RPR revisited (4): Optimising pasture production during the transition from soluble P to RPR; an overview

B.F. Quin and M. Zaman

Quin Environmentals (NZ) Ltd, PO Box 125122, St Heliers, Auckland 1740, New Zealand

Ballance Agri-Nutrients Ltd, Private Bag 12503, Tauranga 3143, New Zealand

Abstract

The use of reactive phosphate rock (RPR) instead of soluble phosphorus (P) as the maintenance fertiliser for New Zealand pastures has been proven to substantially reduce P runoff, especially dissolved reactive P (DRP), into waterways. However, a significant barrier to the adoption of reactive phosphate rock (RPR) as a maintenance fertiliser for pasture is the short-term (typically 2 years) 'lag-phase' in production that can occur after the switch from soluble P fertilisers. A variety of methods designed to overcome the lag-phase are assessed. These include (a) capital applications of RPR, (b) RPR/S co-granulation and mixes, (c) sulphuric partially acidulated RPR's and single superphosphate (SSP)/RPR mixtures, (d) phosphoric partially acidulated RPR's (phosphoric PAPR) and triple superphosphate (TSP)/RPR mixtures, and (e) RPR/soluble P fluidised or wetted fertilisers. The most reliable, and soil type independent method was concluded to be group (d), and with it by inference group (e), which represents simply a very wet form of (d), but with the potential of further efficiencies. This is especially the case when, as is increasingly the case with P applications in New Zealand, N is included at least partly in the form of urea, because fluidised urea (treated with urease inhibitor) is far more efficient than granular urea. Reasons for the effectiveness of (d) and (e) in overcoming the P lag-phase relative to other methods are discussed. They allow farmers to switch from soluble P to solely-RPR at the same rate of applied P over a few years with no decline in production, and thus capture the benefits of substantially reduced loss of P to the waterways.

Additional keywords: Lag-phase, reactive phosphate rock, capital P applications, biosuper, partially acidulated phosphoric acid (PAPR), sulphuric PAPR, phosphoric PAPR, slow-release P, P run-off

Introduction

The use of reactive phosphate rock (RPR) instead of soluble phosphorus (P) as a maintenance P fertiliser has proven environmental benefits, particularly in terms of greatly reduced P run-off into waterways (Nguyen and Quin, 2001; Hart *et al.,* 2004; McDowell and Catto, 2005), and very low manufacturing emissions to the environment.

There is, however, typically a 'lag-phase' (reduced pasture production commonly lasting 1-2 years) following a straight switch from fully-soluble P fertilisers such as single superphosphate (SSP) to RPR as the sole source of P at maintenance rates (Quin and Zaman, 2012). This is due to the slow-release nature of RPR, and is compatible with typical measurements of dissolution of maintenance P applications of RPR in grazed pasture soils of 30-40% per year. The RPR lag-phase can last considerably longer on very highly P-retentive soils, because P adsorption onto hydrous oxides of iron and aluminium on soil particle surfaces competes strongly with plant uptake. This is perceived by farmers to be a significant disincentive to adopt RPR, despite competitive costs per unit P. However, Zaman and Quin (2012) found that virtually all long-term users of RPR were very satisfied with RPR and fully intended to keep using it.

Considerable research has been conducted in New Zealand, particularly from the late 1970s to the late 1990s, comparing pasture production levels with various alternatives to the application of straight RPR at maintenance P rates, particularly during this lag-phase. These alternatives can be divided for discussion into five groups: (a) an initial capital application of RPR followed by annual maintenance applications, (b) the use of RPR with elemental S which is co-granulated, physically blended or sprayed on, (c) sulphuric partially acidulated RPR (sulphuric PAPR) and the chemically similar SSP/RPR blends, and (d) phosphoric partially acidulated RPR (phosphoric PAPR) and PAPR/S, and their chemical equivalent of triple superphosphate (TSP), RPR and elemental S. A relatively new form of (d), *viz.* (e) RPR/soluble P in suspension, fluid or wet form has been added for completion. These groups are described in more detail under the relevant sub-headings in the Results and Interpretation section. Groups (c) and (d) have also been quite widely researched overseas (Garbouchev, 1981; Hagin, 1985), but mostly in glasshouse conditions or on annual or short-term crops as opposed to permanent pasture. In addition, much of this work has been focused on the possible utilisation of indigenous poor quality, unreactive phosphate rocks, especially *via* partial sulphuric acidulation (Hammond *et al.,* 1986; Lopes *et al.,* 1991).

