Which fertiliser phosphorus management strategy for maximum clover production and fertiliser phosphorus efficiency?

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Abstract
The application of single superphosphate (SSP) to leguminous pastures is a successful strategy for pasture production in the high rainfall zone of eastern Australia. Typically, the management of fertiliser phosphorus (P) in these grazing systems involves the addition of SSP to the soil surface early in the growing season. However, it is not known whether this is the 'best' strategy for achieving maximum pasture growth with high fertiliser P efficiency. The aim of this study was to ascertain the effect of different fertiliser P management strategies on clover growth and fertiliser P efficiency. This involved using ^{33}P-labelled SSP to measure the direct recovery of fertiliser P in shoots of a subterranean clover pasture at two field sites and under different management conditions (including timing, placement and initial soil P fertility). In general, maximum clover growth and recovery of fertiliser P by clover plants was obtained when fertiliser P was applied to the soil surface early in the growing season. In addition, the recovery of fertiliser P by clover shoots was highest (46% of applied P) in fields that were maintained with soil test P levels near the optimum for pasture growth.

Key words
Agronomic management; Fertiliser fate; Phosphorus cycle; Radiotracer; *Trifolium subterraneum*.

Introduction
The application of single superphosphate (SSP) to leguminous pastures has been a highly successful strategy for improving and maintaining high pasture yields in the high rainfall zone of south-eastern Australia (Cayley *et a*l. 1999). Single superphosphate is often applied to the soil surface very early in the growing season (autumn). Some of the reasons for favouring broadcasting P early in the growing season include: 1) lower fertiliser costs than in later months; 2) financial incentives to invest in farm operations prior to the end of the financial year; 3) drier soils at the start of the year that favour spreading operations compared with winter, and/or; 4) inability to apply nutrient at depth in permanent pastures. However, there are no published studies that have determined the direct recovery of fertiliser P from SSP (here termed 'fertiliser P efficiency') in leguminous pastures during the first growing season after fertiliser application under field conditions. In addition, there is little information about the 'best' strategy for maximizing pasture production with high fertiliser P efficiency. In developing this set of experiments we hypothesised that the recovery of fertiliser P in clover shoots may be higher when it was applied to pastures mid-season compared to early-season application because roots would be well established and better able to intercept fertiliser P, and that fertiliser placed at depth may be better positioned for root uptake compared to that applied to the soil surface. In this study, we use a novel, rapid and cost-effective approach to label SSP with a ^{33}P radiotracer (^{33}P-labelled SSP), and then applied this to clover monocultures under field conditions to measure the direct recovery of the applied fertiliser P.

Materials and Methods
Field experimentation and management
Two field sites under permanent pasture with low soil P fertility were selected in the temperate region of south-eastern Australia. One field site was located on a property near Inman Valley (sand in the 0 – 20 cm layer), South Australia (35°29'39" S, 138°27'21" E), and the other was located at the CSIRO Ginninderra Experiment Station (sandy loam in the 0 – 20 cm layer), near Hall, the Australian Capital Territory (35°11'49" S, 149°05' 19" E). Some chemical properties of the soils collected from both field sites are shown in Table 1.

A clover pasture was established and 'open-ended' PVC cylinders (15 cm (diameter) × 18 (height) cm) were inserted 15 cm into the soil at each site. Basal nutrients (B, Ca, Cu K, Mg, Mo, S and Zn) were applied across both sites. The fertilised treatments involved the addition of ^{33}P-labelled SSP granules to supply ~ 20 kg P ha^{-1} (~ 4 MBq core^{-1}). Treatments included: 1) a control (no added fertiliser P); 2) application of ^{33}P-labelled SSP to clover pastures at early-season on the soil surface (Ginninderra – April and Inman Valley – June); 3) application of ^{33}P-labelled SSP to clover pastures at mid-season on the soil surface (Ginninderra – July and Inman Valley – August), and; 4) application of ^{33}P-labelled SSP to clover pastures at early-season placed 6 cm below the soil surface (deep). Details of the radio-labelling technique is reported in McLaren et al. (2014). All treatments consisted of six replicates arranged in a randomised block design. If needed, sites were irrigated to ensure the cumulative rainfall throughout the growing season was at least decile 5 (average rainfall), which was not required at the Ginninderra field site.

Table 1. Chemical properties of the soils used in this study. Analyses were carried out on soil samples collected prior to fertiliser addition to the subterranean clover pasture.

