THE AUSTRALIAN NATIONAL REACTIVE PHOSPHATE ROCK PROJECT — AIMS, EXPERIMENTAL APPROACH, AND SITE CHARACTERISTICS

M.J. McLAUGHLIN
CSIRO Land and Water,
Glen Osmond, Australia

Abstract

Field-based cutting trials were established across Australia in a range of environments to evaluate the agronomic effectiveness of 5 phosphate rocks, and 1 partially acidulated phosphate rock, relative to either single superphosphate or triple superphosphate. The phosphate rocks differed in reactivity, as determined by the degree of carbonate substitution for phosphate in the apatite structure and solubility of phosphorus present in the fertilizers in 2% formic acid, 2% citric acid and neutral ammonium citrate. Sechura (Bayovar) and North Carolina phosphate rocks were highly reactive (>70% solubility in 2% formic acid), whilst Khouribja (Moroccan) and Hamrawein (Egypt) phosphate rock were moderately reactive. Duchess phosphate rock from Queensland was relatively unreactive (< 45% solubility in 2% formic acid). The partially acidulated phosphate rock was made by 50% acidulation of North Carolina phosphate rock with sulfuric acid. Phosphate rock effectiveness was assessed by measuring pasture production over a range of phosphorus levels, and by monitoring the bicarbonate-soluble phosphorus extracted from soil samples collected prior to the start of each growing season. Other treatments included single large applications of triple superphosphate, partially acidulated phosphate rock and North Carolina phosphate rock applied at 2 rates, and the application of monocalcium phosphate and North Carolina phosphate rock sources without sulfur to evaluate the importance of sulfur in the potential use of phosphate rock fertilizers.

A broad range of environments was represented over the 30 sites, which were based on pastures using annual and/or perennial legumes and perennial grasses. Rainfall across the network of sites ranged from 560 to 4320 mm, soil pH-$CaCl_2$, from 4.0 to 5.1, and Colwell extractable phosphorus ranged from 3 to 47 µg/g prior to fertilizer application. Two core experiments were established at each site. The first measured the effects of phosphate rock reactivity on agronomic effectiveness, while the second core experiment measured the effects of the degree of water solubility of the phosphorus source on agronomic effectiveness.

The National Reactive Phosphate Rock Project trials provided the opportunity to confirm the suitability of accepted procedures to model fertilizer response and to develop new approaches for comparing different fertilizer responses. The Project also provided the framework for subsidiary studies such as the effect of fertilizer source on soil phosphorus extractability; cadmium and fluorine concentrations in herbage; evaluation of soil phosphorus tests; and the influence of particle size on phosphate rock effectiveness. The National Reactive Phosphate Rock Project presents a valuable model for a large, Australia-wide, collaborative team approach to an important agricultural issue. The use of standard and consistent experimental methodologies at every site ensured that maximum benefit was obtained from data generated. The aims, rationale and methods used for the experiments across the network are presented and discussed.

1. INTRODUCTION

Briefly, the aims of the National Reactive Phosphate Rock (RPR) Program were:

1. to determine those soil, climate and pasture conditions under which RPR products are effective substitutes for water soluble P sources e.g. single superphosphate (SSP), on pastures [1, 2];
2. to determine what the required level of PR reactivity would be for RPRs to be effective in different pasture environments [3-5];
3. to develop a decision-support system to identify pasture environments where RPRs or derived products would be cost-effective substitutes for SSP [6];
4. to determine the role of sulfur (S) in the viability of RPR use [7].

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In addition to these aims, other aspects of the use of RPRs and derived products were also investigated. The other aspects included a comparison of application strategies (annual vs capital) for WSP and RPR fertilizers [8], changes in the effectiveness of RPR during the growing season [9]; the effect of PR on soil pH [10]; the effect of RPR products on soil P concentrations [11]; the effect of fertilizer type on cadmium and fluorine concentrations in clover herbage [12]; a comparison of the range of soil P tests for situations where RPR products are used [13]; identification of pasture environments potentially suitable for RPR use through the use of GIS technology [14]; and the economic analysis of the field performance of North Carolina RPR compared with single superphosphate [15].

2. MATERIALS AND METHODS

2.1. Sites

Thirty sites were established (Fig. 1 and Table I) over a wide range of soil/pasture/ climate environments in 6 States across Australia - Queensland, New South Wales (NSW), Victoria, Tasmania, South Australia and Western Australia.

