

RPR revisited (1): Research, recommendations, promotion and use in New Zealand

B. F. QUIN¹ and M. ZAMAN²

¹*Quin Environmental (NZ) Ltd, PO Box 125122, St Heliers, Auckland 1740, New Zealand*

²*Ballance Agri-Nutrients Ltd, Private Bag 12503, Tauranga 3143, New Zealand*
 quinfert@xtra.co.nz

Abstract

Reactive phosphate rock (RPR) has been studied extensively in field trials and laboratory research in New Zealand since the 1930s. This paper looks at the different approaches to research over the decades, at what conclusions were drawn, at the recommendations made to farmers, and at the commercial promotion and sales of RPR. It is not an exhaustive literature review, but sufficiently comprehensive to demonstrate the large amount of research conducted, and to document the important issues that have arisen, particularly with respect to advice being given to farmers. RPR research has suffered from a series of mishaps which have hindered, in one way or another, the results being accurately interpreted and passed on clearly to farmers. There is a need for specific advice for farmers regarding managing or minimising any lag in production following a switch to RPR. New Zealand's grazed pastures, water quality and "clean and green" image internationally are closely interlinked. Given the proven significant reduction in P losses in run-off to waterways with RPR, the conditions in which RPR can be successfully used in New Zealand's pastoral agriculture have been reassessed.

Key words: reactive phosphate rock, RPR, superphosphate, SSP, TSP, PAPR, long-term comparisons, plot trials, grazing trials, fertiliser recommendations, history

Early RPR research

New Zealand has a long history of research comparing reactive phosphate rocks (RPRs) with single superphosphate (SSP), dating back to unpublished Department of Agriculture trials of the 1930s. Reasons for this continued interest included concerns regarding world sulphur (S) supplies for SSP production, the limited life of the Christmas and Nauru Island deposits for manufacturing SSP as well as their high cadmium (Cd) content, increasing manufacturing costs, and the attraction of RPR as a natural product for organic and biological farming. For cost and uniformity reasons, the vast majority of field comparisons have been mown plot trials rather than under grazing.

The value of the early research was diminished by

lack of awareness of the extent of S deficiency prior to the mid-1950s. Hence, while most trials had basal potassium (K) applications, few had either basal S applications or S treatments (Doak 1942). Walker *et al.* (1955) emphasised the need for basal S, but this did not become standard practice until the late 1960s. Nevertheless, Cullen (1958) was able to conclude, based on trials where S deficiency was considered unlikely, that Gafsa (Tunisia) "soft" rock came to equal the performance of SSP over time, provided heavy lime applications had not been made. Scott and Cullen (1965) reported that Gafsa RPR "gave remarkably high residual yields".

Unfortunately, the value of trials conducted in the 1960s and 1970s received a new blow, this time from the increasing use by SSP manufacturers of the low cost but high aluminium (Al) and iron (Fe)-content Christmas B and C grade phosphate rock during this period. This resulted in the presence of complex calcium iron aluminium phosphates of very poor plant availability in SSP, the seriousness of which, and its explanation, were not proven until 1981 (Brown 1981; Quin 1981b, 1982). As a result, the true efficiency of RPR in any particular trial was difficult to determine, because of doubts regarding the efficacy of the SSP it was being compared with. For example, Grigg (1980), Grigg & Crouchley (1980), Grigg & Thompson (1982) and Grigg *et al.* (1982) used a commercial SSP containing 8.7% total P, 7.2% citric P and only 6.5% water-soluble P in comparisons with Gafsa RPR, Nauru phosphate rock, calcined C-grade Christmas Island phosphate rock and Thermophos. They found that Thermophos (a fused magnesium phosphate) consistently and substantially outperformed SSP, but could not find a reason for this result. Quin (1982) demonstrated that pure monocalcium phosphate and gypsum greatly outperformed commercial SSP made from aluminium- and iron-rich phosphate rock.

The "National Series" and other mown-plot RPR trials of the 1980s

To avoid the complication of variable SSP performance, the MAF "National Series" of RPR trials, commenced in 1982, used a range of application rates of high quality

USA-manufactured triple superphosphate (TSP) for the reference response curve, compared to the same rates of P as Sechura (Peru) RPR, both with basal S (as gypsum) and other major nutrients applied. There were 19 sites in the Series, which were all selected to be at just-maintenance soil P fertility. The Series ran for 6 years (though some sites were changed to investigate residual effects after 3 or 4 years) and involved 12 MAF scientists initially. An excellent detailed description of the trials, treatments and protocol is found in Sinclair & Dyson (1988). Several other products, including locally-manufactured SSP (which had already improved greatly in most cases), TSP/elemental S and RPR/S blends (both without basal S), partially acidulated RPR (PAPR), and other straight RPRs including North Carolina and New Zealand's Chatham Rise RPRs, were also included, at single rates of application calculated at 0.75 of the maintenance P requirement for each site. Annual applications of TSP and RPR were also compared with triennial applications on some sites.

Pasture production data for the first 3 and then 4–5 years (depending on the trial) were published by all the scientists involved (Quin *et al.* 1985, 1987 respectively). The latter publication also presented a predictive model for relative pasture production, incorporating soil pH, P retention, P fertility, climate zone and time. Sinclair *et al.* 1989 presented a summary of the full 6 years. Smith *et al.* (1990, 1991a,b) reported the full data for the entire Series. In a brief published summary, Sinclair *et al.* (1990a) demonstrated that overall, RPR was inferior to TSP in Year 1, but attained equivalence with TSP in the third or fourth year of use, and exceeded TSP by year 6 (Fig. 1).

Because of MAF's dual role in research and extension, through the Agricultural Research and Farm Advisory Divisions respectively, the "National Series" received more prominence than other RPR trials. However, other very significant research was also conducted during the 1980s, principally by researchers from Massey University and the MAF's Agricultural Research Division, such as that presented by various authors in the RPR-specific workshop hosted by Massey University's Fertilizer and Lime Research Centre (FLRC) edited by Syers & Gregg (1981), and followed by many more such as Gregg *et al.* (1988), Korte (1988), Ledgard *et al.* (1992), Loganathan *et al.* (1995), Mackay *et al.* (1982, 1984a,b, 1986), Mackay (1990), McBride (1992), Percival *et al.* (1984), Perrott *et al.* (1993, 1996), Rajan & Upsdell (1981), Rajan & Gillingham (1986), Rajan *et al.* (1994), Rajan (2002), Saggar *et al.* (1992a,b, 1999), Sinclair *et al.* (1998), Smith & Sinclair (1998), and Syers *et al.* (1986). As well as providing additional RPR pasture production data, topics covered by these authors included comparisons of different RPRs, comparisons of PAPRs with SSP and

RPR, the effects of earthworms on RPR dissolution, and soil chemistry studies including the development of the new resin P test, which became widely used by RPR users because it better reflected the P-supplying ability of RPR reserves built up in the soil (Saggar *et al.* 1999).

1987 – RPR is introduced into the New Zealand market

The collective data from these field trials was sufficiently encouraging by 1987 for Fletcher Challenge Corporation to set up a new company (Duraphos International Ltd) to import both Arad RPR and a granulated phosphoric/sulphuric partially acidulated RPR (PAPR) from Israel, which were marketed through their subsidiary Wrightsons. Duraphos also bought out Northern Phosphates Ltd, which had started to import North Carolina RPR into Northland. However, the sharemarket crash which followed led Fletchers to exit what were regarded as "non-core" businesses, and Duraphos was liquidated in 1988. The distribution rights to the Arad and North Carolina RPR were sold to the SSP industry. Arad RPR became too expensive and the high Cd content of North Carolina RPR led the company operating the mine to remove it from sale as an RPR, and use it solely to produce phosphoric acid (from which most of the Cd can be removed). Two new independent companies, Quinphos Fertilisers (NZ) Ltd (later to become Summit-Quinphos (NZ) Ltd), and Norphos (later to become Asura) commenced operation in late 1989. Quinphos imported RPR from Egypt and Tunisia, and increasingly focused on promoting branded products such as Superlife and Dairy King containing RPR blended with TSP and DAP respectively (at 20–40% of the total P). These products were designed to minimise any lag-phase in production. Norphos imported Sechura RPR from Peru.

