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The residual value of superphosphate and rock phosphates for lateritic soils and its evaluation using three soil phosphate tests

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Abstract. The residual value of superphosphate and several rock phosphates was measured in three field experiments in Western Australia. The rock phosphates were Christmas Island C-grade ore, calcined C-grade ore (Calciphos) and apatite rock phosphates. The predictive capacity of the Colwell, Olsen and Bray 1 soil tests for phosphate were also evaluated.

As measured by yields of variously wheat, oats, barley or clover, the effectiveness of an initial application of superphosphate decreased to about 50% of that of newly applied superphosphate between years 1 and 2, and further decreased to about 20% over subsequent years. At low levels of application, all the rock phosphates were between 10–20% as effective as superphosphate in the year of application for all experiments. Relative to newly applied superphosphate their effectiveness remained approximately constant in subsequent years for two experiments and doubled for the other experiment.

The Colwell soil test predicted that the effectiveness of superphosphate decreased to about 45% between years 2 and 3, followed by a more gradual decrease to approximately 15%. At low levels of application, the effectiveness of the rock phosphates as predicted by the Colwell soil test values was initially very low relative to superphosphate (2–30%), and remained low in subsequent years (2–20%). For superphosphate treated soil, the proportion of the added phosphorus extracted generally increased as the level of application increased. By contrast, for rock phosphate treated soil, the proportion of added phosphorus extracted decreased as the level of application increased.

For all three experiments there were highly significant positive correlations between amounts of P extracted by the three soil tests. Consequently all soil tests were equally predictive of yield but usually for each soil test separate calibrations between yield and soil test values were required for the different fertilizers and for each combination of fertilizer and plant species and for each year.

Introduction

Soils in south-western Australia are acutely deficient in phosphorus (P) [31] and profitable agriculture depends on first improving and then maintaining plant available P levels [28]. Before 1974, the price of Australian superphosphate was very cheap and large quantities were applied each year to soils in south-western Australia. However, in 1974 the price per tonne of superphosphate in Western Australia increased from $14 to $50, and in 1987 was about $120. Thus it was no longer profitable to apply liberal quantities of superphosphate to each paddock each year as a matter of routine. Australia has large deposits of potentially cheap rock phosphates. However, it was not known whether these were cheaper alternative fertilizers for superphosphate because the initial and residual value of these fertilizers was not known when they are applied to Western Australian soils. That is the subject of this paper.

After 1974 farmers in Western Australia required more precise fertilizer advice leading to the development of the Decide model [10] and to the more widespread use of soil testing for P to provide this advice. Soil testing for P is also the subject of this paper. Advice for P fertilizer applications is based on a soil test for P on soil samples collected during the dry summer period (November–March). Fertilizer applications for the next winter growing season (April–October) are then calculated with the aid of a model [10] which assumes a knowledge of both the yield response of pastures and crops to freshly applied P fertilizer and the residual value of previous fertilizer dressings. The Colwell sodium bicarbonate soil test [12], which is a modification of the Olsen et al. soil test [26], is currently used in Western Australia. For pastures and crops grown on the diverse range of lateritic soils in south-western Australia, the relationships between yield and soil test values for the different environments, plant species and management practices are not well established. Similarly the residual value of P fertilizers for most of these soils can not be confidently predicted from soil test values or from the amounts of fertilizer applied in previous years.

In this paper results are presented from three long-term field experiments which measured the residual value of superphosphate and several rock phosphates on three different lateritic soils in different environments in south-western Australia. Three soil tests for P (Colwell [12], Olsen [26] and Bray 1 [11]) were evaluated as predictors of yield response to the residual effect of dressings of the fertilizers. The rock phosphates were the potentially cheap and abundant (150 Mt reserves) crandallite and millisite-containing C-grade rock phosphate from Christmas Island (C-ore) applied as either ground C-ore or as 500 °C calcined C-ore (Calciphos) [13, 15, 17, 30]. In one of the experiments apatite rock phosphates from the Duchess deposit in Queensland Australia (QRP) [1], and a mixture of apatite rock phosphates from Nauru Island and Christmas Island (A-grade ore) known locally as ground rock phosphate (GRP) were also used. The Colwell, Olsen and Bray 1 soil tests were compared to determine whether different soil tests for P offered a means of providing more precise fertilizer advice.

Materials and methods

Phosphate fertilizers

Ordinary or single superphosphate was applied as granulated fertilizer and the rock phosphates were applied as fine powders. Some properties of the fertilizers used in the experiments are listed in Table 1. Superphosphate and GRP were obtained from CSBP and Farmers Ltd, Perth, Western Australia. C-ore and Calciphos were donated by the Christmas Island Phosphate Commission. The QRP was ground ore from the Duchess deposit in Queensland, Australia [1] and was donated by Broken Hill South Pty Ltd, Melbourne, Victoria, Australia.

Location, climate and soil

The experiments were located on newly cleared, acutely phosphate-deficient soils in south-western Australia in an area with a mediterranean-type climate of cool wet winters and hot dry summers. Site and soil characteristics are summarized in Table 2.

Field experiments

The design for experiment 1 was a completely randomized block of 16 treatments (nil + [5 levels × 3 P fertilizers]) with three replications. The different fertilizers were applied at different levels because of their different effectiveness [8].