Sites were selected to cover regions that were representative of the major permanent pasture zones in each State where phosphatic fertilizers were regularly applied to pasture. Within regions, sites were situated on the common soil types, which were acidic (pH-$CaCl_2$ < 5.5). Soil profiles at each site were described according to the Australian Soil and Land Survey Field Handbook, and are described in detail by Simpson et al. [16].

Sites were located on a wide range of soils and covered a wide range of environments. Long-term average annual rainfall varied between 560 mm at Jericho in central Tasmania, to 4320 mm at Tully in northern Queensland. Soil pH-$CaCl_2$ (0-10 cm) ranged from 4.0 on the southern tablelands of NSW, up to 5.1 on the Atherton Tablelands in northern Queensland. All sites had an acidic surface layer although some showed a trend in increasing pH with depth. Initial soil P concentrations (0-10 cm) prior to the application of any fertilizer treatments ranged from 3 µg/g Colwell P at Mackay in Queensland to 47 µg/g at Malanda in far northern Queensland indicating that some sites would be more P responsive than others (Table II). Sites were located where there was an adequate legume content in existing pasture, or in some cases oversown with high rates of seed to ensure that an adequate legume component was achieved. Major pasture species present at each site are detailed in Simpson *et al.* [16].

2.2. Fertilizers

Fertilizer treatments used in the National RPR Project trials were chosen to address two basic areas of concern. First, the question of how soluble the P source needs to be in order to be agronomically effective under particular soil, climatic and pasture conditions, and secondly how reactive does the PR need to be in order to be agronomically effective. Both these questions were addressed by comparing PRs with water-soluble P (WSP) sources.

Five apatite PRs covering a range of reactivity (degree of carbonate substitution) were chosen for the comparisons and included Sechura PR (Bayovar, S PR), North Carolina PR (USA, NC PR), Hamrawein PR (Egypt, E PR), Khouribja PR (Morocco, M PR), and Duchess PR (Queensland, D PR). A partially acidulated PR (PAPR) made by 50% acidulation of North Carolina PR with sulfuric acid was also used. Two WSP sources used were single superphosphate (SSP), and triple superphosphate (TSP). Total P content, origin, and solubility in 2% citric acid, 2% formic acid, and neutral ammonium citrate of WSP, PAPR and PR fertilizers are presented in Table III. Major and minor elements present in each fertilizer (analyzed by XRF fusion technique) are shown in Table IV and V, respectively. XRD analysis of the apatite PRs showed that all of the PRs contained moderate levels of quartz and traces of illite were contained in the Sechura and Duchess PRs. Khouribja PR and Hamrawein PR both contained trace and moderate levels of dolomite, respectively. Duchess PR also contained trace levels of kaolinite and calcite.

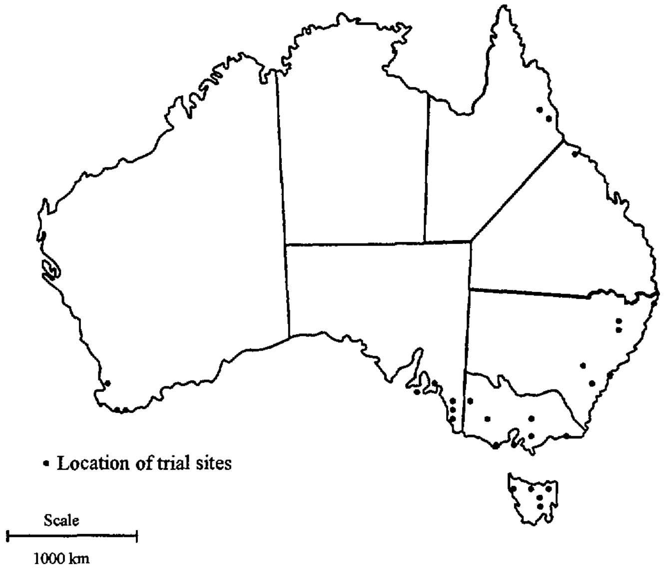

Fig. 1. Location of trial sites for National Reactive Phosphate Rock project (reproduced with permission of CSIRO Publishing [16]).

2.3. Treatments and experimental designs

Two core experiments were established at each trial site. Core Experiment 1 (CE1) was designed to examine the issue of PR reactivity, while Core Experiment 2 (CE2) was designed to address the issue of water solubility of the P source. All trials were field-based small plot experiments. Plot size was 3 x 5 m, except for Tasmania, which used a 2 x 2 m plot size.