The 1990s – a decade of debate

The wide range of sites, soils, pH and rainfall used in the National Series should have made this database ideally suited for production of straightforward and succinct advice to farmers regarding pasture production with RPR relative to soluble P. However once again the opportunity for a definitive scientific assessment of RPR vs SSP was compromised, this time by scientific disputes. Resolution of these was complicated by the lengthy reorganisation of MAF's Agricultural Research Division into MAF Technology (MAFTech) and then into the AgResearch CRI from 1987 until the mid-1990s. The resulting absence of consistent oversight helped lead to a proliferation of confusingly overlapping publications and interpretations of the National Series trial data by different combinations of authors (Sinclair *et al.* 1990a,b,c, 1993a,b, 1994, 1997; Edmeades *et al.* 1991; Perrott *et al.* 1992; Risk *et al.* 1992; Morton *et al.* 1994; Roberts *et al.* 1994).

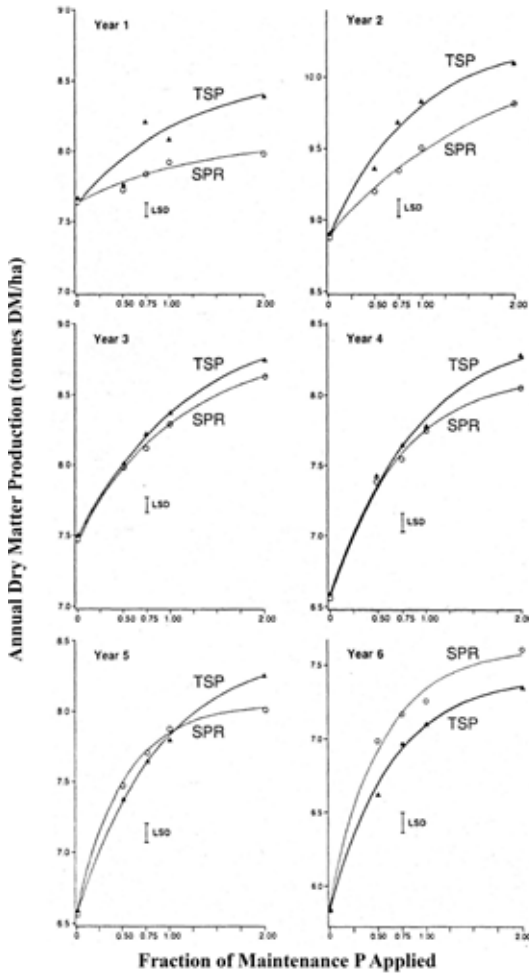


Fig. 1. Mean annual response curves for all operating trials in year 1 to year 6 (from Sinclair *et al.* 1990a), TSP - triple superphosphate; SPR - Sechura Phosphate Rock

Some apparently arbitrary decisions were made regarding which trials were “unreliable” and therefore unsuitable for basing advice to farmers on, or for developing predictive models. For example, 7 of the 19

trials (sites 2–5 in Northland and 16–18 in Southland), were excluded from consideration on the grounds that good RPR performance at these sites may have been in part due to the high levels of molybdenum (Mo) in Sechura RPR, and that these sites “may have been” Mo-deficient (Edmeades *et al.* 1991). In an earlier paper addressing this issue, Sinclair *et al.* (1990b) had demonstrated that Mo levels in pasture were below the MAF’s minimum recommended level for pasture (0.1 ppm) in only two of the sites, both of which (sites 2 and 3) were in Northland. Pasture yield data from Smith *et al.* (1990) demonstrates that pasture production with two other RPRs, both of which had very low Mo, equalled Sechura RPR at the five other sites (Table 1). This important fact appears to have been overlooked or misinterpreted. The removal of sites 2 and 3 does not materially affect Fig. 1.

The Ballard review of 1991 ...

Industry discontent with the treatment of the National Series data, and with various media statements, resulted in the then Director General of MAF publishing a summary of RPR performance written by an invited panel which included independent experts Professor Ian Cornforth and Dr Roger Parfitt (Ballard 1991). The panel was charged with reviewing all the National Series data, and all other published data, and producing recommendations for farmers regarding the use of RPR. It is worth repeating their summary here:

“MAF RPR Recommendations for Farmers (Ballard 1991)

1. Do not use RPR if pH is greater than 6.0 or there is less than 800 mm rain plus irrigation per year.
2. For a rapid increase in soil P status (1–2 years) use a soluble P fertiliser. For a more gradual increase, RPR will be effective.
3. To maintain an adequate soil P status (for the desired stocking rate) if the current P status is more than adequate, either use no P fertiliser or apply a light application of RPR; perhaps half maintenance.

Table 1. Total pasture production in Northland and Southland over 6 years with soluble P forms (averaged), Sechura RPR (high Mo content) and other (low-Mo content) RPRs (averaged), at 0.75 Maintenance P, compared to nil-P. Low plant Mo sites (Northland sites 2 and 3) excluded. Data from Smith *et al.* 1990.

	Nil P control	Soluble P	Sechura RPR	Other RPRs
Northland sites 1,4,5	41561 (100)	46858 (113)	47283 (114)	46336 (111)
Southland sites 16-18	42819 (100)	47553 (110)	46563 (109)	46499 (109)

Note: there were no statistically significant difference in pasture production between Sechura RPR and other RPRs, or between RPR and soluble P fertilisers at these sites.

Use RPR or superphosphate at full maintenance rates when the soil P status approaches the desired range.

4. If the soil P status is currently in the desired range, use RPR or superphosphate. The RPR may produce slightly less dry matter in the first 1–2 years. This decline is unpredictable but it is likely to be less than the seasonal fluctuations normally experienced in pasture production. After 1–2 years of using RPR, the residual effects of early applications should remove any yield differences between RPR and soluble P fertilisers. The decline in production in the first 1–2 years following a change to RPR is likely to be of practical importance only if stocking rates and pasture utilisation are already near maximum.
5. If RPR has already been used regularly for 3 or more years there is unlikely to be any benefit from returning to superphosphate.
6. Where superphosphate and RPR are equally effective, the choice should be based on considerations such as cost, the need for sulphur, or organic farming practices.
7. These recommendations are summarised in the attached “decision tree”. However, the best advice will be obtained by considering more aspects of a farmer’s attitudes to risk, management skills and financial status than can be incorporated in such a diagram.”

...and the aftermath: the ever-lengthening “lag-phase”

A group of AgResearch scientists subsequently criticised these recommendations, insisting that the time to equivalence with soluble P was 4–6 years. Sinclair *et al.* (1993a) excluded all but four of the National Series trials from a re-interpretation. Two of these were high P retention and one had a combination of high soil pH and low rainfall. Overall, these trials indicated a 6 year lag-phase. However, in a later 3-year comparison of SSP and a range of RPRs at two sites, Sinclair *et al.* (1998) concluded that there was a lag-phase of as much as 6 years at the site on a very high (96%) P retention at Te Kuiti, whereas RPR matched SSP by year 3 on the low-medium (41%) P retention site at Woodlands. These trials also demonstrated the much poorer performance of RPR where coarse samples were used. Unfortunately, the conclusion regarding the lag-phase at lower P retention was not incorporated into farmer recommendations.

The commercial impact of the advisory change to a minimum “4–6 year” lag-phase was very significant; many farmers were prepared to accept, and manage, a lag-phase of 1–2 years, but not one of 4–6 years.

The RPR dissolution-based econometric model

Perrott & Wise (1995), Perrott *et al.* (1996), Perrott & Metherell (1997), and Metherell *et al.* (1997) measured RPR dissolution rates at a wide range of sites, and modelled the effects of RPR particle size (i.e. surface area available for dissolution by soil acid), rainfall, exchangeable magnesium, soil P retention and drainage on RPR dissolution. This model, with economic analysis added, appeared to predict a lag-phase of at least 6 years in almost every situation; predicted lags of 15 years were not uncommon. One of the inherent weaknesses of the model is that it makes the unproven assumption that P applied in soluble form is consistently available across all sites, and behaves in the same way over time as P becoming slowly available from RPR. In addition, the far superior residual pasture production with RPR in the years following cessation of multi-year application (due to accumulated reserves of slowly-dissolving RPR, as demonstrated by Perrott *et al.* (1992, 1996) was not incorporated into the model. The model was introduced as a tool for field representatives by the SSP manufacturers in 2003, and it was briefly incorporated into Outlook, the forerunner of Overseer®. It is not now part of Overseer 6® (Wheeler 2012, pers. comm.). While the model may predict RPR performance reasonably well in conditions that are severely adverse for RPR, its possible underestimation of RPR performance in more typical New Zealand farm conditions did nothing to help the uptake of RPR by farmers.