Any assessment of RPR fertilisers in New Zealand needs to recognize the widespread agronomic requirement for maintenance sulphur, either as elemental S or sulphate. This is not as widely seen in other countries, because of atmospheric inputs of sulphate-S in acid rain. In New Zealand, researchers usually apply one of three S strategies: (i) adding equivalent S to RPR to match the P:S ratio of SSP (typically 1 to 1.3), (ii) adding no S to the RPR itself but apply basal S to the whole trial to remove the possibility of S deficiency occurring, or (iii) comparing SSP on an equal P basis with specific RPR-based products containing a fixed amount of S, regardless of their P:S ratio. The latter approach, which is particularly suited to trialing commercial products, simplifies

cost-comparisons, as no adjustment has to be made for factoring in the cost of estimated S requirements in any given situation. This 'cost of S adjustment' aspect has been the cause of considerable confusion and debate over the past 25 years.

Materials and Methods

Sinclair and Dyson (1988) and Smith *et al.* (1990) documented the MAF Agricultural Research Division's 19-site 'National Series" of RPR *vs* soluble P trials. The range of soil types and some other parameters are summarised in Table 1. TSP rather than SSP was used for the reference response curve for fully-soluble P fertiliser. This was because of concerns over the previously poor and variable quality of New Zealand-manufactured SSP (Quin, 1982). Most of the sites did however include a single rate (0.75) of the individually site-assessed maintenance (M) rate of P of one or more commercial or laboratory-made SSP products. The 0.75M rate was chosen specifically to produce sub-optimal yields and therefore generate a single factor (P) response curves. The 'M' rates were estimated using MAF's Computerised Fertiliser Advisory Scheme (CFAS). They varied from 12-50 kgP/ha across the 19 sites (Table 1) and proved over time to be remarkably accurate. Several trials included a 0.75M rate of a phosphoric PAPR, and a 0.75M rate of a SSP/RPR combination. Sechura RPR (Peru) was used as the reference response curve for RPR, with North Carolina (NCPR) and New Zealand's

Chatham Rise phosphorite (CRP) being included at 0.75M in many trials. More than half of the trials compared RPR (with just the normal basal gypsum application) with a product comprising RPR over which fine elemental S had been sprayed, to measure whether any synergistic effects occurring from the acidulation produced during oxidation of the elemental S component. Because of the wide range of locations and product types included in this trial series, and its longevity, several issues were raised, such as how to avoid the lag-phase in pasture production. Most of these issues were able to be addressed by other researchers in separate laboratory work or in additional field trials (Quin & Zaman 2012).

In this overview, the authors have used the results from the National Series as the reference point for the comparison types of relevant products, and have referred to other important studies that helped to clarify certain issues. This approach was not possible with Group (e). However these products are, technically and chemically, simply 'very wet' versions of group (d), but with the potential for partial foliar uptake to increase nutrient efficiency and the reduction in losses, especially nitrogen (N) where included (Quin, 2012).

All field trials referred to in this overview were replicated and statistically analysed. The chemical characteristics of the products tested, and the soil types, soil fertility and rainfall at the various sites have been detailed in the referenced papers.

Table 1: MAF 'National Series' – soil types and range of parameters on chosen sites

| Soil groups (no. of sites)	Podzolised Northern Yellow Brown Earth (2)
	Northern Brown Granular Clay (1)
	Northern Yellow Brown Earth (1)
	Northern Yellow Brown sand (1)
	Gley (1)
	Gley podzol (1)
	Gley Recent (1)
	Yellow Brown Loam (3)*
	Yellow Brown Pumice (1)
	Yellow Grey/Brown Earth (3)*
	Yellow Brown Earth (1)
	Southern Yellow Brown Earth (1)*
	Yellow Grey Earth (2)[1]
Soil pH range	5.5-6.3 (5.6-5.9)[2]
Olsen P range	7-24 (7-16)[2]
P Retention (ASC) range	9-98 (7-98)[2]
Rainfall range (mm/year)	712-2785 (742-1319)[2]
Maintenance (kgP/ha/year)	12-50 (20-37)[2]

[1] soils represented in sites including PA-PAPR

[2] range of parameters in sites comparing PA-PAPR with soluble P and RPR. Note these included the two highest P retention sites 7 and 9 (98 and 95% respectively)