2.3.1. Core experiment 1

In Core Experiment 1 (CE1), the treatments consisted of a nil P treatment (control), 5 PRs and SSP applied annually at 3 levels of P i.e. 2X, 4X, and 8X kg/ha (see below for explanation of 'X') replicated 4 times. The 5 PRs were, Sechura PR (Bayover in Peru), North Carolina PR (USA), Hamrawein PR (Egypt), Khouribja PR (Morocco), and Duchess PR (Queensland). In addition, North Carolina PR and monocalcium phosphate (MCP) were applied once only at a single P level (4X or 8X in the case of the Qld. sites) without S to evaluate the role of S in the use of RPR fertilizers. The phosphate rock (PR) fertilizers used in CE1 were selected to cover a range of PR reactivity (Table III).

2.3.2. Core experiment 2

Core Experiment 2 (CE2) consisted of a nil P treatment, TSP, PAPR and North Carolina PR. These P sources were applied (i) at 2 levels of P (8X and 16X) once only at the start of the experiment in 1992 to examine the response to capital applications of P, and (ii) at 5 P rates (X, 1.5X, 2X, 4X, 8X) annually for TSP and PAPR and at 6 P rates (X, 1.5X, 2X, 4X, 8X and 16X) annually for North Carolina PR. All treatments were replicated 3 times except at sites N7 and N8 where 4 replicates were used. North Carolina PR was used in CE2 because it was a highly reactive PR and has been used widely in other research.

2.3.3. Determining the P rate of application (X)

The P levels (kg/ha) used in the National RPR Project trials varied from site to site and were based on the anticipated response to applied P at each site. The levels of fertilizer required were estimated in each region by experienced research agronomists and extension staff.

TABLE I. LOCATION AND ENTERPRISE DETAILS OF SITES USED IN THE NATIONAL RPR PROJECT (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

Site ID	Region	Area	Pasture species	Regional enterprises	Annual P rate used (kg/ha)
Q1	Nth Qld	Malanda	*Brachiaria decumbens.*	Dairy/beef	10.0
Q2	Nth Qld	Tully	*Brachiaria decumbens.*	Beef	7.5
Q3	Central Nth Qld	Mackay	*Aeschynomene americana.*	Beef	5.0
N4	NSW Nth Tbls.	Armidale	*T. repens, T subterraneum, Festuca arundinacea.*	Sheep/beef/ dairy	10.0/2.5[1]
N5	NSW north coast	Grafton	*T. repens, T subterraneum, Lotononis* spp.	Beef/dairy	10.0/5.0[1]
N6	NSW Nth Tbls.	Armidale	*T. repens, T subterraneum, Festuca arundinacea*	Sheep/beef	10.0/2.5[1]
N7	NSW Sth Tbls	Yass	*T. subterraneum*	Sheep	7.5
N8	NSW Sth Tbls	Tarago	*T. subterraneum*	Sheep/beef	7.5
N9	NSW Sth coast	Berry	*T. repens, Axonopus, Pennisetum clandestinum, Paspalum* spp.	Dairy	10.0
V10	Vic E Gippsland	Bairnsdale	*Dactyls glomerata, T subterraneum*	Sheep/wool	10.0
V11	Vic W Gippsland	Ellinbank	*T. repens, Dactyls glomerata, Lolium perenne.*	Dairy	9.0
V12	Vic Nth-east	Benalla	*T. subterraneum, Holcus spp.*	Sheep/beef	8.0
V13	Vic Sth west	Warrnambool	*T. repens, T subterraneum, Lolium perenne.*	Dairy	7.5/5.0[1]
V14	Vic west	Edenhope	*T. subterraneum, Lolium perenne, Phalaris aquatica.*	Sheep	10.0
V15	Vic west	Hamilton	*T. subterraneum, Lolium perenne, Phalaris aquatica.*	Wool/beef	10.0
V29	Vic Sth	Frankston	*T. repens, T subterraneum, Lolium perenne, Festuca arundinacea.*	Beef/sheep	10.0
T16	Tasa Nth W	Smithton	*T. repens , T subterraneum, T. fragiferum, Lolium perenne, Festuca arundinacea.*	Beef/dairy	8.5
T17	Tas Central	Jericho	*T. repens , T subterranuem, Lolium perenne, Dactyls glomerata, Festuca arundinacea.*	Wool	2.9
T18	Tas Nth east	Gladstone	*T. subterranuem, Lolium perenne, Holcus spp.*	Sheep/beef/ dairy	2.9
T19	Tas Cent'l Nth	Elliot	*T. repens, Lolium perenne, Dactylis glomerata.*	Dairy	5.7
T20	Tas Nth	Cressy	*T. repens, T. subterraneum, Lolium perenne.*	Sheep	5.7
S21	SA Sth east	Willalooka	*T. subterraneum.*	Beef/dairy	7.5
S22	SA Sth east	Wattle Range	*T. subterraneum.*	Lambs/wool/ beef/dairy	7.5
S23	SA Sth east	Nangwarry	*T. subterraneum.*	Beef/lambs/ dairy	7.5
S24	SA south	Mt Jaggard	*T. subterraneum*cv, *Dactyls glomerata, Phalaris aquatica.*	Dairy/lambs/ wool	5.0
S25	SA south	Kangaroo Isl	*T. subterraneum*cv, *Lolium perenne.*	Lambs/wool	5.0
W26	Sth-W WA	Busselton	*T. subterraneum.*	Wool/beef/ dairy	5.0
W27	Sth-W WA	Karridale	*T. subterraneum.*	Beef/lambs/ wool/dairy	7.5
W28	Sth-W WA	Karridale	*T. subterraneum.*	Beef/lambs /wool/dairy	2.5
W30	Sth-W WA	Nornalup	*T. subterraneum.*	Beef/lambs/ wool	10.0