The ongoing debate and confusion surrounding RPR in New Zealand compared poorly with Australia, which ran its own National Series, based on the New Zealand Series. It ran for 4 years from 1992–1995 inclusive, and through consistent management and goodwill, resulted in a better-balanced summary and a relatively sophisticated and inclusive predictive model, with papers on different aspects of the trial results and laboratory research, and a predictive model, being published concurrently in a dedicated issue of the Australian Journal of Experimental Agriculture (Sale *et al.* 1997). Despite this, commercial promotion and use of RPR in Australia has been limited, mainly because of an aversion to dusty non-granulated products.

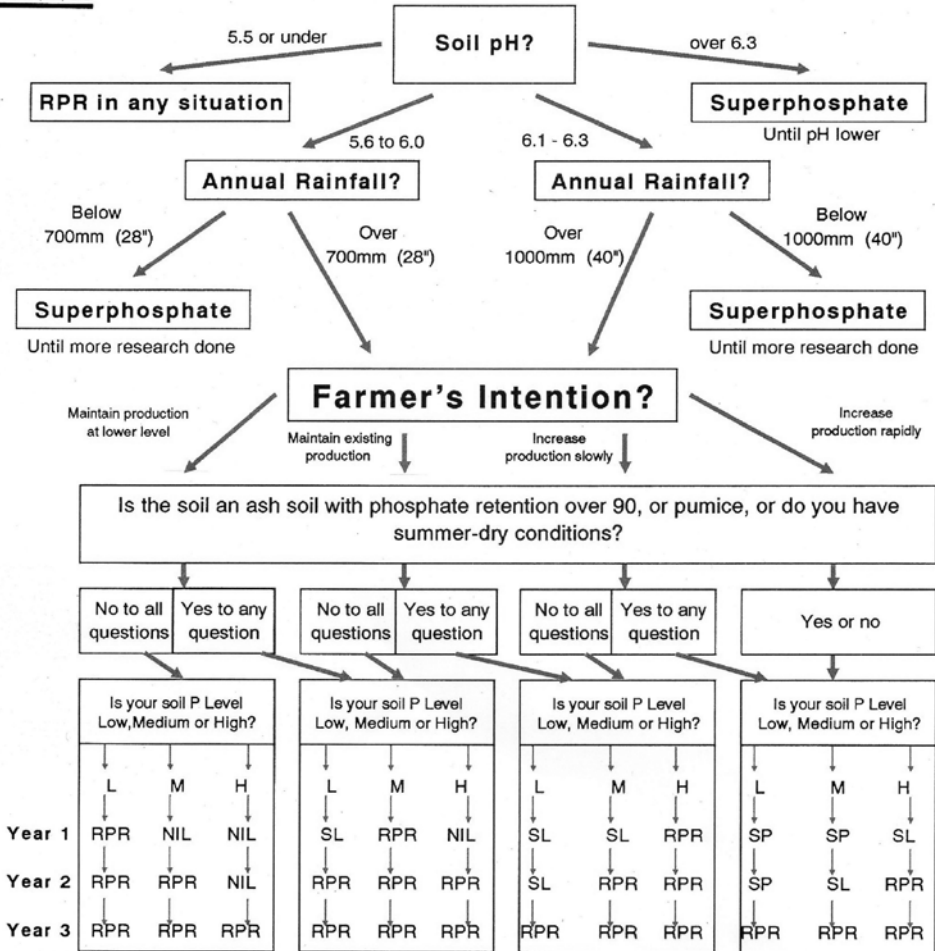
Bridging the lag-phase

Adoption of RPR by farmers in New Zealand was not helped by the absence of any formal advisory information for farmers on how best to change from SSP to RPR with as little lag-phase as possible, which became far more important if a 4–6 year lag was assumed. Field trials conducted with PAPRs and RPR/soluble P mixes (Mackay 1990; Mackay & Wewala 1990; Rajan & Marwaha 1993; Rajan *et al.* 1994; Smith *et al.* 1990) demonstrated that unlike high-gypsum content ‘Longlife’ SSP/RPR products (Ledgard *et*



"QUINPLAN" DECISION TREE FOR SWITCHING PASTURE FARMS FROM SUPERPHOSPHATE TO QUINPHOS RPR

- With absolutely no loss in production and with guaranteed savings -



NOTES:

- | | | |
|----------------------------|--|-------------------------------|
| | <u>Sedimentary and Peat Soils</u> | <u>Pumice & Ash Soils</u> |
| 1) Soil P Status (Olsen P) | - L (Low) <9
- M (Medium) 9 - 19
- H (High) >19 | <15
15 - 30
>30 |
| 2) | This table determines the form of phosphate to be applied in Years 1, 2 and 3. The rate of P to be applied, and which other nutrients such as sulphur, potash and trace elements should be applied, and in what quantity, must be assessed from stocking rate, rainfall, soil tests and plant analysis. In general, to slowly increase production will require 50-100% increase in P over maintenance for 2 years; a rapid increase will require 2 to 3 times maintenance for 1 to 2 years. | |
| 3) | SP is a fully soluble superphosphate with thermal sulphur. Superlife (SL) is a blend of TSP and RPR (and sulphur). Nitrolife, a blend of RPR and sulphate of ammonia, can be substituted for both superphosphate (SP) and Superlife in all cases. It is the preferred option to SP and Superlife where a quick boost in growth is needed to get through an impending feed shortage. A further alternative, where SL is recommended in year 1, is to apply a double application of RPR instead. | |

Fig. 2. Example of the "Quinplan" Decision Tree.

al. 1992), non-gypsum or 'phosphoric' PAPRs and equivalent blends equalled the performance of soluble P from the start. Unfortunately, farmer education on this way of avoiding the lag-phase was left almost entirely to RPR importers, for example that shown in Fig. 2.

RPR definition

The confusion regarding RPR efficacy was exacerbated by the concurrent dispute over just which commercial products qualified as an RPR and which didn't. The industry-agreed definition of an RPR was "a phosphate rock in which at least 30% of the total P was soluble in the 2% citric acid test" (Brown & McGovern 1991). The intention was, by doing the test on RPR in "as sold" condition, products that were too coarse to be effective would not reach 30% solubility. Unfortunately, the test result could not, for example, differentiate between a true RPR and a semi-reactive phosphate rock mixed with highly citric-soluble Sechura RPR. Likewise, very poor solubility tests and field performance could be obtained by the selection of atypical, extremely coarse sub-samples, particularly of the Kosseir RPR from Egypt which contained a proportion of very coarse particles (Sinclair *et al.* 1998). In a detailed comparison of solubilities, Brown & McGovern (1991) demonstrated that RPRs from North Carolina, Sechura, and Kosseir (Egypt) had comparable solubilities on a particle-size basis (Table 2), in accord with the later independent recommendation for a maximum crystal a-axis dimension for recognised RPRs of 9.340 Å (Van Kauwenbergh 1998). Kosseir RPR initially suffered from limitations the Egyptian producer had in ensuring adequate grinding and screening of the product, which on occasion required Summit-Quinphos to screen some

shipments before use, and regrind the coarse material.

Other RPRs that were not available in New Zealand in 1991, but are certain to be ranked alongside those in Table 2, include Gafsa (Tunisia) and the Algerian RPR, which is actually an extension of the Gafsa deposit, where Cd levels are lowest.

Farmer use of RPR

Given the debate and confusion, it is perhaps quite remarkable that the RPR importers managed to grow RPR sales to nearly 150 000 tonnes annually by 2005 (including defensive sales by the SSP manufacturers), far higher than in Australia. Summit-Quinphos sold over 70% of the total, mainly as blends with soluble P and other nutrients. At this time, RPR and RPR blends constituted 10% of the New Zealand fertiliser market on a P nutrient basis (Table 3, from Farm Market Index 2005). Farmer-user enthusiasm for RPR has continued with the incorporation of Summit-Quinphos (now Altum) into Ballance Agri-Nutrients in 2007 (Zaman & Quin 2012).