Results and Discussion

Capital Applications of RPR

Initial capital applications of RPR have been proposed as a way, when capital expenditure permits, of increasing the amount of P being released in the first few years after switching from using soluble P to RPR. However the National Series provided little support for this approach, as shown in the Year 1 response curve averaged for all trials (Figure 1, from Sinclair & Dyson 1988). Note that we have added the Year 1 data from the first triennial application of 2.25M TSP and RPR to this graph. There was little if any additional response at 2.0M (or 2.25M) compared with 1.0M with RPR, unlike the case with TSP. The most likely cause of this is the inhibitory effect of soluble Ca in the soil solution on further dissolution of RPR; recent lime applications have the same effect, as does granulating RPR with gypsum to provide sulphate-S (Quin, 1981).
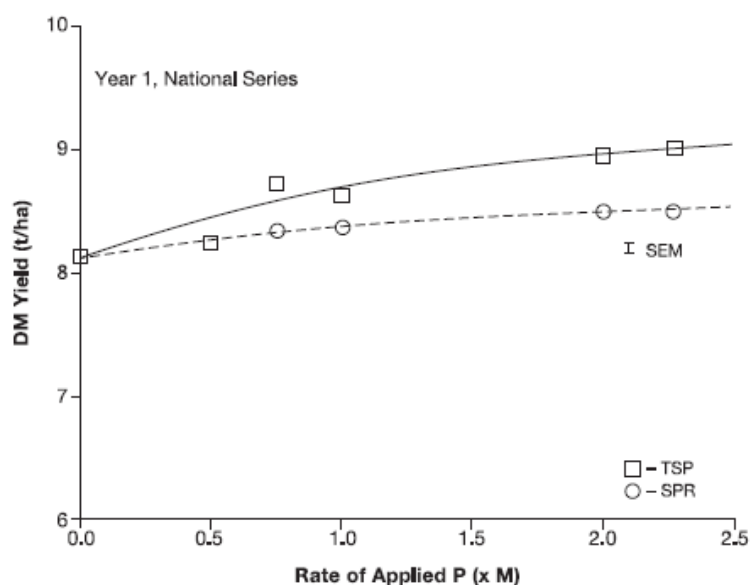
Figure 1: The 'National Series' trials: Fitted Mitsherlich P response curves for pasture production (kgDM/ha) for Year 1, averaged for all sites except the non P-responsive sites (14, 15 and 16) against rate of P, where M=calculated maintenance P requirement (kg P/ha/yr), for TSP (squares) and Sechura RPR (circles). Bar shows SEM. Data from Sinclair & Dyson (1988), but with year 1 data for 2.25M rate added.

RPR/S Granules and Mixes

Blends of RPR with fine elemental S, either mixed with the RPR or sprayed onto it (as in the National Series), even at 12-17% addition of S, do not achieve any reliable increase in the rate of RPR dissolution. The 'National Series' provides a total of 21 year 1 comparisons of RPR and basal gypsum only with RPR/elemental S at the 0.75M rate of application of P. The average pasture production with both are not statistically different, and within-trial variations were small (Table 2, data compiled from Smith *et al.,* 1990). Rajan *et al.* (1982) obtained similar results in pot

trials comparing RPR with mixed RPR/elemental S. Wetting the mix prior to spreading with 5-7% water, which is about the upper moisture limit that can be handled and evenly spread with conventional spreading equipment, helps the RPR and S particles adhere to each other during application, thereby encouraging faster oxidation, and may therefore represent a low-cost means of utilising, to some extent, the acidification from S oxidation without expensive granulation (Quin, 2012).

Adding *Thiobacillus* bacteria to the elemental S appears to improve performance of the RPR (Rajan, 2002).

Table 2: MAF 'National Series' - Year 1 pasture yield (t DM/ha) comparisons of RPR (with basal gypsum) at 0.75 times assessed maintenance P (M), with and without 'sprayed on' fine elemental S. Compiled from Smith *et al.,* 1990.

Trials	Control (0 P)	RPR (basal gypsum only)	RPR/S (basal gypsum + 'sprayed-on' elem. S)
NI[1]	8.97 (n=7)	9.38 (n=13)	9.47 (n=13) $LSD_{(0.05)} = 0.25$
SI[2]	7.66 (n=4)	7.24 (n=8)	7.14 (n=8) $LSD_{(0.05)} = 0.38$

[1]In the North Island (NI), there was a significant response to RPR in Year 1 at the 0.75M rate, but there was no significant difference between the presence or absence of 'sprayed on' elemental S.

[2]In the South Island (SI), there was actually a significant reduction in yield with RPR in Year 1 at the 0.75M rate of P (probably reflecting changes in pasture composition to more nutritious but initially lower-yielding species such as clover), but again no significant differences between the presence or absence of 'sprayed-on' elemental S.