[1] Indicates that this rate was used in the second and subsequent years as it was considered that the initial rate was too high.

TABLE II. SOIL P, K, ELECTRICAL CONDUCTIVITY (EC), pH (WATER AND $CaCl_2$), ORGANIC CARBON AND REACTIVE IRON (Fe) FOR 0-10 CM SOIL LAYER AT SITES USED IN THE NATIONAL RPR PROJECT PRIOR TO FERTILIZER APPLICATION (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

SITE ID	Average Rainfall (mm)	Soil type[1]	P (ppm)	K (ppm)	E.C. (ds/m)	pH (H_2O)	pH ($CaCl_2$)	Organic carbon %	Fe (ppm)
Q1	1690	Gn 3.11	47	256.9	0.110	6.07	5.06	3.68	2622
Q2	4321	Gn 2.11	5	36.4	0.045	5.56	4.33	1.80	687
Q3	1474	Dy 3.43	3	48.3	0.090	5.50	4.56	1.03	725
N4	760		14	124.1	0.069	5.74	4.56	2.30	1017
N5	882		22	81.9	0.063	5.51	4.38	1.68	777
N6	760		19	232.1	0.063	5.86	4.79	3.41	1637
N7	664	Dr 2.21	10	120.9	0.059	5.02	4.67	1.60	1489
N8	700	Dy 3.42	10	109.9	0.102	4.87	4.00	2.13	1087
N9	1500		27	140.2	0.065	6.00	5.00	2.00	1812
V10	650	Dy 3.42	11	64.0	0.065	5.70	4.41	2.42	878
V11	1100	Gn 4.11	41	222.4	0.080	5.42	4.54	4.06	6037
V12	800	Db 2.31	18	221.4	0.074	5.00	4.03	3.53	1336
V13	900	Dy 3.21	17	109.4	0.078	5.20	4.17	3.66	431
V14	550	Dy 3.42	20	151.3	0.071	5.52	4.50	1.97	1340
V15	710	Dy 3.21	15	110.7	0.084	5.64	4.68	3.88	4941
V29	787		33	210.0	0.080	6.12	4.91	1.34	289
T16	1100	Uc 4.24	7	80	0.093	5.10	4.06	3.84	234
T17	560	Dy 5.11	19	248	0.157	5.42	4.60	2.74	1565
T18	750	Dy 5.41	21	82	0.095	5.41	4.33	3.92	1076
T19	1200	Gn 4.11	36	236	0.093	5.58	4.72	5.13	3217
T20	640	Uc 5.11	46	231	0.038	5.46	4.35	1.16	746
S21	1650	Dy 5.21	8	66	0.079	5.81	4.65	1.27	167
S22	600	Dy 5.21	11	57	0.093	5.23	4.16	2.05	162
S23	600	Dy 5.21	15	107	0.086	5.56	4.44	2.03	249
S24	750	Dy 3.41	11	244	0.090	5.67	4.61	3.27	601
S25	600	Dy 3.41	12	462	0.099	6.11	4.99	3.08	2261
W26	855		7	128	0.208	5.44	4.33	2.41	995
W27	1000		17	80	0.068	5.75	4.70	2.22	811
W28	1000		7	121	0.147	5.50	4.39	3.12	133
W30	1392		8.5	134	0.197	5.30	4.30	-	-

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[1] Northcote (1966) classification.