RPR in Overseer®

Overseer® now incorporates RPR, with some slight adjustments, into the "steady-state" model used in its nutrient budget programme, which assumes that P supply from RPR has more or less reached equilibrium with dissolution rates, and is equally effective as recently applied soluble P. It incorporates relatively recent research findings demonstrating that P losses in surface run-off are significantly reduced where RPR is used (McDowell *et al.* 2003; Hart *et al.* 2004; McDowell & Catto 2005; Gillingham & Gray 2007), although these are not as yet reflected in the

Table 2. Comparison of solubility (percent of total P soluble in 2% citric acid) of phosphate rocks by particle size (from Brown & McGovern 1991).

	microns					cm		arithmetic average 75-1000 mm
	0-75	75-150	150-250	250-500	500-1000	1-2	2-4	
RPRs								
Sechura (Peru)	NA	39.4	37.3	34.4	20.4	NA	NA	32.9
Kosseir (Egypt)	47.1	37.0	34.4	29.1	23.8	20.0	18.9	31.1
North Carolina	44.7	34.6	30.8	27.8	24.6	20.5	NA	29.4
Arad (Israel)	34.5	33.1	30.4	27.4	21.7	17.8	18.2	28.2
Med-PR								
Yousouffia (Morocco)	36.1	29.0	25.5	22.9	23.2	21.1	20.2	24.6
Low-PR								
Nauru Island	26.8	23.8	20.7	19.2	15.6	13.0	9.5	19.8

Note: 30% citric solubility in the product as sold became the industry-agreed minimum for sale as an 'RPR'. From these results, it is obvious that it was extremely important to take representative samples for testing and field trials. 'NA' means there was no product in this size range in the samples tested.

Med-PR, Low-PR – medium and low reactive phosphate rocks, respectively.

generation of lower maintenance P recommendations. It does not attempt to address the issue of how to overcome any lag-phase in available P, and therefore production, in the first few years after switching to RPR. The reductions in P run-off with RPR, while not of a size to be a direct economic incentive to farmers, are certainly large enough in many cases to determine whether or not a P-sensitive catchment becomes eutrophic.

A new approach to assessing RPR performance

In this paper, the authors have taken a new approach to assessing RPR vs soluble P pasture production data from the National Series, through the use of distribution curves of the percentage departure in DM yield from the nil-P control, for both soluble P and RPR-P. This technique enables multi-trial, multi-year data from product comparisons to be presented in a simple and compelling way. In this presentation, each full year at each P rate of each trial was treated as a separate input. Each rate of P was plotted separately. Only annually-applied treatments were included. As a precaution, data from Sechura RPR treatments from sites 2 and 3 were not included because of low plant Mo contents. Data from other RPRs at these sites (and all other) were included. Site 16 (Canterbury) was excluded because of its combination of high soil pH (6.3) and low rainfall (712 mm). Each “soluble P” point plotted had a same-trial, same-year, same-rate RPR-P point, to increase the robustness of the comparison. An application rate of 0.75 times the assessed maintenance rate (0.75 M) was the most commonly used. This was useful, as it ensured actual P responsiveness.

The use of both TSP and SSP data for soluble P, as well as data from all three RPRs, greatly increased the number of data-points for soluble P and RPR compared to any previous interpretation of the trials, further increasing the robustness of the comparison, and increasing the strength of the conclusions reached. In

previous scientific publications, the logistical and space difficulties inherent in presenting the mass of available data have resulted in either (i) the condensation of data into a small number of P response curves or tables, each covering many trial sites or years, or (ii) excluding as many trials as possible from evaluation.

Our objective in this paper was to find a method method of presentation that did justice to the data by allowing it to “speak for itself to farmers”, while still being subjected to the rigours of statistical analysis. We came to the conclusion that P response cumulative distribution curves were best suited for this purpose. Within this objective, our priorities were twofold, both with the aim of assisting farmer understanding and inclusion. The first priority was to group the trials into a combination of geographic farming areas and major soil types in which the pattern of response to P itself, and the differences between soluble P and RPR, were broadly similar. On investigation, it was found that the trials could be split into six different groups on this basis (Table 4). The second priority was to examine the duration and extent of the RPR “lag-phase” in each of these groups, to assist in producing, in combination with a survey of long-term RPR users, updated recommendations for RPR use (Zaman & Quin 2012).

P response cumulative normal distribution curves using data for the six different regional/soil P retention groupings, are shown in Fig. 3, split into Years 1 and 2 and Years 3–6 (except in the case of group 3c, which ran for 3 years only). In each graph, the left axis shows the number of results in any particular response interval of 2% for soluble P and RPR. The right axis shows the cumulative percentage of results less than any particular percentage response to P, of the normal cumulative distribution curves of soluble P and RPR represented by continuous and dashed lines, respectively. The grouping of the yearly data into the years 1 and 2 and years 3–6 is based in the statistical analysis (Tables 5a, 5b) which

Table 3 Farm Market Index: Fertiliser Products Containing P. Manufacturer Shares by Regions. Year to end September 2005.

		Ravensdown	Ballance	Summit-Quinphos	All others
		%	%	%	%
	NZ total (weighted)	44	39	10	5
North Island	Total	36	43	13	7
	Northland	16	53	24	5
	Central East	5	76	10	7
	Central West	20	66	6	7
	East Coast	73	7	16	3
	Taranaki	65	16	16	2
	Southern NI	56	17	5	17
South Island	Total	61	31	5	3
	Northern SI	82	10	4	3
	Southern SI	42	49	6	3

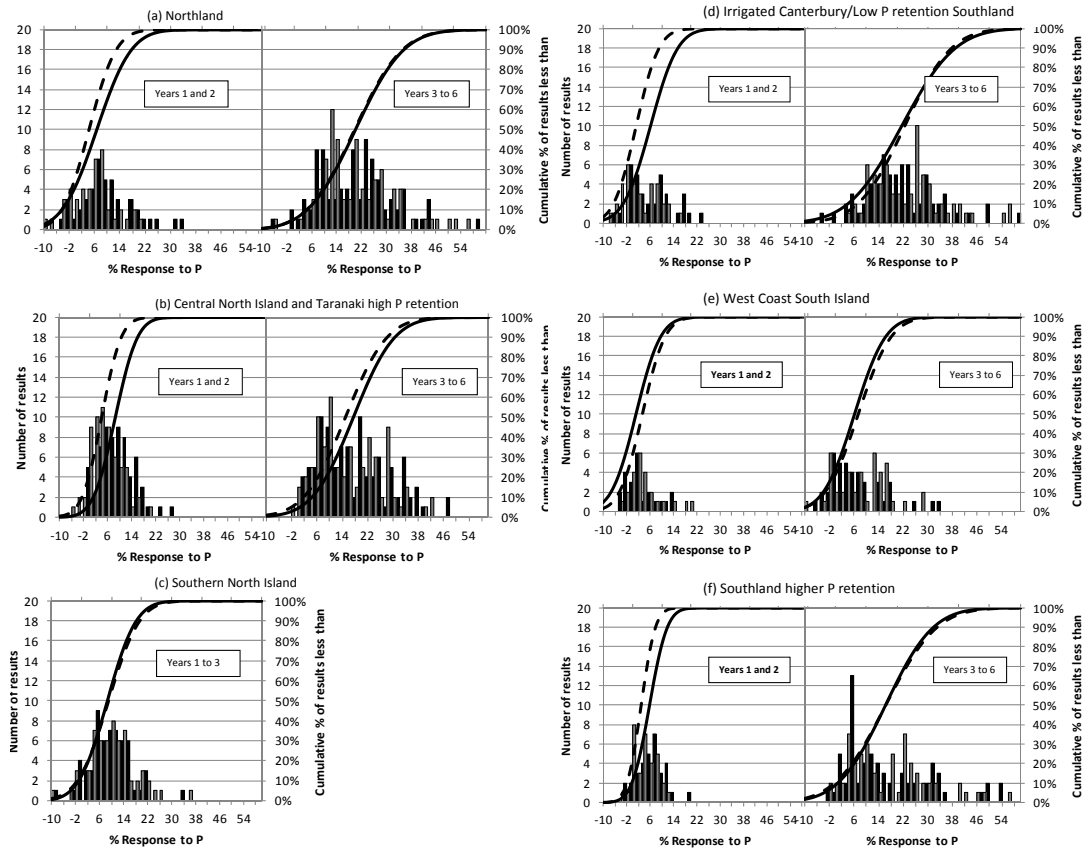


Figure 3 a-f. Frequency distribution (2% group classes) of % response to P from the 'National Series' trials. Soluble P (sol P) responses are shown in black columns and RPR in gray columns. Normal cumulative distribution curves (based on population mean and standard deviations) are shown with solid lines for sol P and dashed lines for RPR. The results are grouped in 6 sets based on geographical location and soil P retention, and show combined results of years 1 and 2 and 3 - 6 in groups a, b, d, e, f, and year 1-3 only in group c, and are based on the statistical analysis in Tables 5a,b.

shows some significant P response differences in the first 2 years between the soluble P and RPR.