Co-granulation of RPR with 10-15% fine elemental S (a product sometimes referred to as 'Biosuper') has been demonstrated in a pot trial to result in considerably faster dissolution of RPR and resulting an increase in ryegrass yield (Figure 2, from Rajan, 1982). In the case of this product, the acidity produced by the oxidation of the elemental S - by *Thiobacillus* bacteria in the soil or incorporated in the granules - remains sufficiently close to the RPR particles to increase the rate of dissolution. However, its efficacy in field trials has been variable; Rajan and Gillingham (1986) found no advantage to RPR/S co-granulation on a medium-high P retention soil. In addition, commercial manufacture of such a product would require substantial new capital expenditure, at several locations in New Zealand, to avoid incurring very substantial costs in transport to farms.

Sulphuric PAPR and SSP/RPR Mixes

This category has been much more widely investigated. The first option in this group is the *direct* partial acidulation of RPR with sulphuric acid to produce a product containing about 10% total P, of which about 50% is present in water-soluble form. Advantages of this technology for New Zealand are that it could easily be done in existing SSP and SA production facilities, and that it automatically contains some sulphate-S as gypsum (typically 6-7% S). The same end result can be achieved by adding a proportion of RPR to SSP, either immediately ex-den (and prior to or during granulation), or after curing. This is called an *indirect* partial sulphuric acidulation. It has been the simpler and more preferred process for SSP manufacturers (e.g., the once widely-made product 'Longlife'), as it does not require any change to raw material inputs and ratios for the SSP component. However where the RPR is added ex-den, it automatically results in some of the RPR being acidulated, and a proportion of the agronomically ineffective SSP-manufacturing rock being left in the final product (Bolan *et al.,* 1987). This effect is minimised if the RPR is added to already-cured SSP. There is also less risk in this case of gypsum-induced inhibition of dissolution of the RPR, especially in non-granulated mixes, due to more separate landing locations of SSP and RPR particles on the soil on spreading. However the components are more susceptible to segregation during transport and spreading.
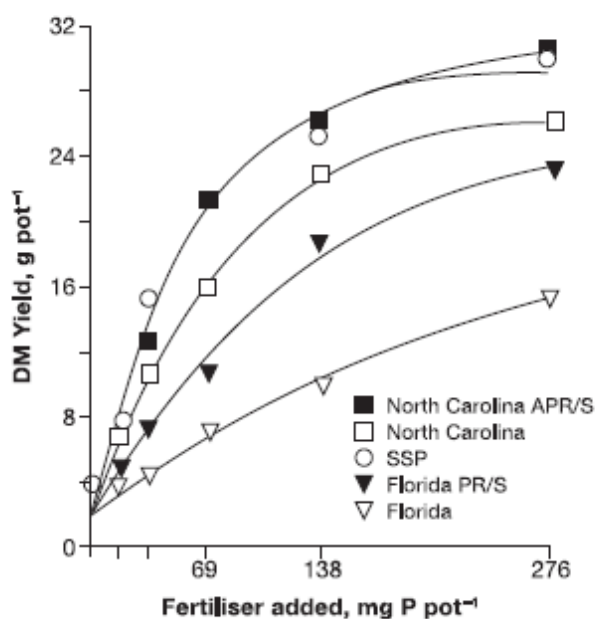
Figure 2: Growth response of ryegrass in pots of high P retention soil for SSP (circles), North Carolina RPR and RPR/S 'biosuper' (squares), and Florida phosphate rock and Fl/S biosuper (inverted triangles). From Rajan (1982).

Regardless, sulphuric PAPR's, whether direct or indirect, have generally performed little better than the arithmetic combination of the water and slow-release P components would predict (Table 3). They do not completely avoid the occurrence of a lag-phase in situations where it occurs, at least when applied at maintenance P rates. In addition, there are many situations where these products have apparently performed more poorly than the arithmetic combination would predict, even over a period of 4 years (Figure 3, from Ledgard *et al.,* 1992), especially on higher P-retention soils. It has been postulated that this is caused by the gypsum content slowing the dissolution of the RPR component (Rajan and Marwaha, 1993), as happens with co-granulation of RPR and gypsum (Quin, 1981). Given that the lag-phase, where it exists at all, very seldom represents a decline in pasture production of more than 4% and 2% in years 1 and 2 respectively (except in pumice soils, Quin and Zaman, 2013), the value in using sulphuric PAPR's is questionable (Ledgard *et al.,* 1992). The use of this type of product has consequently declined considerably.