The design for the other two experiments was a split plot, randomized block, replicated three times. The P fertilizers were the main plots, and the subplots were the levels of application of each fertilizer. In experiment 2, four levels of the P fertilizers were applied once only at the start of experiment in May 1976 (Table 3). In experiment 3, for all but QRP, five levels of each fertilizer were applied once only at the start of the experiment in May 1976 (Table 3). For QRP in experiment 3, three levels were applied once only at the start of the experiment (Table 3).

The P fertilizers were applied to the soil surface from either an experimental 12-row disc drill, or by hand, in plots 2.1 m wide and 50 m long.

Table 1. Some properties of the fertilizers used. Unless indicated, all values are percentages (w/w). SP is superphosphate; C-ore is Christmas Island C-grade ore; QRP is Queensland (Duchess deposit) apatite rock phosphate; and GRP is ground rock phosphate (50% mixture of apatite rock phosphate from Nauru and Christmas Islands).

		SP	C-ore	Calciphos	QRP	GRP
Moisture		NM**	2.6	1.2	0.9	NM
Total phosphorus		9.6	10.9	13.4	14.1	16.1
Water-soluble phosphorus*		7.4	0.1	0.1	0.1	0.1
Neutral ammonium citrate – soluble phosphorus*		1.2	0.1	6.5	1.8	0.1
Acid-soluble phosphorus*		1.0	10.7	6.9	12.2	15.9
Sulfur		11.0	0.18	0.26	0.28	0.10
Aluminium		NM	11.8	11.1	0.93	0.62
Iron		NM	7.7	6.6	0.78	0.44
Calcium		23	9.4	17.6	31.2	33.4
Magnesium		NM	0.05	0.07	0.15	0.31
Potassium		NM	NM	0.03	NM	0.03
Copper (μg g^{-1})		40	120	95	90	NM
Zinc (μg g^{-1})		380	560	560	300	NM
Cobalt (μg g^{-1})		NM	36	35	35	NM
Particle size^{+}:						
BSI sieve no	*Aperture (mm)*					
> 52	> 0.295	(Granulated 0.5–2 mm)	8.2	5	3.8	2.4
52–100	0.295–0.152		14.0	25	7.5	20.9
100–200	0.152–0.076		8.6	29	19.5	19.5
200–300	0.076–0.053		1.7	9	10.5	6.1
< 300	< 0.053		67.6	34	58.7	51.1

* By standard AOAC procedures [2].

+Percentage retained by the finest sieve used, measured by wet sieving.

**NM, not measured.

There was 0.8 m between each plot. Apart from year 1, superphosphate was applied just after sowing to the soil surface across all plots each year, using a new section of the plots each year, and at a level (300 kg P ha^{-1}) sufficient to support the maximum yield.

The following basal fertilizers were applied to the soil surface before sowing in year 1 (May 1976) at these high levels of application: 100 kg ha^{-1} gypsum (18% sulfur), 100 kg ha^{-1} potassium chloride (50% potassium), 10 kg ha^{-1} copper sulfate (27% copper), 2 kg ha^{-1} zinc oxide (80% zinc) and 0.2 kg ha^{-1} molybdenum trioxide (67% molybdenum). In May of subsequent years and before sowing, 100 kg ha^{-1} potassium chloride and 100 kg ha^{-1} gypsum were applied to the soil surface across all plots. A further 100 kg ha^{-1} gypsum and 100 kg ha^{-1} potassium chloride was applied for experiment 1 in early August each year. The amounts of basal fertilizer

Table 2. Location of experiments, climatic information, and properties of the less than 2 mm fraction of the top 10 cm of the unfertilized soil.

	Experiment 1	Experiment 2	Experiment 3
Location	Yallingup	Wongan Hills	Newdegate
Distance from Perth, Western Australia	210 km south	150 km N.E.	325 km S.E.
Average annual rainfall (mm)	1000	348	393
Approximate length of the winter growing season*	7 (April–Oct)	4.5 (May–Sept)	5.5 (May–Sept)
Soil type	Sand over massive laterite	Sandy loam	Lateritic gravelly sand over massive laterite
Soil classification [25]	Dy 3.61	Gn 2.21	KS-Uc 4.11
pH+	4.5	5.4	4.9
Phosphorus buffer capacity ($\mu g\, g^{-1}$) [27]	1	2	9
Total phosphorus ($\mu g\, g^{-1}$)	27	38	52
Bicarbonate-extractable phosphorus ($\mu g\, g^{-1}$) [12]	1	2	1

* From: precipitation (mm)/[evaporation (mm) × 0.7]

+ As measured in 1:5 soil:0.01 M $CaCl_2$

applied were chosen on the basis of previous experiments on these soils and ensured that deficiencies of nutrients other than P did not limit plant growth.