TABLE III. SOURCE, TOTAL P CONTENT, TYPE AND REACTIVITY OF FERTILIZERS USED IN THE NATIONAL RPR PROJECT (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

Fertilizer	Source	Total P (%)	Type[1]	Reactivity[2]	Solubility in 2% citric acid[3] (1st extraction)	Solubility in 2% formic acid[4] (1st extraction)	Solubility in neutral ammonium citrate[5] (2nd extraction)
					% of total P		
Single superphosphate (SSP)	N/A	9.5	Sol	Extremely high	87	105	59
Triple super phosphate (TSP)	N/A	20.2	Sol	Extremely high	99	93	58
Partly acidulated phosphate Rock –North Carolina (PAPR)	N/A	9.7	Partly Sol	Very high	68	71	33
Mo no calcium phosphate 'Aerophos'	N/A	24.0	Sol	Extremely high			
Sechura PR	Peru	12.9	RPR	high	40	70	9
North Carolina PR	USA	12.7	RPR	mod. High	36	74	8
Egyptian PR	Egypt	12.7	RPR	mod.	31	49	8
Moroccan (Khouribja) PR	Morocco	14.2	RPR	low - mod.	28	56	7
Duchess PR	Queensland	10.5	PR	low	30	45	5

[1] Sol = soluble; the fertilizer is a primarily water soluble source of P. RPR = reactive phosphate rock; indicates the rock has undergone some degree of carbonate substitution and will tend to dissolve in acid soil conditions. PR = a phosphate rock that has undergone little carbonate substitution and will be only slightly soluble in acid soil conditions.

[2] Reactivity here refers to the degree (% of total P) to which the PR dissolves in a 2% formic acid solution; N/A = not applicable.

[3] Analyzed using procedure of the Association of Official Analytical chemists (1960) [17].

[4] Analyzed using procedure of Hoffman and Mager (1953) [18].

[5] Analyzed using procedure of Association of Official Analytical chemists (1990) [19].

TABLE IV. MAJOR MINERAL COMPOSITION OF FERTILIZERS USED IN THE NATIONAL RPR PROJECT (XRF — FUSION TECHNIQUE) (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

	Al_2O_3 (%)	SiO_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	MnO (%)	CaO (%)	K_2O (%)	MgO (%)	P_2O_5 (%)	SO_3 (%)	Na_2O (%)	LOI (%)
SSP	1.0	2.1	0.2	0.6	0.0	33.8	0.1	0.2	22.9	33.2	0.4	30.3
TSP	1.6	2.4	0.2	2.0	0.1	21.6	0.3	0.7	49.4	4.2	0.6	18.7
PAPR	0.5	3.9	0.1	0.6	0.0	38.8	0.5	0.4	24.8	20.3	0.8	21.5
S PR	1.6	8.0	0.1	0.5	0.0	46.2	0.3	0.4	29.8	3.1	1.8	6.6
NC PR	0.5	3.5	0.2	0.8	0.0	48.6	0.2	0.5	29.6	2.9	1.1	9.7
E PR	0.5	4.4	0.0	0.9	0.1	47.5	0.1	2.2	28.7	2.2	1.3	9.5
M PR	0.5	2.0	0.1	0.2	0.0	52.5	0.1	0.3	32.7	1.8	1.0	6.3
D PR	6.5	27.2	0.3	2.1	0.1	33.1	0.7	0.8	22.8	0.4	0.6	5.4
Detection	0.05	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.10	0.01	0.05	0.01

SSP = Single Superphosphate
TSP = Triple
PAPR = Partially Acidulated Phosphate Rock
Superphosphate S PR = Sechura Rock Phosphate

NC PR = North Carolina Rock Phosphate
E PR = Egyptian Rock Phosphate
M PR = Moroccan Rock Phosphate
D PR = Duchess Rock Phosphate

TABLE V. MINOR ELEMENT CONTENT OF FERTILIZERS USED IN THE NATIONAL RPR PROJECT (XRF — FUSION TECHNIQUE) (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