Table 3: MAF 'National Series' - Year 1 pasture yield (t DM/ha) comparisons of P fertiliser types at 0.75M (all with basal gypsum), from Sites 7, 9, 13, 17 and 18. From Sinclair and Dyson (1988).

Fertiliser	Pasture DM
Control	7.45 (100)
Imported TSP	7.88 (106)
SSP made from Christmas/Nauru PR's	7.81 (105)
Indirect sulphuric (SA)-PAPR ('SSP/RPR')	7.76 (104)
Direct phosphoric (PA) - PAPR	7.88 (106)
North Carolina RPR	7.37 (99)
Sechura RPR[1]	7.59 (102)
LSD$_{(0.05)}$	0.16 (2)

[1]Note Sechura RPR was not included in this statistical analysis.
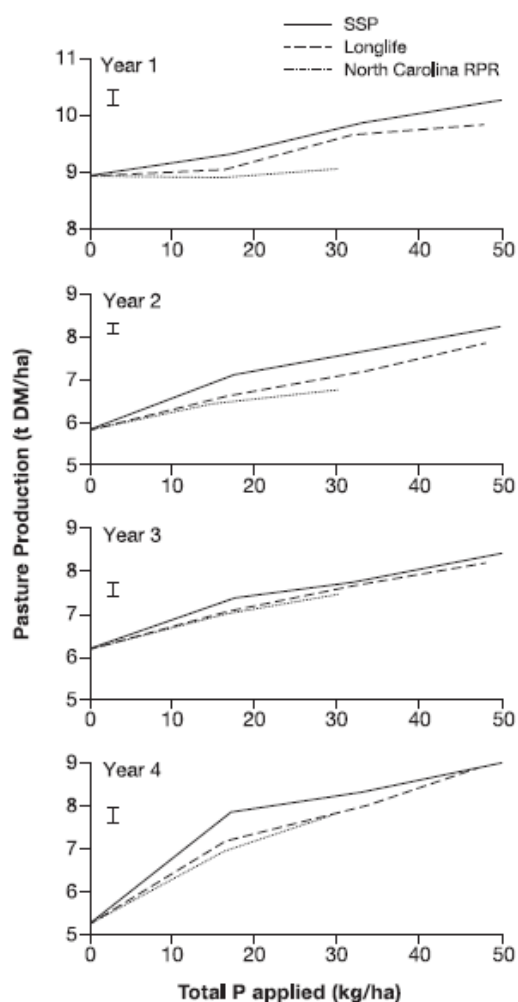
Figure 3: Annual pasture production P over 4 years for SSP (continuous lines), 'Longlife' SSP/RPR post-den SA-PAPR (dashed lines) and North Carolina RPR (dotted lines). Bars represent SED's. From Ledgard *et al*. (1992).

Phosphoric PAPR and TSP (or DAP)/RPR/S Mixes

It is not widely understood in New Zealand that phosphoric PAPR, produced by partial acidulation of RPR with *phosphoric* acid, is a fundamentally different product than that produced by acidulation with sulphuric acid, and has many advantages. Goh *et al.* (1990) used the term 'PAPR' to represent just phosphoric PAPR in their review, and referred to SSP-RPR mixtures as 'Longlife'. This differentiation failed to become widely used however, as the Longlife name was dropped by the industry. Confusion in terminology is particularly evident in Edmeades *et al.* (1991). Differentiation, both in terminology and agronomic effectiveness, between sulphuric and phosphoric PAPR's was not consistent; PARRphos-18 (the 18 refers to the total P content, unobtainable with a sulphuric PAPR) was incorrectly described as a 'sulphuric acid PAPR' rather than a phosphoric PAPR; and the incorrect statement that 'there would also be a prior delay to the start of dissolution of these products (phosphoric PAPR's)' was justified by the inclusion of a reference to Rajan (1987), who made no such statement.

The advantages of phosphoric PAPR include (i) only 20-40% of the total P needs to come from the relatively expensive phosphoric acid component, compared with over 65% in TSP; (ii) the phosphoric acid can itself be manufactured from a wide range of phosphate rocks, including those with a low total P content, without affecting the P content of the PAPR; (iii) compared with the typical 10% total P in sulphuric PAPR's, the 16-18% P in phosphoric PAPR's substantially reduces storage and transport costs; (iv) phosphoric PAPR's do not contain sufficient gypsum to interfere with RPR dissolution, and therefore (v) maintain much higher concentrations of P in the soil solution surrounding the dissolving granule, which stimulates root growth, ultimately leading to better dissolution of the RPR residue as well.