Subterranean clover (*Trifolium subterraneum*) was sown on all experiments in 1976 and 1977. A 50% mixture (by weight of seed) of Mt Barker and Trikkala cultivars was sown in experiment 1, and the Geraldton cultivar was sown in the other two experiments. The seeds were inoculated with *Rhizobium trifolii* strain WU 95 and lime pelleted just before sowing, and were sown from a disc drill at about 100 kg/ha in 1976 and 50 kg/ha in 1977, by driving down each plot with the discs in the soil to about 1 cm. In experiment 1, regenerated clover pasture was used to measure fertilizer effectiveness in subsequent years, except for 1981 (year 6) when the experiment was sown with oats (*Avena sativa* cv. West). Experiment 2 was sown with wheat (*Triticum aestivum* cv. Gamenya) from 1978 onwards, and experiment 3 was sown with barley (*Hordeum vulgare* cv. Clipper) followed by wheat (*T. aestivum* cv. Madden) in a 1-year barley:1 year wheat rotation. Before sowing the cereal crops, weeds were killed by cultivating the top 10 cm of soil by driving a tined implement down each plot. Weeds were

Table 3. Levels of phosphorus (kg ha^{-1}) applied in the experiments once only at the start of the experiment in May 1976.SP = superphosphate; C-ore = Christmas Island C-grade ore; QRP = Queensland (Duchess) apatite rock phosphate, and GRP = ground rock phosphate.

	SP	C-ore	Calciphos	QRP	GRP
Experiment 1	53	134	90		
	105	224	238		
	175	493	476		
	280	986	714		
	420	1478	952		
Experiment 2	80	170	85		
	160	290	260		
	320	635	430		
	400	865	600		
Experiment 3	51	220	95	749	213
	86	367	210	1497	365
	171	734	420	2994	941
	426	1707	770		3021
	599	2987	1600		4518

killed before sowing by spraying with a 1:1 mixture of paraquat and diquat (2–3 litres ha^{-1}). The plots were sown by driving down each plot with a tined seeder which deposited about 55 kg ha^{-1} of seed at a depth of 3–4 cm in the soil. Nitrogen fertilizer, as either ammonium nitrate or urea was applied to the soil surface at about 60 kg nitrogen ha^{-1} across all plots 3 weeks after emergence of the plants for experiment 1, and at sowing for the other 2 experiments.

Clover herbage yields were measured with a rising plate meter [14]. The meter was calibrated by cutting off clover topgrowth at ground level in random quadrats and drying the samples for 3 days at 70 °C in a forced draught oven before weighing. Cuts were taken to allow for the calibration of the meter for the different botanical compositions of the pastures which developed with time as a result of the P treatments. Each year, just after the pasture had emerged at the start of the growing season, it was grazed with 4–5 dry adult sheep ha^{-1} until 4–6 weeks before measurement of herbage yield. After measurement of yield, the experiments were grazed with sheep until most of the dried herbage had been removed from the plots during summer. Yields of dried whole tops of wheat, barley and oats were measured by cutting plants at ground level in random quadrats and drying the samples for 3 days at 70 °C in a forced draught oven before weighing. Grain yields were measured by harvesting grain from each plot with a small harvesting machine and weighing the grain, or by collecting plants in random quadrats and threshing the grain from the heads before weighing.

Soil P tests

Soil tests were done as follows: Colwell [12], all years and experiments; Olsen [26], experiment 1, 1977, 1979, 1980 and 1981, experiment 2, 1979–1983 experiment 3, 1979–1982; Bray 1 [11], experiment 1, 1977, 1979, 1980 and 1981, experiments 2 and 3, 1979–1983. Twenty soil samples were collected from each plot in January or February of each year, using 0–10 cm depth soil samplers (2.5 cm diameter), and the samples were bulked. Subsamples of the less than 2 mm fraction of soil were used for the soil tests. For the Colwell soil test [12], the subsamples of soil were extracted with 0.5 M $NaHCO_3$ at pH 8.5, using a 1:100 soil:solution ratio and a shaking period of 16 hours. For the Olsen soil test [26], the soil:solution ratio was 1:20, and the soil was extracted with 0.5M$NaHCO_3$ at pH 8.5 for 30 minutes. For the Bray 1 soil test [11] (hereafter called the Bray test), the soil:solution ratio was 1:7, and the soil was extracted for one minute with a solution of 0.03 M ammonium fluoride and 0.025 M HCl at pH 3.0. All the soil samples were extracted at a constant temperature of 23 °C. The P concentrations in the extract solutions were measured colorimetrically by the molybdenum blue method using ascorbic acid as a reductant [24].

Analysis of data

The agronomic effectiveness of the fertilizers was determined each year by calculating the initial slope of the relationship between percentage of the maximum (largest) yield measured each year, and the level of P applied ($kg\,ha^{-1}$). Percentage of the largest yield was used in an attempt to reduce variations resulting from different seasonal conditions each year on plant growth. The largest yields were for the freshly applied superphosphate which had been applied across all the plots each year. The initial slope was calculated for each fertilizer, replicate and year using yields for the nil treatment and the first two levels of P applied. In every instance these data were well described by a linear relationship (R^2 greater than 0.92). The relative effectiveness of the fertilizers was calculated by dividing the initial slopes determined for each fertilizer each year by the initial slope determined for freshly applied superphosphate applied at the start of each experiment in May 1976.