	Element												
	V (ppm)	Cr (ppm)	Mn (ppm)	Fe (%)	Co (ppm)	Ni (ppm)	Cu (ppm)	Zn (ppm)	As (ppm)	Cd (ppm)	Hg (ppm)	Pb (ppm)	Bi (ppm)
SSP	39	47	123	0.5	5	16	<5	188	6	15.1	0.09	7.35	<0.1
TSP	120	83	364	1.4	6	22	<5	371	9	4.08	0.054	13.9	<0.1
PAPR	21	114	79	0.7	<5	22	13	319	10	32	2.36	3.77	<0.1
S PR	53	130	77	0.3	<5	15	<5	47	23	34.7	0.018	8.14	<0.1
NC PR	23	169	48	0.5	<5	28	<5	381	13	40.3	0.071	3.6	<0.1
E PR	71	78	322	0.6	5	32	<5	163	7	5.32	0.036	7.91	<0.1
M PR	157	188	<15	0.2	<5	41	16	258	14	11.4	0.036	1.99	<0.1
D PR	94	67	829	1.4	18	36	98	301	7	1.38	0.036	41.4	0.2
Detection	2	10	15	0	5	10	5	5	1	0.1	0.005	1	0.1

SSP = Single Superphosphate
TSP = Triple
PAPR = Partially Acidulated Phosphate Rock
Superphosphate S PR = Sechura Rock Phosphate

NC PR = North Carolina Rock Phosphate
E PR = Egyptian Rock Phosphate
M PR = Moroccan Rock Phosphate
D PR = Duchess Rock Phosphate

Their estimates of P requirements were based on previous fertilizer field trials and regional experience. The X rate was based on the premise that 4X should achieve 90% of maximum yield response to WSP fertilizer under optimum conditions, for a pasture with a satisfactory legume component. It was envisaged that determining X in this way would result in a series of data points occurring on the rising portion of a P response curve. This outcome would enable the P response for different products to be accurately defined. All fertilizer treatment and rate combinations are shown in Table VI.

2.3.4. Experimental design

A randomized complete block design was used for both core experiments at all sites except those located in Victoria, where the two core experiments were combined into one larger trial. An incomplete block design, including treatments from both core experiments plus 6 no P treatments, was used at the Victorian sites. Because of the small overlap (North Carolina PR 2X, 4X, 6X, and control), the total number of treatments used in Victoria was 40.

The complete block designs at sites other than in Victoria meant that blocks consisted of 21 or 24 plots for CE1 and CE2, respectively. In Victoria, blocks consisted of between 6 and 12 plots, depending on site heterogeneity. For the incomplete block design, treatments were allocated to plots so that comparisons between any pair of treatments had as much precision as possible. The allocation was performed using "DESIGNER", a statistical package developed by Agriculture Victoria for trials with unequal replication of treatments and/or unequal sized blocks. Incomplete block designs can produce considerable gains in precision when estimating treatment effects [20]. The disadvantages of such designs were recognized: there were treatment effects that could not be estimated by simple calculation, and remote site operators could have difficulty in analyzing the results without biometrical assistance. Gains in precision have almost certainly been made but inconvenience did occur. The mixing of the two core experiments at the Victorian sites made sorting, separation and collation of samples and results tedious and time consuming, and simple treatment comparisons were more difficult to obtain compared with the comparisons from a randomized complete block design.

2.3.5. Management of experimental sites

The P fertilizers were applied to the soil surface close to the start of the growing season in each year (around October for Queensland sites and April to May at other sites). Basal nutrients were applied to eliminate other nutrient deficiencies apart from P. At sites where nutrient leaching was anticipated, K and S were applied as a split application at the break of season and again at the height of the growing season (August to September at sites in southern Australia). The frequency and rates of application and forms of basal nutrients are shown in Table VII. Basal S dressings were not applied to the minus-S treatments. The experiments were not grazed.

At sites N7, N8, V12, S22, S23, S25, W26, W27, W28, herbicides were used to maintain legume dominance by removing grass and weed species. Mixtures of perennial grass and subterranean and/or white clover were grown at sites N4, N6, T16-T20, V11-V15 and S24. Site Q3 involved the establishment of the tropical legume *Aeschynomene americana* in the first growing season.

Rainfall was recorded at each site, and was supported with records of the landholder where sites were not located on agricultural research stations. Additional meteorological data was obtained from the nearest weather station.

2.3.6. Plant measurements

2.3.6.1. Pasture production

Pasture production was determined at regular intervals during the growing season, when the high P treatments had formed a dense canopy. Cutting and weighing of pasture material was used to measure pasture production except at the Western Australian sites where a rising-plate-meter was used.