Location	Depth (cm)	pHw (1:5)	[A]ECw (µS cm^{-1}; 1:5)	[B]TOC (%)	[C]TON (%)	[D]Colwell P (mg kg^{-1})	[E]PBI	[F]Total P (mg kg^{-1})
Ginninderra,	0 – 2.5	5.5	96.5	3.4	0.27	30	36	439
ACT	2.5 – 5	5.1	54.7	1.7	0.15	14	43	381
	5 – 10	5.2	36.0	1.2	0.10	9	44	346
	10 – 20	5.4	26.0	0.6	0.05	6	14	285
Inman Valley,	0 – 2.5	5.8	47.9	2.1	0.18	12	11	216
SA	2.5 – 5	5.8	35.9	1.7	0.15	12	38	185
	5 – 10	5.6	34.2	1.2	0.10	16	13	170
	10 – 20	5.4	20.1	0.6	0.05	12	12	127

[A]EC, electrical conductivity, [B]TOC, total organic carbon, [C]TON, total organic N, [D]Bicarbonate extractable P (1:100 soil:solution), [E]PBI, phosphorus buffering index, [F]Total soil P using XRF

The existence of a long-term P fertiliser experiment at the CSIRO Ginninderra Experiment Station also provided an opportunity to investigate the recovery of fertiliser P in clover shoots under different levels of initial soil P fertility (Simpson *et al*. 2010). This experiment was established in 1994 and included treatments designed to maintain soil P fertility in the topsoil layer (0 – 10 cm): 1) fields receiving no P fertiliser (P0: control – native soil P fertility between 4 – 6 Olsen P kg^{-1}); 2) fields receiving fertiliser P to maintain a soil P fertility between 10 – 15 Olsen P kg^{-1} (P1), which is a near-optimum soil test P concentration for pasture growth at this site, and; 3) plots receiving fertiliser P to maintain a soil P fertility between 20 – 25 Olsen P kg^{-1} (P2). A subterranean clover monoculture was established in fields at each soil P fertility level (n=3) and ^{33}P-labelled SSP was applied to the soil surface at the 'early-season' application time, using the methods described above. Treatments were arranged in a randomised block design. Experiment details of the long-term P fertiliser experiment and background information have been reported by Simpson *et a*l. (2010).

Four harvests were collected at the Inman Valley field site and five harvests collected at the Ginninderra field sites. The final harvest at Ginninderra and Inman Valley field sites were in November and October, respectively. Clover shoots were cut to 3 cm above the soil surface, except at the final harvest where the clover shoots were removed to the soil surface.

Chemical analyses

Clover shoots were digested and subsequently analysed for radioactive and non-radioactive P as described by McBeath et al. (2012). The specific activity of the fertiliser granules (MBq mg^{-1} water-soluble P– WSP) was corrected for WSP content of the SSP because the ^{33}P radiotracer would have only labelled the WSP fraction. The WSP component of the SSP was 88 % of the total P. The specific activity and recovery of fertiliser P in pasture components was calculated using the equations reported in McBeath et al. (2012).

Statistical analyses

All statistical analyses were carried out using R 3.0.2. A one-way analysis of variance (ANOVA) and orthogonal contrasts was used to compare treatment means at the $P < 0.05$ level of significance.

Results

Cumulative biomass removal and P uptake into clover shoots for the fertilised treatments was higher than in the unfertilised control at both field sites (Table 2). At the Ginninderra field site, cumulative biomass removal and P uptake into clover shoots for the early-season surface application was not significantly different to that of the early-season deep SSP application but was higher than the mid-season surface (Table 2). At the Inman Valley field site, cumulative biomass removal of clover shoots for the early-season surface treatment was not different to that of the early-season deep or mid-season surface applications of SSP at the Inman Valley field site (Table 2).

The recovery of fertiliser P in clover shoots was up to 42 % in the year of application (Table 2). In general, the recovery of fertiliser P in clover shoots at both sites was highest (~ 40 %) when fertiliser P was applied to the soil surface at early-season compared to that at depth or at mid-season to the soil surface (Table 2). However, at the Ginninderra site, the recovery of fertiliser P in clover shoots for the early-season surface treatment was not significantly different to that of the early-season deep treatment (Table 2).

Table 2. Cumulative biomass removal (t DM ha^{-1} equivalent), clover P uptake (kg P ha^{-1} equivalent), and recovery of fertiliser P (as a % of applied ^{33}P-labelled SSP) for clover shoots (> 0 cm above the soil surface) at the Ginninderra and Inman Valley field sites. Values in parentheses are standard errors.