For the relationship between soil test value and the level of P applied, data for each fertilizer and for each year were fitted to the following exponential equation by non-linear regression using a Prime computer and Rothamsted's maximum likelihood program

$$y = A x^{B} \tag{1}$$

where y is the increase in soil test value above the control ($\mu g\,P\,g^{-1}$ soil), x is the level of P applied ($t\,P\,ha^{-1}$), and A and B are coefficients. The control values were always very small and were about 2 $\mu g\,P\,g^{-1}$ soil for the Colwell soil test, 0.6 for the Olsen soil test and 1 for the Bray soil test.

The initial slope of the linear relationship between P extracted from the soil by the soil test and the level of P applied (i.e. $dy/dx = ABx^{B-1}$) was calculated for each fertilizer and replicate each year using nil and the first two data points. This initial slope will be called the extractability of the P that had been applied as fertilizer. A linear relationship could not be used to describe the data for all levels of fertilizer application since the data for some fertilizers showed a marked curvilinear relationship (i.e. B does not equal 1 in Equation 1).

The plant yield results measured in Spring (August–December) were compared with the soil test values for soil samples collected in the previous January–February. The data were fitted to the following equation using Rothamsted's Genstat program:

$$y = A + Bx + Cx^2 \qquad (2)$$

where y is the yield ($kg\,ha^{-1}$) and x the soil test value ($\mu g\,P\,g^{-1}$ soil), and A, B and C are coefficients. When the C coefficient was not significantly different from zero ($P > 0.05$), the data were re-fitted to the linear form of (2):

$$y = A + Bx \qquad (3)$$

Mean yield and soil test data were used for the regression analyses.

Results and discussion

The results of the three experiments are voluminous and as they showed consistent trends only representative data are presented here. A complete listing of the data for all three experiments is available on request to the senior author.

Plant response to fertilizer

No data are available for experiment 1 in year 3. Experiment 2 was affected by drought in years 2, 5 and 8, and experiment 3 was affected by drought in years 1, 2 and 5, so that no yield data are available for these years.

Superphosphate was the most effective fertilizer in all experiments in all years (Fig. 1) even though the effectiveness of superphosphate relative to freshly applied superphosphate (relative effectiveness) decreased markedly with time. In experiment 1, the relative effectiveness of superphosphate decreased to about 50% between year 1 (year of application) and year 2, and it further decreased to about 20% over the remaining 5 years. In experiment 2, the relative effectiveness of superphosphate also decreased to about 50% between years 1 and 3 (year 2 was affected by drought), and it decreased to about 25% between years 3 and 4, and to about 20% between years 4 and 9. Thus superphosphate was initially highly effective in promoting plant growth, but with time as this soluble P reacted with soil constituents it becomes increasingly less available to plants [3].

The relative effectiveness of all the rock phosphates was much lower than for superphosphate and remained approximately constant through time. Calciphos was about 20% as effective as freshly applied superphosphate and C-ore was 10–17% as effective. Experiment 3 was badly affected by drought in the first 2 years so that no data are available, but trends in effectiveness values in subsequent years were similar to those observed in the other two experiments. Both C-ore and QRP were very ineffective fertilizers at this site being always less than 10% as effective as freshly applied superphosphate.

The low agronomic effectiveness of the rock phosphates is probably a consequence of the low water soluble P content of the rock phosphate and the inability of these soils to promote extensive dissolution of rock phosphate [23]. In contrast to the high solution P levels provided by freshly applied superphosphate the P concentrations in soil solution for rock phosphates were probably initially low and remained low [32].

All four rock phosphates were poorly effective in both the short and long term. These results are consistent with results from other field experiments in south-western Australia including many on different soil types, in different environments, which used various plant species and which experienced different management practices [5, 7, 8, 9]. Consequently it appears that rock phosphates are unlikely to be effective substitutes for superphosphate on lateritic soils in the south-west of Western Australia. This very poor performance of rock phosphates is probably because the pH of the soils is relatively high (> 5.0 in water), and the soils are poorly buffered against changes in pH occurring during fertilizer dissolution. These soils also have low water-holding capacities so that the near-surface fertilized soil horizon dries between rainfall events in the comparatively short winter growing season of south-western Australia. Consequently dissolution of rock phosphate in this soil horizon will be restricted to periods when the soil is sufficiently wet [21]. Thus a combination of soil and climatic factors do not favour dissolution of rock phosphates whereas these factors do not greatly