As an overall observation, the curves for the six groups clearly illustrate that (i) the differences in effectiveness between the two forms of P are small (especially after year 2), and (ii) the range of responses to P in any group are similar. Both forms of P unquestionably "work"; that is, do their job of maintaining pasture production over time.

Statistical analysis (t-tests) of the year-by-year data within the six groups (Table 5a) enables more specific conclusions to be drawn:

- In Year 1, soluble P produced significantly ($P < 0.05$) higher pasture response than RPR in groups a, b, d and f (see Table 4 for definitions).
- In Year 2, this occurred in groups a, b and d.
- In Year 3, this occurred in group f only.
- In Year 4, there were no significant differences between soluble P and RPR.
- In Year 5, RPR produced significantly ($P < 0.05$)

higher pasture production response than soluble P in group e.

- In Year 6, there were again no significant differences between soluble P and RPR.
- Overall assessment of the data in Fig. 3 and Table 5 leads to the conclusion that, with the possible exclusion of high P retention soils, the "lag-phase" lasts for the first 2 years of use only. (Note that this conclusion is slightly less clear regarding the West Coast soils (group e), because of the low responsiveness to P initially).
- When this high P retention Southland data (group f) is considered in conjunction with the indication of numerically quite large (but statistically non-significant) differences in pasture response in favour of soluble P for the first 5 years in group b (high P retention, central North Island and Taranaki), it seems reasonable to assume that the lag-phase *can be* significantly longer than 2 years on very high (>80%) P retention soils, perhaps

as much as 5 years or more. This is in agreement with the findings of Sinclair *et al.* 1998. This longer lag-phase may reflect the ability of recent soluble P applications to temporarily flood the soil with plant-available P in the vicinity of fertiliser particles, before equilibrium is reached with P adsorption sites in the soil, giving a temporary response advantage in some situations. It would seem prudent for farmers on these soils to consider using, at least for the first few years, a blend of RPR and (low-gypsum content) soluble P, rather than solely RPR as the P source.

- In the four other groupings, the question arises, in the context of farmers managing much larger but uncontrollable year-to-year variations in production due to climatic variation (Fig. 1), whether there is any real point in farmers, and hill country farmers in particular, worrying about attempting to avoid a 2-year lag-phase that is scientifically real, but unlikely to impact on the farm operation in any practical way.

Grazing vs mowing

Much higher costs and resource requirements, and inherently greater variability, have restricted the number of comparisons of RPR and soluble P conducted under grazing, that is, in “real” conditions. However, the beneficial effects of animal treading on RPR entry into the soil for dissolution by soil acid have long been suspected.

Thomson & Roberts (1995) reported the results of a 4-year, unreplicated comparison of milksolids production with maintenance RPR/S and SSP at two stocking rates on a very high P retention soil on the Taranaki Agricultural Research Station (TARS). Despite the barely-adequate initial Olsen P levels of 28–30, no differences were recorded in any of the 4 years. This compares to the median 2.7% lower pasture production from RPR/S on similar soils under mown plot conditions (Table 4).

Mackay (1990) compared responses to SSP, RPR/S and a phosphoric PAPR on a low P retention, low pH soil (5.2), Olsen P 11, under both mown and grazed conditions near Woodville. Under mowing, SSP outperformed RPR and to a lesser extent PAPR in Year 1,

but no differences occurred under grazing. In Year 2, no responses to fertiliser P were obtained under mowing on rolling hill country, whereas under grazing, both RPR and PAPR indicated higher production than SSP on moderate and steep slopes, indicating less transfer in pasture resulting from luxury P uptake (Gillingham & During 1973).

Ledgard & Jones (1991) compared Arad RPR and SSP over 3 years under both mown plots (pasture yields measured only) and sheep-grazed pasture on a hill country soil with low Olsen P (8-10) and very high P retention (96%). The site was located close to Site 7 of the National Series. Ewe liveweights, ewe and lamb fleeceweights and lamb weaning weights were all measured under grazing. RPR was initially much less effective but improved sufficiently by Year 3 for the authors to conclude that equivalence was likely to have been reached in the following year. In these conditions, the lag-phase appeared to be no shorter under grazing.

McBride (1992) reported the results of a 10-year comparison of pasture production with RPR/S and SSP on an irrigated, shallow soil in Canterbury with low P retention. Despite the site being very low fertility to start, having had no fertiliser for many years, and a relatively high pH of 6.0, a modest capital application of 71 kg P/ha was sufficient for production with RPR to equal that of SSP in only 2 years, and thereafter to at least equal it with maintenance applications. This compares to a median annual difference of -2.9% under grazing (Table 4).

These grazing studies compensate to some degree for having less or in some cases no statistical analysis with the advantage of reflecting “real-life” conditions. The fact that, except under the combination of very high P retention and very low Olsen P, similar results were obtained with soluble P and RPR fertiliser in every case should be given due consideration.

Recent emphasis on P run-off research

In the last decade, research with RPR has been focused on comparing losses of P in surface run-off from RPR and SSP (Nguyen & Quin 2001; Nguyen *et al.* 2002; McDowell *et al.* 2003; Hart *et al.* 2004; McDowell & Catto 2005; Gillingham & Gray 2007 (later scientifically published by McDowell *et al.* 2010); McDowell 2012).

Table 4. Division of National Series trials into six regional/soil P retention groups

Group a	Northland (n=22 each for sol P and RPR for each of 6 years)
Group b	Central North Island and Taranaki high P retention (n=32 in years 1–3, n=25 in years 4 and 5, and n=18 in year 6)
Group c	Southern North Island (n=20 in years 1–3, trials then discontinued)
Group d	Irrigated Canterbury and low P retention Southland (n=17 years 1–6)
Group e	West Coast South Island (n=12 in years 1–5, n=6 in year 6 – site 15 only)
Group f	Southland medium-high P retention (n=16 years 1–6)

RPR has invariably shown significantly lower P run-off losses, particularly as dissolved reactive phosphate (DRP), a fact which in 2005 became recognised in Overseer[®], and provides a real opportunity for both farmers and regional councils in P-sensitive catchments. Farmers in P-sensitive catchments should be given the opportunity to consider changing to RPR as a P run-off mitigation strategy, rather than be subjected to P caps

that ignore the form of P being used.

The fine size distribution of RPR can cause problems with wind-drift during spreading, particularly from aircraft, and therefore direct entry into waterways. RPR particles that enter waterways in this way will be subject to slow dissolution if the receiving water is acidic (Nguyen *et al.* 2002). Particulate entry into receiving water is, however, less likely than with soluble

Table 5(a). Yearly mean and statistical P values (Student t test, double tailed) for the % responses of pasture to the application of soluble P Fertiliser (Sol P) and reactive phosphate rock (RPR) in the National Series trials.

Groups	Sol P	RPR	P values (t-test)	Sol P	RPR	P values (t-test)
Year 1			Year 2			
a	6.73*	1.31*	0.00	12.60*	7.20*	0.04
b	8.01*	3.20*	0.00	9.29*	5.03*	0.00
c	6.56	5.92	0.81	7.38	6.65	0.64
d	2.19*	-2.71*	0.01	10.28*	5.31*	0.01
e	1.32	1.43	0.95	1.17	5.42	0.20
f	3.79*	0.79*	0.01	7.95	5.22	0.09
Year 3			Year 4			
a	16.68	15.31	0.61	28.15	24.90	0.40
b	9.63	7.43	0.09	18.34	15.40	0.31
c	12.05	14.62	0.30			
d	21.11	16.95	0.18	16.68	17.87	0.63
e	2.64	1.43	0.54	10.18	12.66	0.55
f	7.74*	4.90*	0.05	17.24	16.95	0.93
Year 5			Year 6			
a	14.78	15.23	0.86	17.41	20.47	0.44
b	24.56	20.70	0.26	20.27	19.79	0.88
c						
d	15.99	19.63	0.35	32.09	35.38	0.48
e	5.71*	11.88*	0.02	5.78	-0.58	0.31
f	14.75	14.98	0.96	25.05	28.12	0.62

* indicated statistical difference within year and trial groups.