Field site	Treatments Timing of fertiliser P[A]	Placement of fertiliser P[B]	Cumulative biomass (t DM ha^{-1})	Cumulative P uptake (kg P ha^{-1})	Recovery of fertiliser P (as a % of applied)
Ginninderra	Early-season	Surface	14.8 (0.7)	17.9 (0.6)	38.4 (2.1)
	Early-season	Deep	14.3 (0.3)	17.7 (0.6)	40.0 (1.5)
	Mid-season	Surface	11.1 (0.4)	13.7 (0.6)	28.5 (0.5)
	Nil	Nil	8.0 (0.4)	7.0 (0.8)	
Inman Valley	Early-season	Surface	11.3 (0.3)	25.5 (0.7)	42.4 (1.1)
	Early-season	Deep	9.5 (0.6)	21.8 (0.8)	27.3 (2.3)
	Mid-season	Surface	11.4 (0.8)	28.3 (1.3)	28.6 (1.3)
	Nil	Nil	8.8 (0.7)	15.2 (0.8)	

[A]Fertiliser P was applied to clover pastures at early-season (late April for the Ginninderra field site and early June for the Inman Valley field site) or mid-season (late July and mid August, respectively). [B]Fertiliser P was applied to clover pastures on the soil surface (surface) or at 6 cm below the soil surface (deep).

Cumulative biomass removal was higher in clover shoots at the P1 and P2 levels of soil P fertility than at the P0 level of soil P fertility with the addition of SSP (Table 3). Cumulative biomass removal in clover shoots at the P1 level of soil P fertility was similar to that at the P2 level of soil P fertility (Table 3). However, the cumulative P uptake in clover shoots increased 2-fold from P0 to P1, and then slightly more at P3 (Table 3).

The highest recovery of fertiliser P in clover shoots (46 %) occurred at the P1 level of soil P fertility (Table 3).

Table 3. Cumulative biomass removal (t DM ha^{-1} equivalent), clover P uptake (kg P ha^{-1} equivalent), and recovery of fertiliser P (as a % of applied from the ^{33}P-labelled SSP) for clover shoots (> 0 cm above the soil surface) across three levels of soil P fertility at the Ginninderra field site. Fertiliser P was applied at early-season to the soil surface. Values in parentheses are standard errors.

Field site	Treatments[A] (early-season surface)	Cumulative biomass (t DM ha^{-1})	Cumulative P uptake (kg P ha^{-1})	Recovery of fertiliser P (as a % of applied)
Ginninderra	P0	15.3 (0.4)	19.9 (1.5)	40.3 (1.3)
	P1	18.0 (0.6)	41.7 (2.3)	45.5 (0.8)
	P2	20.5 (1.1)	51.9 (2.6)	42.5 (1.5)

[A]Initial levels of soil P fertility in the topsoil layer (0 – 10 cm) include: 1) P0, 4 – 6 Olsen P kg^{-1}; 2) P1, 10 – 15 Olsen P kg^{-1}, and 3) P2, 20 – 25 Olsen P kg^{-1}.

Discussion

Clover pastures responded to the application of ~ 20 kg P ha^{-1} as ^{33}P-labelled SSP at both sites. This was expected due to the low concentrations of soil test P in the soil. The rate of fertiliser P used in this experiment was chosen to supply enough P so that a clover response to fertiliser P would be observed, but also at a rate that would be considered ‘plausible’ to primary producers as part of their P fertiliser management. At the Ginninderra site, Simpson *et al*. (2010) reported that an application of ~ 40 kg P ha^{-1} would be needed to obtain optimum clover yield when applying P to pasture growing at the P0 level of soil P fertility.

In general, high recoveries of fertiliser P in clover shoots were found for the surface application of fertiliser P when applied at early-season for both sites, but also when fertiliser P was applied at depth for the Ginninderra site. This showed that a considerable proportion of the fertiliser P was taken up into herbage in the year of application for these treatments and at these sites. Recoveries of 40 – 45 % for the early-season surface treatments at the Ginninderra and Inman Valley field sites were at the upper end of those typically reported for arable crops (McBeath *et al*. 2012). Some of the reasons for this high level of fertiliser recovery may include: 1) the presence of an established root system, which was concentrated in the surface layer of the soil profile when the fertiliser P was added; 2) the majority of P within SSP was water soluble and available to plants; and; 3) fertiliser P was unlikely to become rapidly unavailable to plants over the growing season in soils of low to moderate sorption capacity. Similar recoveries of fertiliser P in clover shoots between early-season surface and early-season depth treatments at the Ginninderra site suggest the latter may be advantageous in some soils at the pasture rejuvenation phase to provide nutrients at a depth less prone to wetting and drying. However, the ability to maximise pasture production and fertiliser P recovery with surface applications is advantageous to primary producers for economic and operational reasons.

Interestingly, fertility management considered to be near-optimal for high production, also proved to be the most efficient in terms of direct recovery of P after fertiliser application.

Conclusion

Our results indicate that clover pastures have a relatively high capacity to recover fertiliser P. High recoveries of fertiliser P by clover pastures were generally found when fertiliser P was applied to the soil surface at early-season, although there was evidence at the Ginninderra field site that applications of fertiliser P at depth can be utilised at a similar efficiency. A key consequence of our findings is that the cause of low efficiency of P (P exported in products relative to P inputs) fertilization in pasture systems is only partially due to low direct uptake of fertilizer P by pasture species.

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