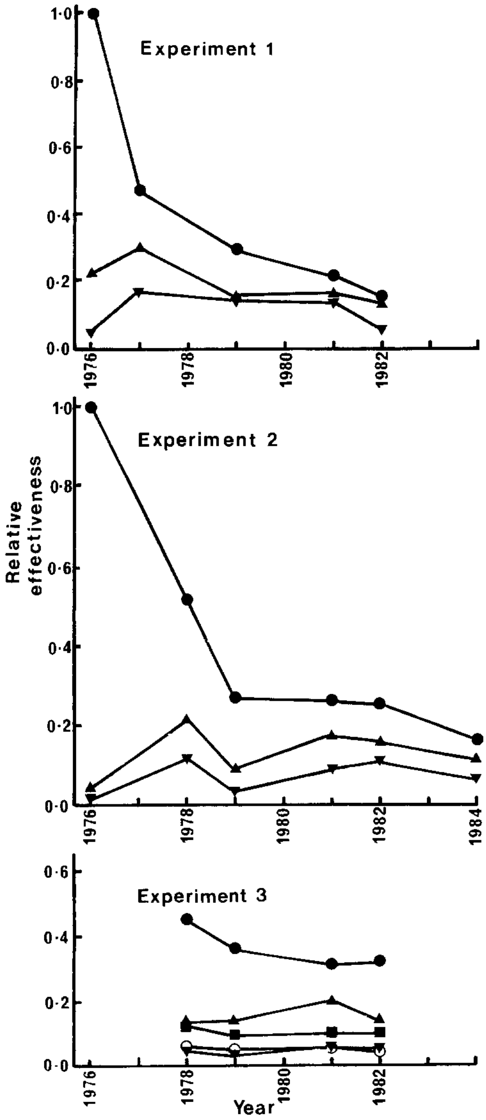


Fig. 1. Effectiveness of the fertilizers calculated from plant yield relative to the effectiveness of newly-applied superphosphate (relative effectiveness). ● superphosphate, ▼ C-ore, ▲ Calciphos, ○ QRP and ■ GRP.

influence the effectiveness of freshly applied superphosphate so that consequently the agronomic effectiveness of rock phosphates is low relative to freshly applied superphosphate.

The relative effectiveness of the fertilizers was calculated for low levels of application. The relative effectiveness of the rock phosphates decreased as the level of application increased, which is consistent with results of laboratory studies [22], a glasshouse pot experiment [16] and another field experiment [6]. Thus there is no single value for the relative effectiveness of the rock phosphates, and the relative effectiveness values calculated for the rock phosphates are the maximum values.

P extracted by the Colwell soil test

Colwell P values were measured for all years in all 3 experiments and increased with level of applied P for all fertilizers. Values for rock phosphates were much smaller than those for equivalent levels of application of superphosphate. Colwell P values for superphosphate decreased with increasing period of contact with the soil as illustrated by the data for experiment 3 in Fig. 2. Conversely for the rock phosphates, Colwell P mostly increased with time with a particularly large increase occurring between years 2 and 3. However, Colwell P values for rock phosphate-treated soil generally remained lower than those for superphosphate throughout the 10-year duration of these experiments. These trends are reflected in the extractability values for all three experiments (Fig. 3). For superphosphate-fertilized soil, extractability of P decreased to about 45% between years 2 and 3, followed by a more gradual decrease to about 15% over the subsequent years. By contrast, the extractability of P from rock phosphate-fertilized soil was much smaller initially and remained smaller in the longer term. Thus much P from superphosphate was initially soluble (i.e. up to 47% was soluble in bicarbonate in experiment 3) but with increasing time there was increased retention of P by soil constituents [3] so that its extractability declined markedly. By contrast rock phosphate fertilizers were apparently only sparingly soluble in soil solution, consequently only a small fraction of applied rock phosphate dissolved. Consequently relatively little P was in a form that could be extracted by the Colwell soil test. For experiment 3 the extractability of P for all rock phosphates increased with time but never exceeded that for superphosphate. In all experiments the extractability value for Calciphos reached similar values to those for superphosphate although this occurred after about 3, 8 and 10 years respectively for experiments 1, 2 and 3 and these values were much smaller than for freshly applied superphosphate.

The extractability parameter only relates to the initial and assumed linear relationship between Colwell P and level of applied P whereas in some instances and over the full range of P-applied values the data followed a distinct curvilinear relationship. This tendency was particularly marked for rock phosphates (Fig. 2). The relationship between soil test value and the level of P applied was well described by the exponential equation (1) over the

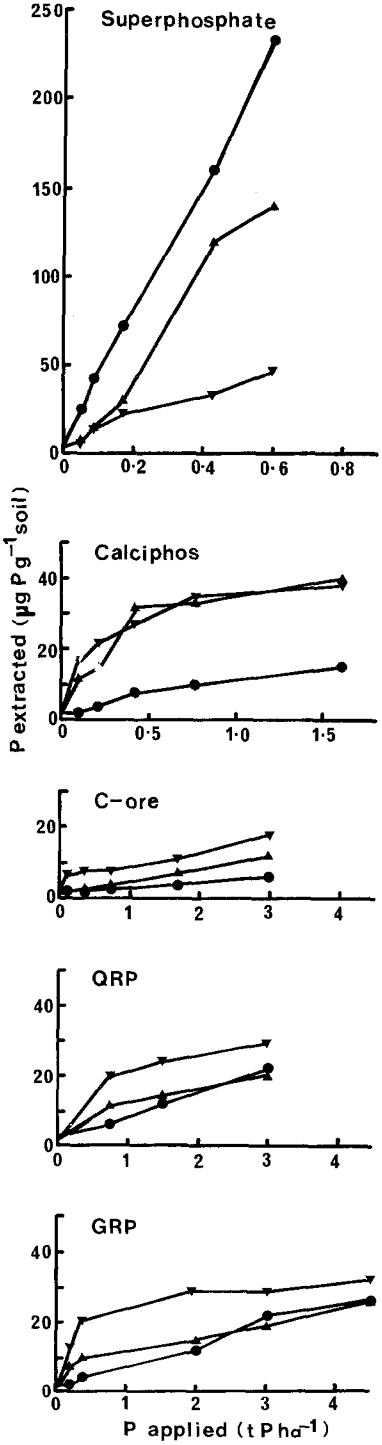


Fig. 2. Relationship between Colwell soil test values and the level of P applied for experiment 3 measured in 1977 (●), 1979 (▲) and 1982 (▼).