Table 5(b). Mean and statistical P values (Student t test, double tailed) for the % responses of pasture to the application of soluble P fertiliser (Sol P) and reactive phosphate rock (RPR) in the National Series trials. Trial data is grouped by geographic and soil P retention and presented as combined years 1 and 2, and 3 to 6 years.

Groups	Sol P	RPR	P values (t-test)	Sol P	RPR	P values (t-test)
Year 1 and 2			Years 3 to 6			
a	9.67*	4.25*	<0.01	19.25	18.98	0.88
b	8.65*	4.11*	<0.01	17.45	14.97	0.10
c#	8.66	9.06	0.78			
d	6.24*	1.30*	<0.01	21.47	22.46	0.64
e	1.24	3.43	0.24	6.12	7.34	0.53
f	5.87*	3.01*	0.01	16.20	16.24	0.99

* indicated statistical difference within year and trial groups.

group C data is for the combined 3 years of the trial.

P fertilisers, because of the much higher density of RPR particles (bulk density 1.6-1.7 tonnes/cubic meter) relative to soluble P granules (1.0 – 1.2) and water (1.0). Nevertheless, care needs to be taken to avoid the possibility of water surface tension allowing very fine particles of RPR being floated off in flood irrigation, at least in the few instances where runoff water return is not practised. This risk, and that of direct entry into waterways during spreading, can easily be avoided, and spreading evenness improved, by ensuring that the RPR is dampened with 4-6% water, or granulated, or applied as a high-solids fluid (Quin 2012).

Conclusions

The reassessment of RPR performance under mown plot conditions presented here, and particularly the reduced significance of the “lag-phase” on all but very high (>80%) P retention soils, a conclusion supported by data from under grazing trials, suggests that it is time for a full reconsideration of its role in New Zealand’s pastoral agriculture. This is particularly true given the proven reduction in P run-off where RPR is used instead of soluble P. Farmers need and deserve publication of a clear set of recommendations that succinctly explain how and for how long the level of pasture production achieved with RPR differs from that obtained with soluble P.

Given that RPR has been commercially available in New Zealand for 25 years now, it seemed logical that the drafting of new recommendations for farmers would be aided by surveying farmers who have been using predominantly RPR as their P source long-term. The results of this study, and the new recommendations, are reported in these Proceedings by Zaman and Quin (2012).

ACKNOWLEDGEMENTS

The authors thank Allan Gillingham and Long Nguyen for their many useful comments and suggestions on the manuscript. Peter Bishop of Bishop Research Ltd provided the statistical analysis and additional comments.

REFERENCES

- Ballard, R. 1991. RPR Recommendations for Farmers. A document provided by I. Cornforth and R. Parfitt, at the invitation of the Director General of the Ministry of Agriculture and Fisheries, 31 July 1991; 9pp.
- Brown, M.W. 1981. Analysis reveals drastic decline in superphosphate quality. *The New Zealand Farmer* 102 (22): 10-11.
- Brown, M.W.; McGovern, C.G 1991. Chemical and physical analysis of phosphate rocks. MAF Technology, Ruakura Agricultural Centre, Nov. 1991: 18pp.
- Cullen, N.A. 1958. Comparison of phosphatic fertilisers. *New Zealand Journal of Agricultural Research* 1: 418-431.
- Doak, B. W. 1942. Top-dressing of grassland with phosphates. *The New Zealand Journal of Science and Technology* Aug. 1942: 71A-77A.
- Edmeades, D.C.; Watkinson, J.H.; Perrott, K.W.; Sinclair, A.G.; Ledgard, S.F.; Rajan, S.S.S.; Brown, M.W., Roberts, A.H.; Thorrold, B.T.; O’Connor, M.B.; Floate, M.J.S.; Risk, W.H.; Morton, J. 1991. Comparing the agronomic performance of soluble and slow release phosphate fertilisers: the experimental basis for RPR recommendations. *Proceedings of the New Zealand Grassland Association* 53: 181-190.
- Farm Market Index. 2005. Fertiliser purchases in the livestock and cropping sectors: Year to end September 2005. Farm Market Index, A.C. Nielsen. 28pp.
- Gillingham, A.G.; During, C. 1973. Pasture production and transfer of fertility within a long established hill pasture. *New Zealand Journal of Experimental Agriculture* 1: 227-232.
- Gillingham, A.G.; Gray, M.H. 2007. Measurement of phosphorus losses in runoff from grazed catchments receiving contrasting phosphorus fertiliser types. Report prepared for Summit-Quinphosm, June 2007. AgResearch 2007. 23pp.
- Gregg, P.E.H.; Mackay, A.D.; Currie, L.D.; Syers, J.K. 1988. Application strategies for Sechura phosphate rock use on permanent pasture. *Fertilizer Research* 17: 219-234.
- Grigg, J.L. 1980. Relative efficiency of phosphate fertilisers in pasture topdressing. I. Introduction and design of experiments. *New Zealand Journal of Agricultural Research* 23: 43-47.
- Grigg, J. L.; Crouchley, G. 1980. Relative efficiency of phosphate fertilisers in pasture topdressing. II. On a Kotokau silt loam. *New Zealand Journal of Agricultural Research* 23: 49-65.
- Grigg, J.L.; Thompson, A. 1982. Relative efficiency of phosphatic fertilisers in pasture topdressing. IV. Effects on a Takapau silt loam. *New Zealand Journal of Agricultural Research* 25: 577-585.
- Grigg, J. L.; Crouchley, G.; Pownall, D.B. 1982. Relative efficiency of phosphatic fertilisers in pasture topdressing. III. On a Rosedale silt loam. *New Zealand Journal of Agricultural Research* 25: 565-576.
- Hart, M.R.; Quin, B.F.; Nguyen, M.L. 2004. Phosphorus runoff from agricultural land and direct fertilizer effects: a review. *Journal of Environmental Quality* 33: 1954-1972.
- Korte, C.J. 1988. Reactive rock phosphate on Gisborne Hill Country. A Report for Northern Phosphate Co. Ltd, MAF Technology, Gisborne, March 1988: 11pp.
- Ledgard, S.F.; Jones, K. R. 1991. Effects of reactive phosphate rock and superphosphate on sheep and pasture production in hill country. *Proceedings of the New Zealand Grassland Association* 53: 197-202.

