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Management of soil phosphorus fertility determines the phosphorus budget of a temperate grazing system and is the key to improving phosphorus efficiency

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ABSTRACT

The phosphorus (P) efficiency of fertilised grazing systems on P deficient soils is often very low. P budgets (P input vs P output) were developed to examine P use in a long-term experiment in which grazing systems were managed with contrasting soil test P concentrations: (i) no P-fertiliser (P0; Olsen P = 2–5 mg/kg), (ii) near-optimum soil P fertility (P1; Olsen P = 10–15 mg/kg), (iii) supra-optimal P fertility (P2; Olsen P = 20–25 mg/kg), or (iv) with variable P fertility. Pastures were grazed with either 9 or 18 sheep/ha. P was exported as liveweight gain in sheep removed from the fields. Fertilised fields accumulated 89–93% of their P input over the whole P-budgeting period (1994–2006). However, this included P that was contributing to a “build up” in soil fertility (1994–2000). The efficiency of P fertiliser use was better demonstrated by P budgets during a soil P fertility “maintenance” phase (2001–2006) in which P inputs and soil test P concentrations of the grazing system treatments were relatively stable. When the amounts of P associated with the small changes in soil fertility were accounted for, the accumulation of P was 43–52 kg P/ha (83–87% of P inputs) in P1 fields and 87 kg P/ha (88% of P inputs) in P2 fields over the six-year period. Differences due to stocking rate were relatively small. Audits of the total P in sheep camp soil and field soil demonstrated that sheep camps were not a major sink for the P that was accumulating in the grazed fields. P was mainly accumulated in soil in the non-camp area of fields when they were fertilised and this was the major reason for low P-balance efficiency. It was concluded that the annual rate of P accumulation in fertilised soil (due mainly to P-sorption reactions) was higher when soil is being maintained at higher extractable-P concentrations. Consequently, strategies that can achieve equivalent pasture production with lower concentrations of extractable-P in the soil should reduce the amount of P fertiliser necessary for high production.

1. Introduction

Phosphorus (P) is a key input for agriculture supporting high productivity in many Mediterranean and temperate pasture systems (Carter and Day, 1970; Curll, 1977; Cayley et al., 1999; Osman et al., 1991; Smith et al., 2012; Crespo et al., 2004; Tunney et al., 2010). However, the efficiency of P use is often relatively poor when P-fertiliser is applied to agriculture based on P deficient soils. A useful measure for summarising the overall P efficiency of an agricultural system is its P-balance efficiency (PBE); defined as the ratio of P outputs in products, to P inputs in fertiliser and feed (Syers et al., 2008; Weaver and Wong, 2011). Under ideal circumstances, P inputs will equal P removals (i.e., no P surplus) indicating maximum P use efficiency. Grazing enterprises in southern Australia, for example, exhibit very low PBE. Data collated for wool, meat, milk and live-animal enterprises indicate that only 10–30% of the amount of P applied as fertiliser is exported in animal products. By comparison, the PBE of grain production systems on similar soil types is 45–54% (McLaughlin et al., 1992; Weaver and Wong, 2011).

Inefficient use of P in grazing systems can be the result of P losses from a field and/or accumulations of P in the soil (Simpson et al., 2014). Large losses can occur when soils have a low P-sorption capacity (e.g., sandy soils; Russell, 1960; Ozanne et al., 1961) or are eroded. P loss in runoff from pastures is usually a relatively small term in soil P budgets (e.g., Ridley et al., 2003). Here, we use the term “P sorption”, as proposed by Barrow (1999), to represent the net process of phosphate movement from soil solution to the solid phase

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of the soil and the continuing slow reactions between phosphate and soil particles that ultimately result in phosphate being only sparingly available for plant uptake. In contrast to soils where loss of P can occur, there is a net accumulation of phosphate in sparingly-available forms when P fertiliser is applied to soils with a moderate to high P-sorption capacity (Barrow, 1999; McLaughlin et al., 2011). Some of the P is also incorporated into organic materials that resist mineralisation (Barrow, 1969; Turner et al., 2005). In addition, grazed fields accumulate P in stock camp areas as a result of disproportionate deposition of excrement in these areas (Williams and Haynes, 1992).

For a low P soil with moderate to high P-sorption capacity, accumulation of P in the soil is not in itself an adverse outcome of P fertiliser use because it contributes to the overall improvement in soil P fertility. Initially, P applications build soil P pools to levels that assist the rate of P cycling in the pasture system. P applications also slowly change the P-buffering and P-sorption capacity of the soil and improve the effectiveness of subsequent P fertiliser applications (Barrow 2015). However, the timeframe for these changes is long and, in the meantime, the P accumulated by sorption to soil particles only returns to the soil solution when P fertiliser is withheld and at rates that are usually much slower than necessary for high pasture growth rates (Simpson et al., 2014). The world's high grade phosphate rock "reserves" that are used to manufacture fertilisers are effectively finite (Van Kauwenbergh, 2010). P accumulations in soil that do not directly generate financial income are, consequently, undesirable because they result in a scarce resource being used with low efficiency and because they add unproductive cost to production systems on low P soils.