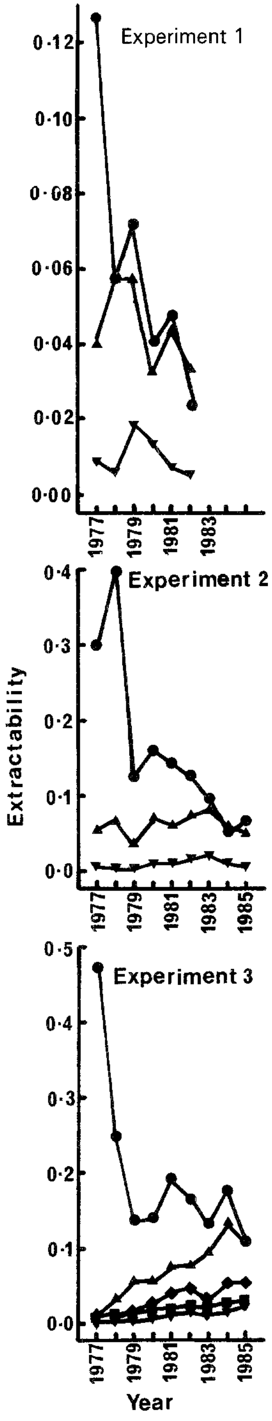


Fig. 3. Extractability values calculated for each fertilizer each year from the initial slope of the relationship between Colwell soil test values and the level of P applied. Standard errors for the extractability values varied between 10–30% of the mean values. ● Superphosphate, ▼ C-ore, ▲ Calciphos, ■ QRP and ◆ GRP.

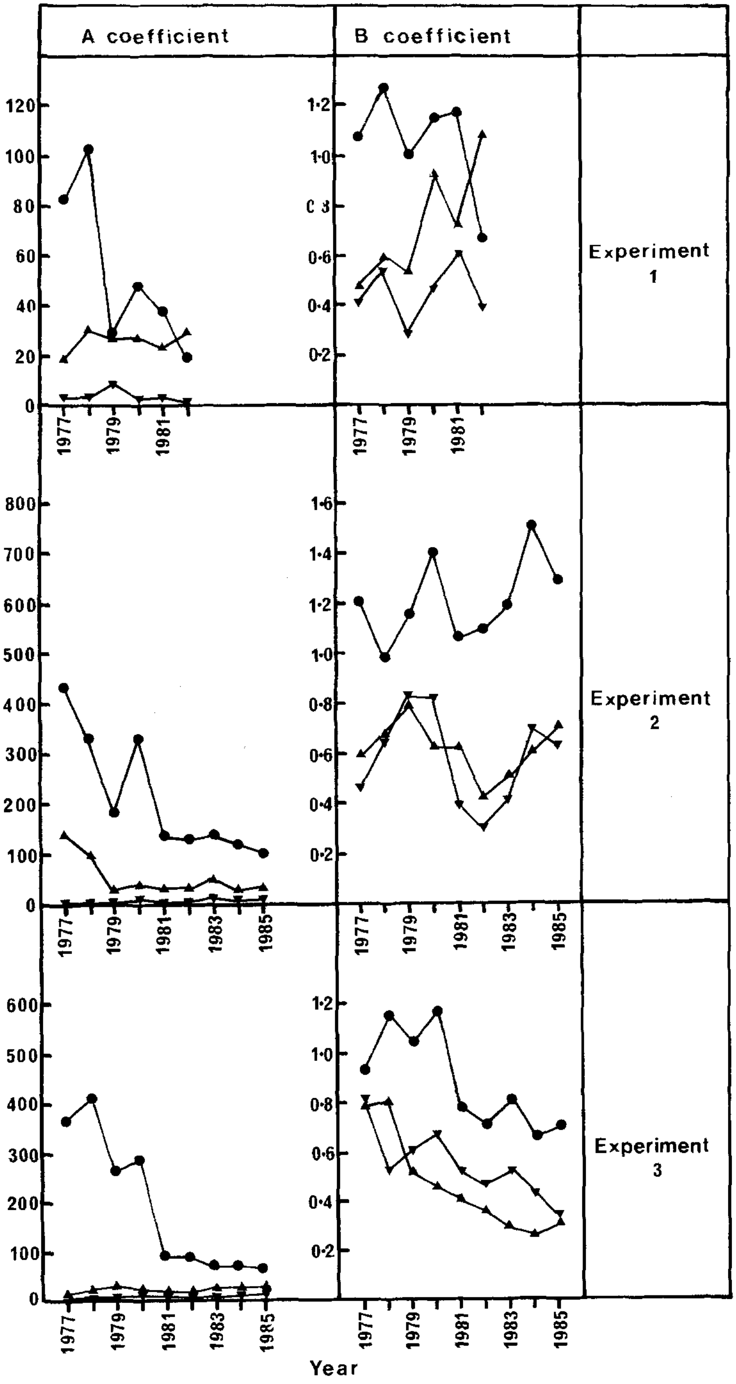
complete range of data. The A parameter of equation (1) can be considered to primarily reflect the proportion of applied P available for extraction, and the B parameter can be considered as a coefficient that describes the proportional solubility of applied P with increasing level of fertilizer applied. Where there is no influence of level of application on dissolution the value of B in equation (1) will be one (i.e. a straight-line relationship). The value of the B coefficient (i.e. proportional solubility coefficient) is larger than one for where the proportion of added P that is extracted by the soil test increases with level of fertilizer application. Conversely, a smaller proportion of a poorly soluble fertilizer may dissolve in the soil at high levels of application so that the proportional solubility of soil P may decrease and the value of the B coefficient is less than one. This relationship between percentage dissolution of rock phosphate and level of application is well known and resembles the negative feedback relationship that describes many physical, chemical and biological systems. It has been demonstrated with rock phosphates by a variety of laboratory experiments [19, 22, 23] and inferred from results of glasshouse [16] and field experiments [6]. Direct measurements of the extent of dissolution of rock phosphates in soil in field and glasshouse experiments together with plant yield and P content have been undertaken and the data support the interpretation that the low effectiveness of rock phosphates at high rates of application may be due to this negative feedback relationship (A.J. Weatherley, personal communication).

