and mobilization. Large stores of organic P exist in arable and grassland soils and strategies that increase the plant availability of these P stores could reduce the reliance on external P inputs, creating more sustainable P use. However, more detailed, mechanistic knowledge of soil organic P cycling, especially through the microbial biomass, is required. Furthermore, caution is needed to ensure that increasing the availability of organic P does not increase P loss in runoff effectively turning P sinks into P sources.

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1. Introduction

The accelerated eutrophication of freshwaters and to a lesser extent some coastal waters is primarily driven by phosphorus (P) inputs. While efforts to identify and limit point source inputs of P to surface waters have seen some success, nonpoint sources have remained elusive and more difficult to identify, quantify, target, and remediate. Thus, attention has focused more on nonpoint source reduction, particularly the role of agriculture. This attention has heightened over the last 10 years due to the fact that impaired water quality has not seen as great an improvement as expected after adoption of conservation practices and recent high profile harmful algal bloom outbreaks (Sharpley et al., 2013; Smith et al., 2015).

In addition, an inability to meet targeted nutrient load reductions in large basins, such as Chesapeake Bay, Lake Erie, and Mississippi River, has brought into question the effectiveness of current and future conservation strategies designed to mitigate

such loads. The concerns with increased P runoff from certain agricultural operations are counter-intuitive to the fact that economically extractable supplies of phosphate rock are limited both in amount and geographically. While the geoeconomics of fertilizer supply, demand, and use are complex and dependent on highly variable and interdependent factors, the bottom line is that we need to adopt more sustainable P use and recycling strategies sooner rather than later.

The above issues related to P management in agricultural production systems, all act to reinforce the importance of carefully managing P resources more than ever. In part response to this, conservation practice implementation has been promoted by several State and Federal initiatives in the U.S. Conservation practices for agriculture and nutrient management and structural practices that enhance resources-saving agriculture, strive to achieve acceptable profits with high sustained production levels while concurrently conserving the environment (Food and Agriculture Organization, 2007). For instance, the Healthy Mississippi Basin River Initiative (MRBI – <http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=stelprdb1048200>), the Chesapeake Bay Watershed Initiative, and the Lake Erie Basin

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International Joint Commission made available about US\$320, US\$10, and US\$2 million, respectively, to farmers for adoption of conservation practices aimed at reducing nutrient runoff (Great Lakes Restoration, 2014; U.S. Department of Agriculture – Natural Resources Conservation Service, 2009, 2011, 2015). These funds are administered mainly through the Environmental Quality Incentives Program (EQIP), a voluntary program that provides financial and technical assistance to farmers to help plan and implement conservation practices that address natural resource concerns (U.S. Department of Agriculture – Natural Resources Conservation Service, 2014). However, there has been a less than expected improvement in water quality despite these conservation efforts due in part to the legacies of past management (Jarvie et al., 2013; Kronvang et al., 2005; Sharpley et al., 2013).

The limited water quality response to conservation practice implementation can also be attributed to changes in agricultural management, such as reduced tillage and use of organic fertilizers, such as animal manures, which can impact soil P cycling, dynamics, P mobilization, and ultimately the transfer of P to surface and subsurface water flows. For instance, several studies have found a limited crop response to fertilizer P application or at least a lower than expected response than was estimated from current soil test P methods (Dodd and Mallarino, 2005; Heckman et al., 2006; Slaton et al., 2006). This may be due to several factors that include:

- few attempts to update soil test P – crop P uptake response relationships in the field over the last two decades with general cutbacks in soil fertility – crop response research,
- the introduction and use by farmers of new crop varieties that may more efficiently absorb soil P and from greater depths in the profile, than earlier crop varieties,
- a change in soil management that can result in a shift in residual soil P forms and fractions, which may not be as readily extracted by existing soil test P methodologies.

The U.S. along with other countries have seen a general move to agricultural production systems with fewer tillage operations (e.g., no-till, reduced-till, and conservation-tillage), with a managed build-up of soil organic matter that increases soil aggregate stability, degree and extent of infiltration, and soil water retention and holding capacity. Much of the resource management shift is captured in the recent, widely promoted “soil health” initiative and its overall benefit to agro-ecosystem health, along with soil and water quality benefits (Karlen et al., 2014; Singh and Ryan, 2015; Stika, 2013).