- Ledgard, S.F.; Thorrold, B.S.; Sinclair, A.G.; Rajan, S.S.S.; Edmeades, D.C. 1992. Summary of eleven long-term trials with 'Longlife' phosphatic fertiliser. *Proceedings of the New Zealand Grassland Association* 54: 35-40.
- Loganathan, P.; Hedley, M.J.; Saggar, S. 1995. Liming effect of reactive phosphate rocks: A laboratory evaluation. pp. 641-645 *In: Plant-soil interactions at low pH: principles and management*. Eds. Date, R.A.; Grundon, N.J.; Rayment, G.E.; Probert, M.E. Kluwer Academic Publishers, Dordrecht.
- Mackay, A.D. 1990. Comparison of phosphate fertilisers in a grazed hill country pasture. *Proceedings of the New Zealand Grassland Association* 51: 97-100.
- Mackay, A.D.; Wewala, G.S. 1990. Evaluation of partially acidulated phosphate fertilizers and reactive phosphate rock for hill pastures. *Fertilizer Research* 21: 149-156.
- Mackay, A.D.; Syers, J.K.; Springett, J.A.; Gregg, P.E.H. 1982. Plant availability of phosphorus in superphosphate and a phosphate rock as influenced by earthworms. *Soil Biology and Biochemistry* 14: 281-287.
- Mackay, A.D.; Gregg, P.E.H.; Syers, J.K. 1984a. Field evaluation of Chatham Rise phosphorite as a phosphatic fertiliser for pasture. *New Zealand Journal of Agricultural Research* 27: 65-82.
- Mackay, A.D.; Syers, J.K.; Gregg, P.E.H.; Tillman, R.W. 1984b. A comparison of 3 soil-testing procedures for estimating the plant availability of phosphorus in soils receiving either superphosphate or phosphate rock. *New Zealand Journal of Agricultural Research* 27: 231-245.
- Mackay, A.D.; Syers, J.K.; Tillman, R.W.; Gregg, P.E.H. 1986. A simple model to describe the dissolution of phosphate rock in soils. *Soil Science Society of America Journal* 50: 291-296.
- McBride, S.D. 1992. Agronomic performance of RPR fertiliser in a grazed pasture. *Proceedings of the New Zealand Grassland Association* 54: 41-44.
- McDowell, R.W.; Monaghan, R.M.; Carey, P.L. 2003. Potential phosphorus losses in overland flow from pastoral soils receiving long-term applications of either superphosphate or reactive phosphate rock. *New Zealand Journal of Agricultural Research* 46: 329-337.
- McDowell, W.; Catto, W. 2005. Alternative fertilisers and management to decrease incidental phosphorus loss. *Environmental Chemistry Letters* 2: 169-174.
- McDowell, R.W.; Littlejohn, R.P.; Blennerhassett, J.D. 2010. Phosphorus fertilizer form affects phosphorus loss to waterways: a paired catchment study. *Soil Use and Management* 26: 365-371.
- McDowell, R. 2012. Challenges and opportunities to decrease phosphorus losses. *In: Proceedings of the Workshop "Advanced Nutrient Management: Gains from the Past - Goals for the Future"*, 7-9 Feb 2012. Eds L.D. Currie and J.A. Hanly, Fertilizer and Lime Research Centre occasional Report No. 25, Massey University, Palmerston North, New Zealand.
- Metherell, A.K., Thorrold, B.S., Woodward, S.J.R., McCall, D.G., Marshall, P.R., Morton, J.D., Johns, K.L. 1997. A decision support model for fertiliser recommendations for grazed pasture. *Proceedings of the New Zealand Grassland Association* 59: 137-140.
- Morton, J.D.; O'Connor, M.B.; Risk, W.H.; Nguyen, L.; Johnstone, P.D.; Smith, L.; Roberts, A.H.C. 1994. Effects of triple superphosphate and Sechura phosphate rock on clover and nitrogen content of pasture. *New Zealand Journal of Agricultural Research* 37: 569-575.
- Nguyen, L.; Quin, B.F. 2001. Potential phosphorus losses in runoff from New Zealand pastoral soils receiving superphosphate and reactive phosphate rock applications. *In: Proceedings of the Workshop Connecting Phosphorus Transfer from Agriculture to Impacts in Surface Waters*, Eds. Haygarth, P.M.; Condon, L.M.; Butler, P.J.; Chisholm, J.S. 28 August-1 September, Plymouth University, UK.
- Nguyen, L.; Quin, B.F.; Sukias, J. 2002. Potential losses of phosphorus and nitrogen in runoff and drainage from pastoral soil applied with superphosphate and reactive phosphate rock. pp. 137-153 *In: Proceedings of the Workshop "Dairy Farm Management"*, 13-14 February 2002, Massey University, Palmerston North, New Zealand, eds Currie, L.D.; Loganathan, P. Occasional Report No. 15, Fertilizer and Lime Research Centre.
- Percival, N.S.; O'Connor, M.B.; Every, J.P.; Rajan, S.S.S. 1984. Alternative phosphatic fertilisers for hill country. *Proceedings of the New Zealand Grassland Association* 45: 107-115.
- Perrott K. W. & Metherell, A.K. 1997. Incorporation of reactive phosphate rock into a phosphorus fertiliser decision support model for grazed pasture. *Proceedings Dahlia Greidlinger International Symposium on Fertilization and the Environment* : 133-146.
- Perrott, L.W.; Wise, R.G. 1995. A routine test for quantifying RPR residues in soil. pp 85-108 *In: Fertilizer Requirements of Grazed Pasture and Field Crops*. Ed. Currie, L.D. Occasional Report No.8, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.
- Perrott, K.W.; Roberts, A.H.C.; Saggar, S.; Shannon, P.W.; O'Connor, M.B.; Nguyen, L.; Risk, W.H.; 1992. Pasture production and soil phosphorus fractions

- resulting from six previous annual applications of triple superphosphate or Sechura phosphate rock. *New Zealand Journal of Agricultural Research* 35: 307-319.
- Perrott, K.W.; Saggat, S.; Menon, R.G. 1993. Evaluation of soil phosphate status where phosphate rock based fertilisers have been used. *Fertilizer Research* 35: 67-82.
- Perrott, K.W.; Kerr, B.E.; Watkinson, J.H.; Waller, J.E. 1996. Phosphorus status of pastoral soils where reactive phosphate rock fertilisers have been used. *Proceedings of the New Zealand Grassland Association* 57: 133-137.
- Quin, B.F. 1981a. The performance of reactive phosphate rocks on irrigated and non-irrigated pasture. pp. 12-31 *In: Proceedings of the Technical Workshop: Potential of Phosphate Rock as a Direct Application Fertilizer in New Zealand, 27-28 May 1981.* Eds. Syers, J.K.; Gregg, P.E.H. Occasional Report No. 3, Massey University, Palmerston North, New Zealand,.
- Quin, B.F. 1981b. How the decline came about. *The New Zealand Farmer* 102 (22): 11-13.
- Quin, B.F. 1982. The quality of New Zealand superphosphate. *New Zealand Agricultural Science* 16: 93-100.
- Quin, B.F. 2012. Fertiliser innovations to improve efficiency. Proceedings of the South Island Dairy Event Conference (SIDE, Dunedin, New Zealand, 25-27 June 2012, 290-306.
- Quin, B.F.; Dyson, C.B.; Shannon, P.O.; O'Connor, M. B.; Percival, N.; Roberts, A.; Smith, G.; Nguyen, M.L.; Williams, P.; Risk, W. 1985. The MAF "National Series" forms of phosphate trials. Proceedings 20th Technical Conference, New Zealand Fertiliser Manufacturers Research Association (Inc). 604-628.
- Quin, B.F.; Dyson, C.B.; Chiao, Y.S.; Dow, B.; Littlejohn, R.; Nguyen, M.L.; O'Connor, M.B.; Percival, N.; Pringle, R.; Risk, W.; Roberts, A.; Shannon, P.D.; Smith, R.G., Waller, J.; Williams, P. 1987. Agronomic and economic aspects of reactive phosphate rocks for pasture – development of a predictive model. pp. 147-163 *In: The Use of Reactive Phosphate Rocks and their Derivatives as Fertilizers.* (Eds White, R.E.; Currie, L.D.) <http://flrc.massey.ac.nz/publications.html>. Occasional Report No. 1, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.
- Rajan, S.S.S. 2002. Comparison of phosphate fertilizers for pasture and their effect on soil solution phosphate. *Communications in Soil Science and Plant Analysis* 33 (13&14): 2227-2245.
- Rajan, S.S.S.; Gillingham, A.G. 1986. Phosphate rocks and phosphate rock/sulphur granules as fertilisers for hill country pastures. *New Zealand Journal of Experimental Agriculture* 14: 313-318.
- Rajan, S.S.S.; Marwaha, B.C. 1993. Use of partially acidulated phosphate rocks as phosphate fertilizers. *Fertilizer Research* 35: 47-59.
- Rajan, S.S.S.; Upsdell, M. 1981. Comparison of ground and mini-granulated phosphate rocks with superphosphate as phosphate fertilisers. *New Zealand Journal of Agricultural Research* 24: 153-160.
- Rajan, S.S.S.; O'Connor, M.B.; Sinclair, A.G. 1994. Partially acidulated phosphate rocks: Controlled release phosphorus fertilizers for more sustainable agriculture. *Fertilizer Research* 37: 69-78.
- Risk, W.H.; Smith, L.C.; Sinclair, A.G.; Johnstone, P.D.; Shannon, P.W.; O'Connor, M.B.; Nguyen, L. 1992. Effects of frequency of maintenance phosphate applications on dry matter production from permanent pastures. *Proceedings of the New Zealand Grassland Association* 54: 55-58.
- Roberts, A.H.C.; Sinclair, A.G.; Johnstone, P.D., Risk, W.H.; Smith, L.C.; O'Connor, M.B.; Nguyen, L.; Morton, J.D.; Shannon, P.W. 1994. Changes in soil Olsen P over 6 years with annual applications of triple superphosphate or reactive phosphate rock (Sechura). *New Zealand Journal of Agricultural Research* 37: 229-237.
- Saggat, S.; Hedley, M.J.; White, R.E. 1992a. Development of an improved test for phosphorus: 1. The influence of phosphorus solubility and soil properties on the extractability of soil P. *Fertilizer Research* 33: 81-91.
- Saggat, S.; Hedley, M.J.; White, R.E.; Gregg, P.E.H.; Perrott, K.W.; Cornforth, I.S. 1992b. Development and evaluation of an improved soil test for phosphorus. 2. Comparison of the Olsen and mixed cation-anion exchange resin tests for predicting the yield of ryegrass grown in pots. *Fertilizer Research* 33: 135-144.
- Saggat, S.; Hedley, M.J.; White, R.E.; Perrott, K.W.; Gregg, P.E.H.; Cornforth, I.S.; Sinclair, A.G. 1999. Development and evaluation of an improved soil test for phosphorus, 3: field comparison of Alsen, Colwell and Resin soil P tests for New Zealand pasture soils. *Nutrient Cycling in Agroecosystems* 55: 35-50.
- Sale, P.W.G.; Simpson, C.A.; Muir, L.L. 1997. The role of reactive phosphate rock fertilisers for pastures in Australia. *Australian Journal of Experimental Agriculture* 37: 845-1098.
- Scott, R.S.; Cullen, N.A. 1965. Some residual effects of phosphatic fertilisers. *New Zealand Journal of Agricultural Research* 8: 652-666.
- Sinclair, A.G.; Dyson, C.B. 1988. An interim report on the "National Series" forms of phosphate fertiliser