Values of the A coefficient differed greatly between experiments (Fig. 4) but in each experiment it was initially high for superphosphate and decreased with time. Thus much of the P from soils containing recently applied superphosphate was extracted, but with increasing time, as P continued to react with soil constituents, it became increasingly less soluble. By comparison, A values for rock phosphates were much lower and changed little with time. These differences therefore presumably reflect the low initial solubility of rock phosphates in the soil and the minor continuing dissolution of the residual rock phosphate during the period of these experiments. An exception to this trend for rock phosphates is shown by the A coefficient for Calciphos for experiment 2 which decreased substantially during the first three years of the experiment. This behaviour more closely resembles that for superphosphate and may indicate that some Calciphos dissolved during 1977 and that little dissolved in subsequent years. However, this initial dissolution of some Calciphos was not associated with a higher value of relative agronomic effectiveness compared with results of experiments 1 and 3.

The B coefficient was mostly 1.0 ± 0.3 for superphosphate (i.e. denoting an almost linear relationship due to an almost constant proportion of added

P dissolving in the bicarbonate reagent for each level of application of superphosphate), although for experiment 3 it decreased to about 0.65 after 1983 and was as high as 1.5 in experiment 2 in 1984 (Fig. 4). Because values of B for superphosphate were generally 1.0 ± 0.3 for each sampling time and experiment we can as a first approximation consider that a constant proportion of applied superphosphate was soluble in the bicarbonate reagent for all fertilizer application levels. Values of B greater than one indicate that an increasing proportion of applied P was soluble in bicarbonate (i.e. positive feedback) and values smaller than one (i.e. negative feedback) indicate the reverse trend. There were systematic differences between experiments in this respect and also different trends with time for the three experiments. Those instances where $B > 1$ (positive feedback) indicate that P retained by the soil was more easily extracted for higher levels of P application. It has been shown in laboratory studies that the proportion of previously added P which was initially displaced by bicarbonate decreased as the period of prior contact between soil and P increased [4]. Values of B for rock phosphates are much smaller than for superphosphate generally being about 0.3–0.8 (i.e. generally showing a negative feedback effect). As more rock phosphate was applied to the soil more P was extracted by the soil test; however, for each incremental addition of rock phosphate a smaller proportion of the added P was extracted (i.e. B was less than one). This corresponds to values of the rate of change of extractability with level of application which is the second differential of Equation 1 being negative because $B\text{-}1 < 0$ when $B < 1$ (i.e. $d^2y/dx^2 = AB(B\text{-}1)x^{B\text{-}2} < 0$). Values of B for rock phosphates showed different trends with time for all the three experiments and only for Calciphos in experiment 1 did they reach similar values to those for superphosphate after four years.

From the above discussion it appears that the different effects of rate of application on the B coefficient for the two fertilizer types can be explained by reference to published work on the chemical behaviour of fertilizers in soils [e.g. 3, 4, 18, 19, 20, 29]. In the case of superphosphate, most of the applied P of freshly applied fertilizer dissolves quickly and reacts with soil constituents. Thus increasing levels of application may result in an increasing proportion of P being extracted by the soil test and values of coefficient B will therefore be greater than one. This situation continued for ten years in experiment 2 showing that the form of the original fertilizer influenced bicarbonate extractable P levels for many years after application. In experiments 1 and 3 the value of B for superphosphate decreased to or below a value of 1 after four years indicating that P was becoming increasingly less soluble in bicarbonate and that some form of negative feedback was operating.


