

Efficient use of phosphorus in temperate grassland systems

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Abstract. Phosphorus (P) fertilisers are important for high production in many grassland systems. However, there are increasing environmental, economic and strategic issues associated with using P, which is a non-renewable and “effectively finite” global resource. We review the P balance of temperate pastures to identify the factors that contribute to inefficient P use and discuss ways to improve P use efficiency. The most immediate gains can be made by ensuring that pastures are not over-fertilised. Plants with low critical P requirements, particularly as a result of better root foraging, will be important. Root traits such as fine roots (root diameter), branching, length and root hairs, and mycorrhizal associations all contribute to improved root foraging; some are amenable to plant breeding. Plants that can “mine” sparingly-available P in soils by producing organic anions and phosphatases are also needed; as are innovations in fertiliser technology. Soil microorganisms play a crucial role in P acquisition by pastures but are not particularly amenable to management. Selection of pasture species for root characteristics offers a more realistic approach to improving P efficiency but progress, to date, has been minimal. Traditional plant breeding, augmented by marker assisted selection and interspecific hybridisation, are likely to be necessary for progress. Inevitably, P efficient pastures will be achieved most effectively by a combination of plant genetic, fertiliser innovation and management responses. Success will bring economic and environmental benefits from reduced P fertiliser use, with consequent benefits for global resource and food security.

Keywords: Phosphorus use efficiency, phosphorus balance/surplus, root foraging, phosphorus mining, fertilisers

Introduction

Phosphorus (P) fertilisers are now essential for supporting the present and future human population of the world. Currently, about 18 Tg of P per annum is used globally as fertiliser (Cordell and White 2011), with considerable disparity in usage across continents and between different agricultural systems. Additional P inputs to agriculture in the form of manure are probably about 8–17 Tg P/year (estimates vary considerably: Cordell *et al.* 2009; Bouwman *et al.* 2011).

Global rock phosphate “reserves” (high quality deposits) and P “resources” (phosphate rock deposits of lower quality or harder to access; not currently economic to mine) are extensive (van Kauwenburgh 2010). Although there is continuing debate about when the availability of P from global reserves will “peak” (Cordell and White 2011), a recent re-assessment of global P reserves indicates that they may be sufficient to meet global needs for up to 300–400 years at current rates of use (van Kauwenburgh 2010). Irrespective of this debate there are many reasons why it is important that P is used as effectively and efficiently as possible:

- High-quality phosphate rock reserves are non-renewable and, effectively, a finite resource.
- Access to high quality and affordable sources of P is critical for global food security. Presently, the underlying cost of P fertilisers is rising and has more than

doubled since 2000, and the world’s lower-grade P resources will be even more costly to extract.

- P fertiliser is a significant cost for many grazing farms in developed economies and it is often not affordable for smallholder farmers in P deficient areas of the developing world (*e.g.* sub Saharan Africa).
- P use in agriculture is often associated with P loss to the wider environment; even small losses of P to waterways can cause substantial environmental problems.

P balance of grassland farming systems

Under ideal circumstances, P inputs to agriculture would equal P outputs in products (*i.e.* no P surplus; phosphorus balance efficiency [PBE] = P output/P input = 100%). Examples of highly efficient use of P include wheat production on soil with a long history of fertiliser use (United Kingdom), PBE = 90% (Johnston and Syers 2009); extensive cattle production with P supplementation (Australia), PBE = ~100% (McIvor *et al.* 2011). However, high apparent PBE can also be achieved by using relatively poor practices. For example, farms on low P soils that use minimal or no P fertiliser and have relatively low production will achieve a high PBE. PBE may even exceed 100% for very low input farms, indicating unsustainable mining of soil P resources (Burkitt *et al.* 2007).

When P fertilisers are being used in productive agriculture, it is more common that significant P surpluses

are observed (e.g. Bouwman *et al.* 2009; Weaver and Wong 2011). For example, in farming systems in Australia, PBE's reported by Weaver and Wong (2011) reflect significant P surpluses (*i.e.* median PBE = 48% for cropping, 29% for dairy, 11-19% for sheep/beef grazing). The ranges in PBE for every enterprise type, however, were very large and reflect a wide range in production goals, fertiliser and management practices. P surpluses in grazing systems are a consequence of either: unavoidable P accumulation in high P-sorbing soils and/or in animal camps; unnecessary accumulations of P in fields due to over-application of P fertiliser and manure; and/or because P is being lost from fields by soil erosion, runoff or leaching.

P accumulation in soil under pasture production

Building soil P fertility: Agricultural soils that are P deficient and cannot, as a consequence, support optimum production are often improved by applying P fertiliser and/or manure at rates that purposefully exceed the rates of P removal and loss so that P accumulates in the soil. P cycling is increased and the plant-available P concentration of the soil is increased to support faster plant growth. Ideally, the build up in soil fertility should not exceed the "critical P requirement" of a pasture. This is typically defined as the plant-available P concentration of soil that corresponds with 90% or 95% of maximum pasture growth.