Most importantly in the context of this paper, the National Series demonstrated that pasture yield obtained with a phosphoric PAPR containing 50% of the total P in water-soluble form (achieved with a 30% stoichiometric acidulation), equalled fully-soluble P from year 1, in all National Series trials in which it was included. This included sites 7 and 9, the two highest P retention sites (98 and 95% respectively) in the Series (Table 1, from Sinclair and Dyson, 1988). Mackay (1990) demonstrated that phosphoric PAPR at least matched SSP in both mown and grazed pasture trials (Figure 4). Rajan and Quin (1985) demonstrated that provided the RPR was finely ground, even a 20% stoichiometric acidulation with phosphoric acid (giving about 30% of the total P in water-soluble form) equalled the performance of fully-soluble P (Table 4) at normal rates of application. Goh *et al.* (1990) reported similar findings.
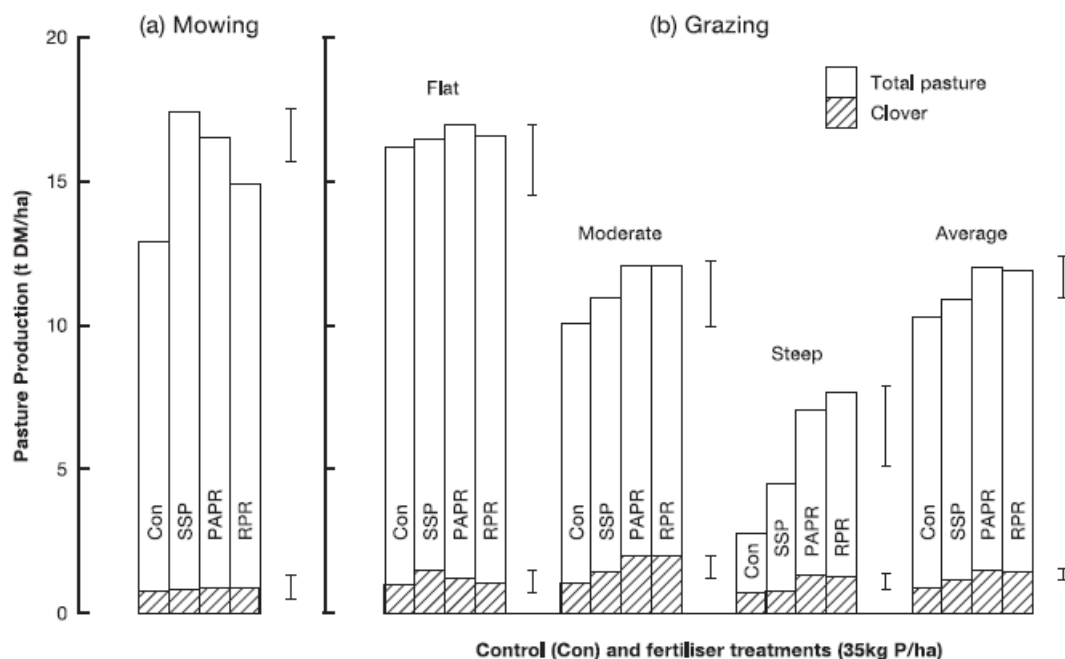
Figure 4: Effect of Control (0 P), SSP, phosphoric-PAPR and unground North Carolina RPR on pasture production under grazed and mown conditions. Bars represent LSD values at the 5% level. From Mackay (1990). Flat refers to <10 degrees slope, moderate 10-30 degrees, and steep >30%.

Table 4: Year One pasture production (t DM/ha) with TSP and phosphoric-PAPR's of differing acidulation rates and water solubilities (% WSP). From Rajan and Quin (1985). Basal S was applied. Numbers in brackets are yields relative to Control=100.