TABLE VI. FERTILIZER TREATMENT COMBINATIONS FOR RANDOMIZED COMPLETE BLOCK DESIGN USED IN ALL EXCEPT THE VICTORIAN SITES (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16])

Treatment No.	Treatment	Total P rate	Treatment No.	Treatment	Total P rate
	Core Experiment 1			Core Experiment 2	
1	Control	nil	22	Control	nil
			23	Control	nil
2	SSP Superphosphate	2X[1]			
3	SSP Superphosphate	4X	24	Annual soluble P(as TSP)	X
4	SSP Superphosphate	8X	25	Annual soluble P(as TSP)	1.5X
			26	Annual soluble P(as TSP)	2X
5	Sechura PR 'As Recvd'[2]	2X	27	Annual soluble P(as TSP)	4X
6	Sechura PR 'As Recvd'	4X	28	Annual soluble P(as TSP)	8X
7	Sechura PR 'As Recvd'	8X			
			29	Annual PAPR(N.Carolina)	X
8	North Carolina PR 'As Recvd'	2X	30	Annual PAPR(N.Carolina)	1.5X
9	North Carolina PR 'As Recvd'	4X	31	Annual PAPR(N.Carolina)	2X
10	North Carolina PR 'As Recvd'	8X	32	Annual PAPR(N.Carolina)	4X
			33	Annual PAPR(N.Carolina)	8X
11	Egyptian PR 'As Recvd 92'	2X			
12	Egyptian PR 'As Recvd 92'	4X	34	Annual RPR (N.Carolina)	X
13	Egyptian PR 'As Recvd 92'	8X	35	Annual RPR (N.Carolina)	1.5X
			36	Annual RPR (N.Carolina)	2X
14	Moroccan PR 'As Recvd'	2X	37	Annual RPR (N.Carolina)	4X
15	Moroccan PR 'As Recvd'	4X	38	Annual RPR (N.Carolina)	8X
16	Moroccan PR 'As Recvd'	8X	39	Annual RPR (N.Carolina)	16X
17	Duchess(fine) PR 'As Recvd'	2X	40	Year one soluble P(as TSP)	8X
18	Duchess(fine) PR 'As Recvd'	4X	41	Year one soluble P(as TSP)	16X
19	Duchess(fine) PR 'As Recvd'	8X			
			42	Year one PAPR(N.Carolina)	8X
20	Aerophos (MCP)-S	4X	43	Year one PAPR(N.Carolina)	16X
21	RPR(North Carolina)-S	4X			
			44	Year one RPR(N.Carolina)	8X
			45	Year one RPR(N.Carolina)	16X

Total plots/rep. = 21
No. reps = 4
Total plot No. = 84

Total plots/rep = 24
No. reps = 3
Total plot No. = 72

GRAND TOTAL NO. PLOTS = 156

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[1] The rates of X indicated above are on the basis of 4X being at 90% of maximum water soluble P fertilizer yield *response* under optimum conditions with a good clover component.

[2] As received.

TABLE VII. TYPE, FREQUENCY, SUGGESTED RATES, AND FORM OF BASAL NUTRIENTS APPLIED TO NATIONAL RPR PROJECT SITES (REPRODUCED WITH PERMISSION OF CSIRO PUBLISHING [16]).

Nutrient	Application frequency	Rate kg/ha	Form
K	Annual (1/1)[1]	60 kg K/ha as KCl	Muriate of potash
S	split annual(2/1)	30 kg S/ha	Gypsum
Mg	1/2	15 kg Mg/ha	Magnesium sulfate
Zn	1/2	2 kg Zn/ha	Zinc sulfate
Cu	1/2	1 kg Cu/ha	Copper Sulfate
Mo	1/4	75 g Mo/ha	Sodium molybdate
B	1/4	1 kg B/ha	Ulexite (slow release B)
For -S plots			
Mg	1/2	15 kg Mg/ha	Magnesium chloride
Zn	1/2	2 kg Zn/ha	Zinc chloride
Cu	1/2	1 kg Cu/ha	Copper chloride

[1] 1/1 indicates the nutrient should be applied every year (ie once every one year), 1/2 indicates the nutrient should be applied once every two years, 1/4 indicates application once every four years. 2/1 indicates an application twice per year.