- trials: herbage dry matter production for growing seasons 1982/83 to 1986/87 inclusive. MAFTECH, Ministry of Agriculture and Fisheries Report 100pp.
- Sinclair, A.G.; Johnstone, P.D.; Dyson, C.B.; Shannon, P.W.; O'Connor, M.B.; Roberts, A.H.C.; Smith, R.G.; Nguyen, L.; Morton, J.; Risk, W.H. 1989. Comparison of Sechura phosphate rock and triple superphosphate as phosphate fertilizers for pastures in New Zealand. *In: FACE Conference, Manila.*
- Sinclair, A.G.; Dyson, C.B.; Shannon, P.W. 1990a. The long-term effectiveness of reactive phosphate rock as a phosphate fertiliser for NZ pastures. *Proceedings of the New Zealand Grassland Association 51: 101-104.*
- Sinclair, A.G.; Shannon, P.W.; Risk, W.H. 1990b. Sechura phosphate rock supplies plant-available molybdenum for pastures. *New Zealand Journal of Agricultural Research 33: 499-502.*
- Sinclair, A.G.; Bowbitch, M.; Perrott, K.W.; Watkinson, J. H. 1990c. A new approach to the economic evaluation of reactive phosphate rock as a replacement for single superphosphate. *Proceedings of the New Zealand Fertiliser Manufacturers Research Association Conference: 249-252.*
- Sinclair, A.G.; Johnstone, P.D.; Smith, L.C.; O'Connor, M.B.; Nguyen, L. 1993a. Agronomy, modeling and economics of reactive phosphate rocks as slow-release phosphate fertilizers for grasslands. *Fertiliser Research 36: 229-238.*
- Sinclair, A.G.; Johnstone, P.D.; Smith, L.C.; Risk, W.H.; O'Connor, M.B.; Roberts, A.H.; Morton, J.D.; Nguyen, L.; Shannon, P.W. 1993b. Effect of reactive phosphate rock on the pH of soil under pasture. *New Zealand Journal of Agricultural Research 36: 381-384.*
- Sinclair, A.G.; Johnstone, P.D.; Smith, L.C.; Risk, W.H.; Morton, J.D.; O'Connor, M.B.; Roberts, A.H.C.; Nguyen, L.; Shannon, P.W. 1994. Patterns of, and a model for, dry matter yield response in grass/clover pastures to annual applications of triple superphosphate fertiliser. *New Zealand Journal of Agricultural Research 37: 239-253.*
- Sinclair, A.G.; Johnstone, P.D.; Smith, L.C.; Roberts, A.H.C.; O'Connor, M.B.; Morton, J.D. 1997. Relationship between pasture dry matter and soil Olsen P from a series of long-term field trials. *New Zealand Journal of Agricultural Research 40: 559-567.*
- Sinclair, A.G.; Johnstone, P.D.; Watkinson, J.H.; Morton, J.; Judge, A. 1998. Comparison of six phosphate rocks and single superphosphate as phosphate fertilisers for clover-based pasture. *New Zealand Journal of Agricultural Research 41: 415-420.*
- Smith, L.C.; Sinclair, A.G. 1998. Effects and interactions of P fertiliser forms and rates of lime on a clover/ryegrass sward. *New Zealand Journal of Agricultural Research 41: 75-79.*
- Smith, L.C.; Johnstone, P.D.; Sinclair, A.G.; Shannon, P.W.; O'Connor, M.B.; Percival, N.; Roberts, A.H.; Smith, R.G.; Mansell, G.; Morton, J.D.; Nguyen, L.; Dyson, C.B.; Risk, W.H. 1990. Final report on the MAF "National Series" forms of phosphate fertiliser trials. Part 1: Description of the trials and annual herbage dry matter production. Ministry of Agriculture and Fisheries, Wellington, New Zealand, December 1990. 87 pp.
- Smith, L.C.; Johnstone, P.D.; Sinclair, A.G.; Shannon, P.W.; O'Connor, M.B.; Percival, N.; Roberts, A.H.; Smith, R.G.; Mansell, G.; Morton, J.D.; Nguyen, L.; Dyson, C.B.; Risk, W.H. 1991a. Final report on the MAF "National Series" forms of phosphate fertiliser trials. Part 2: Phosphorus content of herbage. Ministry of Agriculture and Fisheries, Wellington, New Zealand, May 1991. 240 pp.
- Smith, L.C.; Johnstone, P.D.; Sinclair, A.G.; Shannon, P.W.; O'Connor, M.B.; Percival, N.; Roberts, A.H.; Smith, R.G.; Mansell, G.; Morton, J.D.; Nguyen, L.; Dyson, C.B.; Risk, W.H. 1991b. Final report on the MAF "National Series" forms of phosphate fertiliser trials. Part 3. Soil Olsen P and pH. Ministry of Agriculture and Fisheries, Wellington, New Zealand, June 1991. 92 pp.
- Syers, J.K & Gregg, P.E.H. 1981 (eds). Proceedings on the technical workshop on potential of phosphate rock as a direct application fertilizer in New Zealand. Palmerston North, New Zealand, 27-28 May 1981. Massey University Occasional Report No. 3, 168 pp.
- Syers, J.K.; Mackay, A.D.; Brown, M.W.; Currie, L.D. 1986. Chemical and physical characteristics of phosphate rock materials of varying reactivity. *Journal of the Science of Food and Agriculture 37: 1057-1064.*
- Thomson, N.; Roberts, A.H. 1995. Phosphate fertiliser – farmlet study. Research Newsletter. Taranaki Agricultural Research Station, Normanby, Taranaki, Newsletter May 1995, 3pp.
- Van Kauwenbergh, S. J. 1998. Chemical and mineralogic evaluation of a phosphate rock from Egypt (Kosseir deposit) for direct application, as imported into New Zealand by Summit-Quinphos (NZ) Ltd. Report Prepared by the International Fertilizer Development Centre, Muscle Shoals, Alabama, USA, June 1998.
- Walker, T. W.; Adams, A.F.R.; Orchiston, H.O. 1955. The effects and interaction of sulphur, phosphorus and molybdenum on the growth and composition of clovers. *New Zealand Journal of Science and Technology A36: 470-482.*
- Zaman, M.; Quin, B.F. 2012. RPR revisited (2): Long-term farmer experience helps define the role of RPR on grazed pastures. *Proceedings of the New Zealand Grassland Association 74: 269-276.*