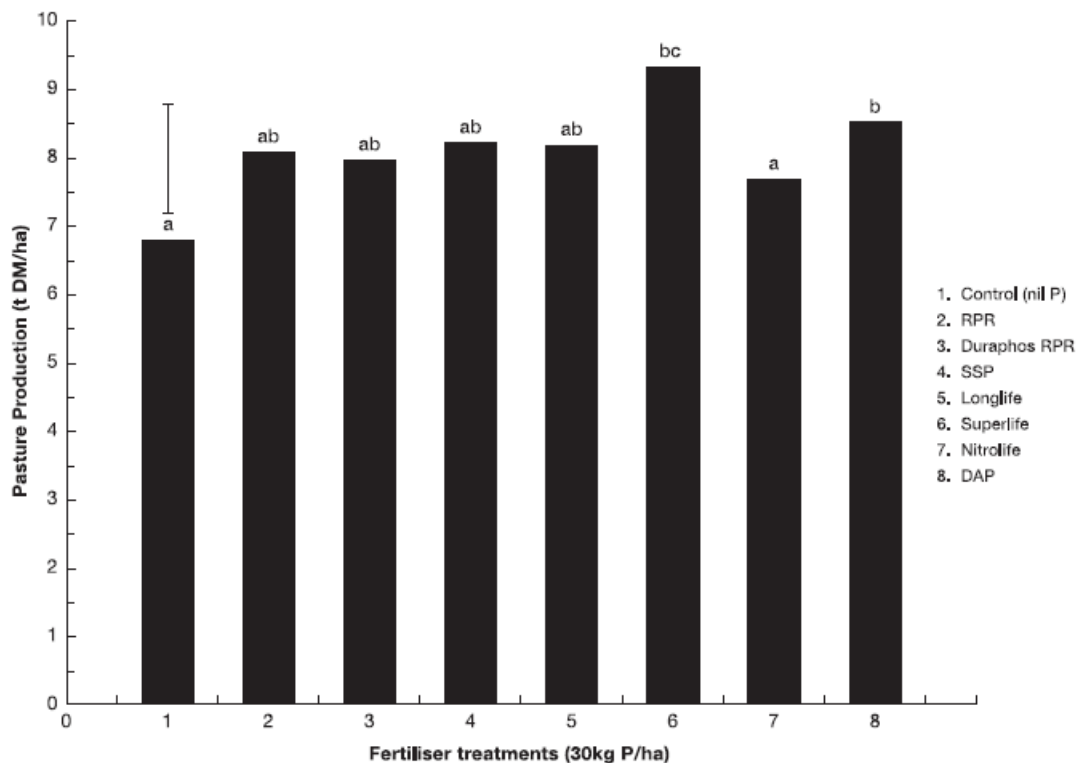| Fertiliser	Rate of P applied (kg P/ha)				
	0	21	42	63	126
Control (no P)	9.3 (100)				
TSP (83% WSP)		10.2 (109)	10.6 (113)	11.1 (119)	11.3 (121)
20% PAPR (40% WSP)		10.3 (110)	10.9 (117)	10.9 (117)	-
30% PAPR (52% WSP)		10.2 (109)	10.6 (113)	11.3 (121)	-
50% PAPR (77% WSP)		10.2 (109)	10.6 (113)	11.3 (121)	-
SED 0.33 t/ha (3)					

Such products were sold in New Zealand in the 1980s. The product 'Hyphos' was manufactured by East Coast Fertiliser (since absorbed into Ravensdown), using imported RPR and phosphoric acid. 'PARRphos 18' was imported as a finished product from North Carolina by FERNZ. These products contained 16 and 18% total P respectively, and 7-8% water-soluble P. Water-dispersible granulated fine elemental S (e.g. 'Terrasul'), or highly-sulphurised SSP were blended in with these products to supply the required S content. Duraphos International Ltd imported a combination phosphoric/sulphuric PAPR made in Israel using 80% phosphoric/20% sulphuric partial acidulation of Arad RPR. This gave the dried product 15.5% P, 6.5% WSP and 5% sulphate-S. Rajan and Watkinson (1992) noted that phosphoric PAPR's need a higher level of acidulation to equal water-soluble P if they are to be made from unground RPR.

Interestingly, there is clear evidence (Bolan et al., 1990; Condron *et al.,* 1994; Di *et al.,* 1994) that the non-acidulated RPR residue in direct phosphoric PAPR's has lower solubility, including, in some cases, a larger crystal a-axis dimension, than the pre-acidulated RPR. This has been assessed as being caused by a combination of several factors, including preferential acidulation of the most reactive sites, and coating of the residual RPR with relatively insoluble complex iron-aluminium phosphates originating either from the RPR or more often from the commercial phosphoric acid used for acidulation. Regardless, there is no evidence that these effects actually reduce field performance relative to commercial 'fully-soluble' P fertilisers; any such effects, if present, are presumed to be at least balanced by the root stimulation provided by the much higher concentrations of P in the soil solution developed around granules of phosphoric PAPR compared with RPR (Bolan *et al.,* 1990).

The major product sold by RPR importer Quinphos Fertilisers (called Summit-Quinphos from 1995) in the 1990s was an indirect phosphoric PAPR made by blending fine ('run-of pile') TSP, RPR and elemental S ('Superlife'). Indirect phosphoric PAPR's, provided intimate contact is maintained between the components in particles, provide the advantages of granulated phosphoric PAPR's while avoiding any possible reduction in solubility of the RPR component. With the required amount of S, Superlife at least matched SSP and Longlife from the commencement of P-responsiveness, and even di-ammonium phosphate (DAP) in non N-responsive situations (Figure 5, from AgResearch 1992).

