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Review

# Using organic phosphorus to sustain pasture productivity: A perspective

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## ABSTRACT

Organic phosphorus (P) in grazed pastures/grasslands could sustain production systems that historically relied on inorganic P fertiliser. Interactions between inorganic P, plants and soils have been studied extensively. However, less is known about the transformation of organic P to inorganic orthophosphate. This paper investigates what is known about organic P in pasture/grassland soils used for agriculture, as well as the research needed to utilise organic P for sustainable plant production.

Organic P comprises >50% of total soil P in agricultural systems depending on location, soil type and land use. Organic P hydrolysis and release of orthophosphate by phosphatase enzymatic activity is affected by a range of factors including: (a) the chemical nature of the organic P and its ability to interact with the soil matrix; (b) microorganisms that facilitate mineralisation; (c) soil mineralogy; (d) soil water electrolytes; and (e) soil physicochemical properties.

Current biogeochemical knowledge of organic P processing in soil limits our ability to develop management strategies that promote the use of organic P in plant production. Information is particularly needed on the types and sources of organic P in grassland systems and the factors affecting the activity of enzymes that mineralise organic P. Integrated approaches analysing the soil matrix, soil water and soil biology are suggested to address this knowledge gap.

**Contents**

## 1. Introduction

Phosphorus (P) is an essential input for many agricultural production systems. For example, the productivity of most Australian soils in their native state was limited by P and nitrogen (N) availability (Sale, 1992). Through the use of P fertilisers, productive pasture-based grazing systems have been developed in which legumes, predominantly introduced clovers, fix atmospheric N, helping to rectify both P and N

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limitations (Magid et al., 1996). While some recent studies suggest that the need for P fertilisers has diminished, especially in the more intensive systems (Condron, 2004; Gourley et al., 2012), ongoing P additions are often required to sustain optimal production (Frossard et al., 2000). In most instances the use of P remains inefficient and there is clear need to increase P-use efficiency (Burkitt et al., 2002; Haygarth et al., 2013; Richardson et al., 2011; Simpson et al., 2011).

Inorganic P in the form of orthophosphate is a primary constituent of most P fertilisers. When added to soil, orthophosphate is either sequestered into forms that are not immediately available to plants (Engelstad and Terman, 1980; McLaughlin et al., 2011) or extracted from soil water and incorporated into plant and microbial biomass. In grazing systems, P is further transferred into animal biomass and may be exported from farms as animal (or plant) product. Phosphorus in biomass is otherwise returned to the soil when plant and animal biomass, and their wastes, are recycled and decomposed.

Decomposing plant and animal products, along with the soil microflora and fauna that undertake such decomposition, provide a significant store and a source of organic P, which commonly comprises >50% of total soil P in agricultural systems (Stutter et al., 2012), and inorganic P (Tisdale et al., 1985). In grazed pastures, up to 85% of the P taken up by plants is returned to the soil in dung. Such deposits can represent P inputs of 35 and 280 kg P $ha^{-1}$ annually for individual sheep and cattle, respectively (Haynes and Williams, 1993). Importantly, P is often returned to soil at a location far removed from where it was consumed, so stock transfer represents a loss in pastoral systems (Kemp et al., 2000) that can account for approximately 5% of P fertiliser inputs (Simpson et al., 2011).

Despite predictions of future P shortages (Cordell et al., 2009), there appears to be no immediate concerns regarding the supply of P fertilisers (Heffer and Prud'homme, 2011). However, the offsite impacts of P derived from farmland (Schröder et al., 2010) and the susceptibility of the supply chain to short-term disruptions in nations supplying raw materials (i.e. Morocco) and associated market volatility, has increased scientific interest in accessing 'stored' organic P for plant production, thereby lowering the short to medium term (i.e. <10 year) need for continued P additions (Haygarth et al., 2013; Stutter et al., 2012).

An important consideration for more sustainable use of world P reserves and agriculture production is whether the productivity of pasture-based grazing systems can be sustained by greater utilisation of soil organic P if fertiliser applications are curtailed? In this paper we consider the forms of organic P in pasture soils and factors that regulate their bio-availability, with an emphasis on phosphomonoesters, the singly most abundant form of organic P. In this context we use the term "pasture" to refer to native or introduced grass species that are grazed as part of an agricultural production system established through the use of P amendments. Our aim is to identify gaps in knowledge that need to be addressed in order to optimise the use of organic P for pasture production, particularly in Australia and New Zealand.