Excessive applications of P: If P fertiliser continues to be applied at a rate that allows P to accumulate in the grazing system, the critical available P concentration of the topsoil will eventually be exceeded and fertiliser is then being applied in excess of its need. P is often applied in excess of requirements as a result of ignorance of the critical P concentration that is appropriate for a soil-crop system, but over application can also be a consequence of deliberate but poor agronomic practice. In some developed economies it can be the consequence of logistics and disposal problems that occur when animal production facilities in an area generate more manure than the surrounding land can accept for good agronomic practice (Smit *et al.* 2009).

Accumulation of P in soil in "sparingly-available" forms: Even when soil P fertility is being managed adequately, soils that have a moderate to high P-sorption capacity are a net sink for some of the P that is applied. Here we use the term "P sorption" to represent the net process of phosphate movement from soil solution to the solid phase of the soil and ultimately into sparingly-available forms of phosphate as proposed by Barrow (1999) (Fig. 1). The chemistry of sorption reactions in soil is complex and is described elsewhere in more detail (e.g. Sample *et al.* 1980; McLaughlin *et al.* 2011). The net rate of phosphate sorption in non-calcareous soils is determined by the sorption capacity of the soil, and is proportional to the concentration of P in soil solution and the time over which phosphate is in contact with the soil. In calcareous soils, the drivers are initially similar but precipitation of calcium phosphates quickly decreases the phosphate concentration of the soil solution to levels that are determined by the solubility product (Barrow 1980).

P also accumulates in slowly-cycling soil organic compounds with the amount of accumulated organic P often being similar to that of sparingly-available phosphate

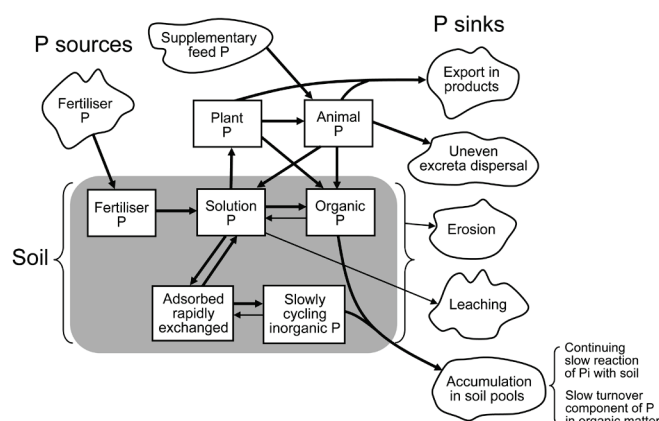


Figure 1. Schematic overview of the P cycle and the sources and net sinks for P in a grazing system (from Simpson *et al.* 2011).

(Helyar *et al.* 1997; George *et al.* 2007). Various components of soil organic matter are mineralised at different rates depending on their chemical and physical protection (Krull *et al.* 2003). Even very resistant materials (such as humus) are mineralised albeit very slowly, so accumulated forms of organic P are also not "fixed". There are some organic P compounds that are recognised components of accumulated organic P (e.g. phytate, Turner *et al.* 2002), however, there is also a large component (up to 50%) of high molecular weight organic P material that is associated with stabilised soil organic matter and remains poorly characterised.

The annual rate of P accumulation in grazed fields (*i.e.* the sum of phosphate and organic P accumulations in the soil and in animal camps) has been shown to be positively correlated with the concentration of plant-available P at which the fields were being managed (Fig. 2). This indicates that managing soil fertility at the lowest available P concentration that can deliver high production, or developing pastures that can yield well at lower plant-available soil P concentrations, should also lead to lower rates of P accumulation and reductions in the P surplus of fertilised pasture systems.

P budgets for grazing systems (e.g. Lewis *et al.* 1987; McCaskill and Cayley 2000; Simpson *et al.* 2010; Nguyen and Goh 1992) help identify the factors that contribute to inefficient use of P inputs. This is especially the case for budgets of P balance in systems where the plant-available P concentration of the soil has been maintained at a stable level because P accumulations in soil are not then due to an increase in soil P fertility (*i.e.* available P) or excessive fertiliser use:

$$P_{\text{fertiliser}} = P_{\text{export}} + P_{\text{erosion/leaching}} + P_{\text{excreta dispersal}} + P_{\text{soil accum}} \dots \dots (\text{Eqn 1})$$

where: P_{export} = removal of P in products; $P_{\text{erosion/leaching}}$ = P lost by leaching, runoff or soil movement; $P_{\text{excreta dispersal}}$ = P accumulated in small areas of farms as a result of uneven dispersal of animal excreta rendering the P less available; $P_{\text{soil accum}}$ = P accumulating as sparingly-available phosphate or organic P compounds that are slowly mineralised. If the plant-available P concentration of the soil is being maintained at a stable level then: $P_{\text{fertiliser}}$ = the "maintenance" fertiliser requirement.

It becomes clear that P-sorption capacity of a soil is a