Where cutting was carried out, lawn mowers fitted with catchers were used to collect pasture material. At the Queensland sites sickle bar mowers were used due to the height and density of the tropical pasture species. Plant material was collected from the central portion of the plots after the borders had been cut and discarded. Plant material was then weighed wet and sub-sampled for moisture content determination (oven dried at ~ 60^0 C before weighing). Plant material equal to approximately 50% of that harvested from the total plot area was then returned to the plots, evenly spread over the plot area, and mulched back into the plot using Bolans (Masport) mulching mowers. These mowers finely chopped the returned plant material and directed it down toward the soil surface. This recycling of clippings was considered important in an attempt to simulate some return of nutrients to the pasture as would occur in a paddock grazing system. McLaughlin et al. [21] highlighted the importance of returning clippings in obtaining P responses in their work with WSP and RPR fertilizers. Any regrowth on plots (such as annual grasses or summer weeds) after the end of a growing season and prior to the beginning of the next was mowed off and discarded.

2.3.6.2. Botanical composition.

For the majority of sites, botanical composition was visually assessed for each plot in the spring of each year where a mixed pasture sward existed. Many sites were maintained at 100% legume with the control of annual grasses, or were 100% grass as in case sites Q1 and Q2.

2.3.6.3. Tissue analysis.

Plant material from the first control (treatment 22 in the randomized complete block design (Table VI) and from the 3 control replicates at Victorian sites) and from the X, 2X, and 8X rates of North Carolina PR, PAPR and TSP in Core Experiment 2 was collected for determining P uptake. The sample used for determining P content was a composite sample made up of material from each harvest. At the end of each growing season dried and ground plant material from each plot at each harvest was proportionally combined, on the basis of pasture yields at each harvest. Phosphorus content was measured by Incitec Analysis Systems at the Port Kembla laboratory.

Plant material was dried (80^0 C) ground and digested by the Kjeldahl method (concentrated H_2SO_4 and selenium catalyst) and measured colorimetrically in a segmented flow analyzer.

Analyses for macro- and micro-nutrients including N, S, P, K, Ca, Mg, Na, Cl, Cu, Zn, Fe, B, Mo, and Al, were carried out annually by Incitec Analysis Systems to check that no nutrient deficiencies were present. Samples were collected each year from the first control and the highest rates of North Carolina PR (16X) and TSP (8X) in Core Experiment 2 in the spring in southern Australia and in the middle of the growing season in northern Australia. Except for sites Q1 and Q2, where the pasture was 100% grass, legume material collected for these analyses consisted of the terminal and last 2-3 leaflets from stolons or runners, for white (*Trifolium repens*) and subterranean (*T. subterraneum*) clover, respectively. At site Q3 where Lee Joint Vetch (*Aeschynomene americana* cv Lee) was grown, the last 2 leaflets and growing tip of stems were collected. Except for P on the control plots at some sites, no major nutrient deficiencies for either macro or trace elements were detected (data not presented) based on critical levels for nutrients in pasture tissue [22].

On two occasions, plant samples from various North Carolina PR, PAPR, and SSP treatments were collected to study the effects of fertilizer cadmium content on the cadmium concentration of pasture. Collection and preparation of these samples are described further below in Section 4.

2.3.7. Soil measurements

Prior to fertilizer application in each year, soil from all plots was sampled to monitor the changes in extractable P concentrations and soil pH over time. This involved taking 10 soil cores (100 mm depth and 20 mm diameter) from the central portion of each plot and bulking the 10 cores together. Soil samples were air dried and forwarded to the CSBP laboratory in Western Australia where they were crushed and sieved (<2 mm) prior to routine analysis. Analyses for extractable P, K, organic carbon, electrical conductivity, and pH (water and $CaCl_2$) were carried out using methods 9B (bicarbonate extractable P- 'Colwell'), 18A1 (bicarbonate extractable K), 6A1 (Walkley & Black), 3A1, 4A1 and 4B1 respectively, from Rayment and Higginson [23]. Oxalate extractable 'reactive' iron was also measured in the first year (method 13A1 [17]), except that a 1 hr shaking period was used. Sub-samples of soil taken from the minus-S treatments were prepared and forwarded to the University of New England, where they were analyzed for extractable S. Procedures used and the results of these analyses are presented in Blair et al. [7]. Sub-samples of the annual plot soil samples for 1993 and 1995 were also used in work that investigated the efficacy of different soil P tests for situations where RPR and WSP fertilizers have been used [13]. Site soil profiles were sampled to characterize the site and results are presented in Simpson et al. [16] and in Sale *et al.* [1]. Studies of the PR dissolution process, and measures of P sorption capacity and titrateable acidity were also conducted on the 0-2 cm fraction [4]. The effect of particle size on the effectiveness of a moderately reactive RPR was also examined [4].

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