All the above factors have combined to increase the importance of soil organic matter in general soil management, soil productivity, and potentially the impact of soil management on water quality. This review explores those land management changes promoted under the Soil Health Initiative, the resulting changes in soil processes, how they impact water quality, and how farmers might best manage soil to enhance the benefits and avoid the unintended consequences of increasing organic matter content and soil organic P cycling.

2. Role of soil organic P in soil fertility

In most soils, organic P can comprise 30–65% of total P (TP) (Condon et al., 2005). Furthermore, in a wide range of agricultural soils from medium to long-term field trials (5–25 years) with varying P inputs, 5–52% of total P (TP) was found in the labile and moderately labile organic P pools, as determined by Hedley fractionation (NaHCO₃-organic P and NaOH-organic P) (Negassa and Leinweber, 2009), highlighting the potential role of organic P in plant nutrition. In order to utilize the soil organic P fraction to its

full agricultural potential, we first need to understand the speciation of soil organic P and the processes involved in its accumulation and mobilization.

Orthophosphate monoesters and diesters make up the majority of organic P agricultural soils, while phosphonates and polyphosphates can be present in small quantities (Condon et al., 2005). Phosphate monoesters can be classed into two groups, labile monoesters, consisting of mononucleotides and are the breakdown products of DNA and RNA, and inositol phosphates, in particular, inositol hexisphosphate (IHP, also known as phytate-P), which is a storage complex found in plant cells. Phosphate diesters mainly consist of nucleic acids in the form of DNA and RNA and originate from microbial cells and plant detritus. Phosphonates and polyphosphates also originate from the microbial biomass, and along with phosphate diesters, their detection in soil is considered to be an indicator of microbial P cycling (Turner et al., 2003).

Characterization of soil P forms range in analytical complexity. The simplest and most widely applied method is the use of sequential fractionation. Soil is extracted with increasingly aggressive chemicals designed to release specific groups of chemicals (e.g. Chang and Jackson, 1957; Hedley et al., 1982). The contribution of organic P forms can then be determined as the difference between molybdate reactive P in the extractant before and after total P determination via digestion. While such methods provide useful information they are unable to characterize individual organic P compounds and provide no information on their bioavailability. Recent advances in synchrotron based techniques, such as X-ray adsorption near edge structure (XANES) spectroscopy, have greatly advanced the characterization of inorganic P forms (e.g. Beauchemin et al., 2003) but has been less successful for organic P species (Cade-Menun and Liu, 2013). Solution ³¹P NMR spectroscopy remains the main method for determination of organic P species in soils and has greatly expanded the knowledge of soil organic P chemistry. However, there are challenges and limitations of this technique. Cade-Menun and Liu (2013) recently reviewed these challenges, which include (i) standardization of soil preparation, extraction methods, sample preparation and NMR analysis parameters; (ii) the potential degradation of certain organic P species, especially diesters, during analysis; and (iii) peak broadening due to extraction of paramagnetic ions present in soils, such as iron (Fe) and manganese (Mn). The authors discuss recent advances to improve the technique and recommendations for analytical protocols. Following these recommendations, coupled with recent advances in developing a spectral library of organic P forms (Cade-Menun, 2015), will significantly advance our understanding of soil organic P.

Plants take up P through their roots in the form of orthophosphate ions (H₂PO₄⁻ and HPO₄²⁻). The concentration of these ions in soil solution is governed by complex interactive solid and liquid phase, chemical and biological processes influenced by large number of environmental factors such as temperature and soil moisture (Pierzynski and McDowell, 2005). Similarly to soil inorganic P, organic P can be considered to exist in two pools (Müller and Bünemann, 2014) as depicted in Fig. 1, a rapidly cycling pool (fast organic P) and a more slowly cycling pool (slow organic P).

Fast organic P consists of P contained within the microbial biomass, which is in constant flux, immobilizing P from the soil solution during microbial growth and resupplying P to the soil solution following cell death. The microbial biomass can represent a significant pool of P and has been found to constitute 2.0–7.5% of TP in the topsoil of temperate, fertilized pastures and 0.7–2.5% of TP in crop soils (Oberson and Joner, 2005). The release of P to the soil solution occurs via three different processes; (i) mineralization, this occurs when the readily available carbon (C) stores are depleted and cells die (Oehl et al., 2001); (ii) rapid release of a pulse of P following cell lysis in response to a change in environmental

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