## 2. Forms of organic phosphorus in pasture soils

Orthophosphate, the predominant form of inorganic P in soil, can be derived from dissolution of primary P containing minerals such as apatite, through the application of mineral P fertilisers or by mineralisation of organic forms of P by microorganisms (Frossard et al., 2000; Stewart and Tiessen, 1987). Other forms of inorganic P commonly found in soils include pyrophosphate and polyphosphates which may be associated with high levels of fungal activity (Bunemann et al., 2008; Makarov et al., 2005). Organic P on the other hand is derived mainly from biological processes involving assimilation of orthophosphate and subsequent release as microbial, animal and plant materials mature and decompose (Condron et al., 2005).

Typical organic P compounds (Figs. 1 and 2) include: (i) phosphomonoesters (compounds with a single ester linkage to orthophosphate) such as the inositol phosphates; (ii) phosphodiesters (compounds with two ester linkages to orthophosphate) such as ribonucleic acid (RNA), deoxyribonucleic acid (DNA), lipoteichoic acid, phospholipid fatty acids (e.g. lecithin); and (iii) organic polyphosphates such as adenosine triphosphate. Phosphomonoesters and diesters, including specific compounds such as *myo*-inositol hexakisphosphate ($IP_6$) and DNA are routinely determined by extraction with a solution containing 0.25 M NaOH and 50 mM $Na_2EDTA$ and detection by solution $^{31}P$ nuclear magnetic resonance (NMR) spectroscopy (Cade-Menun, 2005; Condron et al., 2005; Murphy et al., 2009). Lower extractant concentrations may enhance phosphodiester recovery compared to phosphomonoester recovery (Turner, 2008), while hydrolysis of phosphodiesters during extraction and analysis has been shown to occur with manures and may bias quantitative assessments (Cade-Menun, 2011; Turner et al., 2003d).

Some characteristics of P in NaOH-EDTA extracts of selected pasture/grassland soils analysed using $^{31}P$ NMR are presented in Table 1. Collectively, phosphomonoesters and diesters predominate and comprise ~25% of the total P in pasture soils. The most prevalent phosphomonoester is *myo*-$IP_6$ (Fig. 2) (Cosgrove, 1980; Turner et al., 2002a), which contains six phosphate moieties and exists as nine possible stereoisomers, although only four of these appear to occur in the environment (Turner, 2007). The *myo*-$IP_6$ stereoisomer (also termed phytic acid (Shears and Turner, 2007)) is the most common form identified in soil, followed by the *scyllo*-, *neo*-, and D-*chiro*- forms (Turner, 2007; Turner et al., 2012). Phytic acid is synthesised by plants and is stored primarily in seeds where it can represent 60% to 80% of total plant P. Seeds of major cereal crops typically contain between 3.0 and 4.0 mg P/g dry weight (Raboy, 1997), so *myo*-$IP_6$ enters the soil through direct deposition of plant material (including seeds) (Noack et al., 2012), and from animal faeces, especially non-ruminant animals that consume feed containing $IP_6$ (Maguire et al., 2004). Non-ruminant animals do not produce gut phytase (i.e. phosphatase enzyme required for specific hydrolysis of $IP_6$) so a large proportion of $IP_6$ in the diet may be excreted in the faeces (Lei and Porres, 2007; Leytem et al., 2004; Turner, 2004; Turner and Leytem, 2004). Nonetheless the origins of phytate in soil remain to be more fully elucidated. For example, the presence of hexakisphosphates of *scyllo*-, *neo*-, and D-*chiro*-inositol stereoisomers in soil, which do not occur in higher plants, suggests that direct synthesis by microorganisms may be a significant source of inositol phosphates in some soils (Anderson, 1980; Turner, 2007).

From a production standpoint the considerable variability in organic P forms and their concentration in different soils and across farming systems (see Table 1), are both an opportunity and a concern. Moreover, the significance of organic P in plant nutrition is not reflected in agronomic soil tests which commonly involve dissolution and extraction of inorganic P and thus do not take adequate account of biological processes (Condron and Newman, 2011; Coventry et al., 2001; Murphy et al., 2009). Therefore, accessing the potential value of organic P as a 'fertiliser' resource requires a more comprehensive understanding of organic P transformations in soil and factors that affect its mineralisation, along with possibly new methods of assessing its role in plant nutrition in different pastoral systems. The variability in organic P between otherwise similarly managed sites also suggests that rates of organic P mineralisation vary widely and could be manipulated to release inorganic P for plant production.

## 3. Factors affecting organic phosphorus species and concentrations in pasture soils

Forms of organic P in soil are affected, or at least correlated with a wide range of soil geochemical, physical and climatic factors, including precipitation and temperature, which have major impacts on biological processes (Harrison, 1987). The proportion of phosphodiesters extracted from bulk soil and the clay fraction increased with mean annual precipitation and temperature in a study of pasture/grassland soils of western USA (Sumann et al., 1998). Phosphomonoester proportions in