Barrow (1980a,b) determined that the empirical isothermic relationship between net phosphate sorption by soil (Ps), P concentration in the soil solution (*c*) and time (*t*) for non-calcareous soils was of the form:

$$\mathrm{Ps} = a \times c^{b1} \times t^{b2} \tag{1}$$

where: *a* approximates the amount of P sorbing material in a soil, and *b*1 and *b*2 are coefficients that describe the shape of the sorption relationship. These coefficients varied considerably between soils. However, *b*1 and *b*2 were reasonably well correlated when compared across a wide range of soils (Barrow, 1980a,b) and, consequently, Ps was positively related to the concentration of phosphate in soil solution and the time that phosphate is in contact with the soil. From this, it can be deduced that reactions that lead to accumulation of sparingly-available phosphate in soil will be promoted when a soil is fertilised. The rate of phosphate sorption is reflected in the size of the *b*1 and *b*2 parameters that are relevant to the soil. However, at the scale of a grazed field, P accumulations are the net result of phosphate sorption, as well as increases in the organic P content of the soil and P accumulation in stock camps.

We examined the P budgets of pastures fertilised to achieve contrasting levels of soil P fertility and grazed by sheep in a long-term experiment. The primary aim of the study was to assess whether increasing the extractable-P concentration of soil for pasture production purposes, also promoted the net accumulation of P at field scale. The location of P accumulated in the fields was also quantified.

2. Materials and methods

2.1. Experiment site

The experiment was located at CSIRO's Ginninderra Experiment Station (Hall, Australian Capital Territory). Daily maximum and minimum temperatures and rainfall (Fig. 1) were collected using an automated station, situated 4 km from the experiment. On a few occasions when the automated station failed, missing records were filled using manual records.

The soil was an acidic Alfisol (USDA, 1999), or a Yellow Chromosol in the Australian classification system (Isbell, 1996), with a topsoil (0–10 cm depth) Phosphorus Buffering Index (PBI) of 50 (Burkitt et al., 2002, 2008). The extractable-P concentration of the surface soil at the beginning of the experiment was 4 mg P/kg soil (Olsen et al., 1954) or 8 mg P/kg soil (Colwell, 1963). Soil pH was 4.6 in $CaCl_2$, KCl40-extractable sulfur (S) was 5 mg/kg (Blair et al., 1991), organic C (method 6A1) was 2.0%, exchangeable potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) (method 15D3) and aluminum (Al) (method 15G1) concentrations and cation exchange capacity were ($cmol_c$/kg): 0.6, 2.3, 1.0, 0.06, 0.15 and 4.1, respectively (Rayment and Lyons, 2011).

2.2. Grazing system treatments

Seven grazing system treatments were established in 1994 by dividing a single field (35°10′34.5″S, 149°02′37.5″E; 597 m elevation) with an established *Phalaris aquatica* L. (phalaris) and *Trifolium subterraneum* L. (subterranean clover) pasture into 21 smaller fields and applying different combinations of soil P management and sheep stocking rates (see Fig. 2 for an overview of the treatments). The grazing system treatments were arranged in a randomised complete block design with three replicates.

Management records for the original field were incomplete, but it was known that the pasture had not been resown with *P. aquatica*, the dominant perennial grass, since at least 1970. *P.*

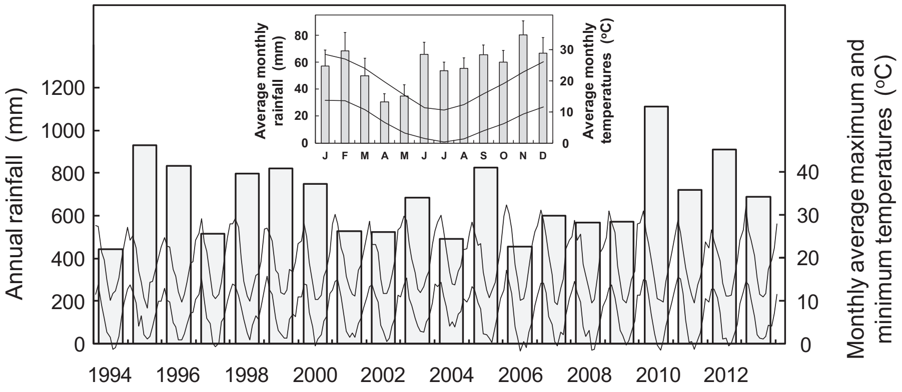

Fig. 1. Annual rainfall (columns) and monthly average maximum and minimum temperatures for the period 1994–2013 at Ginninderra Experiment Station, Hall, ACT. Inset shows the average seasonal conditions for the same period in the form of average monthly maximum and minimum temperatures and average monthly rainfall. Rainfall variability is indicated by the bars (1xSE, $n = 20$).