In the same way that DAP has become increasingly widely used as a replacement for SSP on ryegrass-dominant, N-responsive dairy and intensive beef farms since the late 1990s, DAP simultaneously took over from TSP as the soluble P component form of choice in blends with RPR. Summit-Quinphos developed a product called 'Dairy King', which, besides having the same 20% P content as TSP, the 18% N in DAP provides N at very competitive cost to urea for use in N-responsive situations. Again, fine elemental S, either granules or simply blended in to the RPR/DAP mix, was used to supply the S required.

Figure 5: Pasture yield September 1991-May 1992 for a range of P fertilisers applied once at 30 kg P/ha. Nitrolife (7) is a blend of RPR and sulphate of ammonia. Longlife (5) is a semi-granulated post-den blend of RPR and SSP. Superlife (6) is a dampened blend of RPR, TSP and elemental S. Bar represents LSD at 1% level. From AgResearch (1992).

Fluidised or Wetted Mixes of RPR, DAP and S

In New Zealand, suspension-type type fertilisers were spread on pasture by helicopter, and because of high operating costs, were typically applied at below-maintenance rates. The rationale for low application rates was a claimed but unsubstantiated 10-fold higher nutrient efficiency. In recent years however, fluidised (high-solids liquid) and wetted products have started to establish themselves as 'mainstream' fertilisers, at maintenance levels of application by both air and land.

While there is no known evidence that the application of P in DAP/RPR mixes in solution, fluidised or wetted form is more efficient than if the P is applied in dry form, there are indirect advantages, as follows. First, the product makes a good base for the addition of extra N where required, in the form of fluidised or wetted urea treated with a urease inhibitor such as the N-(n-butyl) thiophosphoric triamide (nPTPT) product sold as 'Agrotain'. This product has been shown to be far more efficient than granular urea - now used in large quantities on dairy farms - due to partial foliar uptake, and reductions in both ammonia volatilisation

and nitrate leaching (Quin *et al.,* 2005; Quin and Findlay, 2009; Dawar *et al.,* 2011; Zaman *et al.,* 2013). Secondly, trace elements are almost invariably far more efficient when applied in liquid as opposed to solid form, as this both facilitates foliar absorption, reducing the risk of their fixation onto soil particles. Third, major nutrients show either none or some benefit because of partial foliar uptake; none are known to be less efficient. Fourth, micro-uniformity of distribution is achieved. Fifth, physical placement of finer particle products may be more tightly controlled, and wind drift potentially reduced (Quin 2012). Last but not least, a wide variety of different physical forms of fertilisers (fine, coarse, granulated, and liquids) can be applied at the same time, and virtually any additives (solid or liquid) or growth-promoters such as gibberellic acid can easily be incorporated. RPR, DAP and elemental S blends, with and without urea, make a suitable base for such products.

Quin and Zaman (2012) and Quin and Zaman (2013) demonstrated that the size and duration of the 'lag-phase' in pasture production on switching from soluble P such as SSP to RPR was far less than reported by other authors (Perrott and Metherell, 1997). Typical and (maximum) levels of the lag were 3(5) % in year 1, and 1(3) % in year 2 in all soils reported (Quin and Zaman, 2012), but the maximum was found to be higher (7%) in year 1 on pumice soils (Quin and Zaman, 2013). Nevertheless, any lag creates a significant barrier to adoption by farmers. Most are aware in general terms of the environmental benefits of RPR in terms of greatly reduced P run-off (Hart *et al.*, 2004), but there is currently little advisory encouragement to use it; the one exception is in the P-sensitive Lake Brunner catchment in Westland. The survey reported by Zaman and Quin (2012) found that virtually all farmers who had switched to RPR some years before were totally satisfied with the production they achieved with it, and intended to keep using it, but most recalled that the possibility of a lag-phase was a concern initially.

Conclusions

This paper demonstrates that there are readily available options for farmers to manage the switch to RPR-based fertiliser. These alternatives generally incur no additional fertiliser cost to the farmer. Options (a), (b) and (c) are less advantageous because they incur a small lag in pasture production. The recommended options are (d) and (e), *viz.* direct or indirect partially acidulated phosphoric acid products in either dry or wetted form, as these options exhibit no lag phase. Granulated versions of (d) would combine the agronomic benefits with wider spreading width.

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