A coefficient
B coefficient
Experiment 1
Experiment 2
Experiment 3
120
100
80
60
40
20
0
1·2
1·0
0·8
0·6
0·4
0·2
800
700
600
500
400
300
200
100
1·6
1·4
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0·4
0·2
1977
1979
1981
1983
1985
Year

The P dissolved from rock phosphates will experience the same adsorption phenomenon as for superphosphate but as the proportion of fertilizer that dissolves in the soil decreases in an approximately exponentially manner with level of application [22] this effect will dominate and values of B will generally be less than one. Most published results that show that increasing the rate of appliction of rock phosphate decreases the proportional dissolution have been for apatite rock phosphates [19, 20, 23, 29] but a similar trend has been shown to occur for Calciphos [18].

A comparison of soil tests

For equivalent levels of application of all fertilizers the Olsen soil test values were generally smallest, and the Bray soil test values were largest. For all 3 experiments, Olsen P, Bray P, and Colwell P values were highly correlated (R^2 was greater than 0.96 in all cases). This trend is illustrated in Fig. 5 by data for experiment 3 and soil samples collected in January 1980. The data for all samples and soil tests could be described by Equation 1 and generally the lines were highly curved towards the P applied axis for the rock phosphate fertilizers for all three soil tests (i.e. $B < 1$).

For all fertilizers and experiments, the value of the A coefficient of equation (1) was always smallest for the Olsen soil test indicating that this extractant dissolved a relatively smaller amount of soil P than the other extractants (Fig. 6). The values of A for the Bray soil test was always the largest for the rock phosphates and were generally much larger for Calciphos than for the other rock phosphates (Fig. 6). The value of the A coefficient for superphosphate decreased with time and again this is because the amount of P extracted by all the soil tests declined markedly with time as P from the superphosphate reacted with and was retained by soil constituents. For Calciphos, the value of the A coefficient for the Bray soil test also decreased substantially through time, particularly for Experiments 2 and 3. The high A values for the acidic Bray soil test may indicate that this extractant dissolves residual Calciphos in the soil. This amount decreased with time as progressively more of the Calciphos had dissolved in soil solution so that the P had become associated with soil minerals as in the case of superphosphate.

The value of the B coefficient calculated from equation (1) was between 0.3 and 1.5 for superphosphate for all soil tests and was lowest for the Olsen

Fig. 4. Values for the A and B coefficients calculated for equation (1) for the Colwell soil test for levels of fertilizer applied in May 1976. Standard errors for the A coefficient varied between 5–20% of the mean values, and for the B coefficient between 10–30%. For clarity values for the A and B coefficients of both apatite rock phosphates in Experiment 3 are not shown but they were similar to the values shown for C-ore. In each case: ● Superphosphate, ▲ Calciphos and ▼ C-ore.

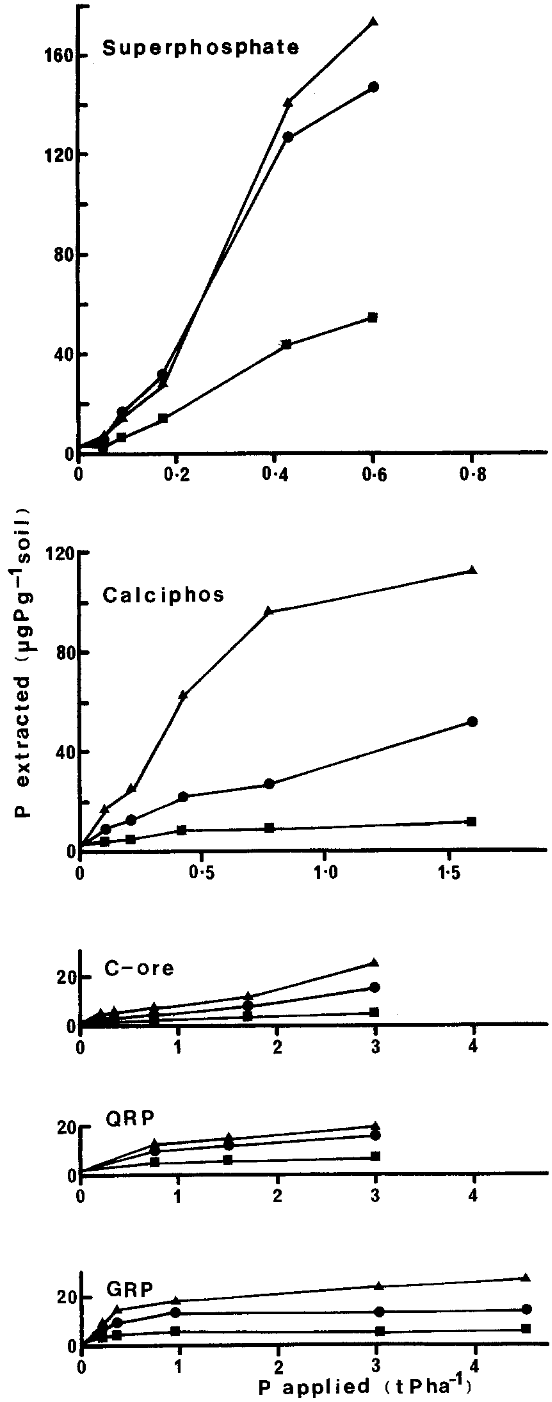


Fig. 5. Relationship for experiment 3 between P extracted by the three soil tests and the level of P applied in May 1976 measured for soil samples collected January 1980. In each case: ● Colwell, ■ Olsen and ▲ Bray.

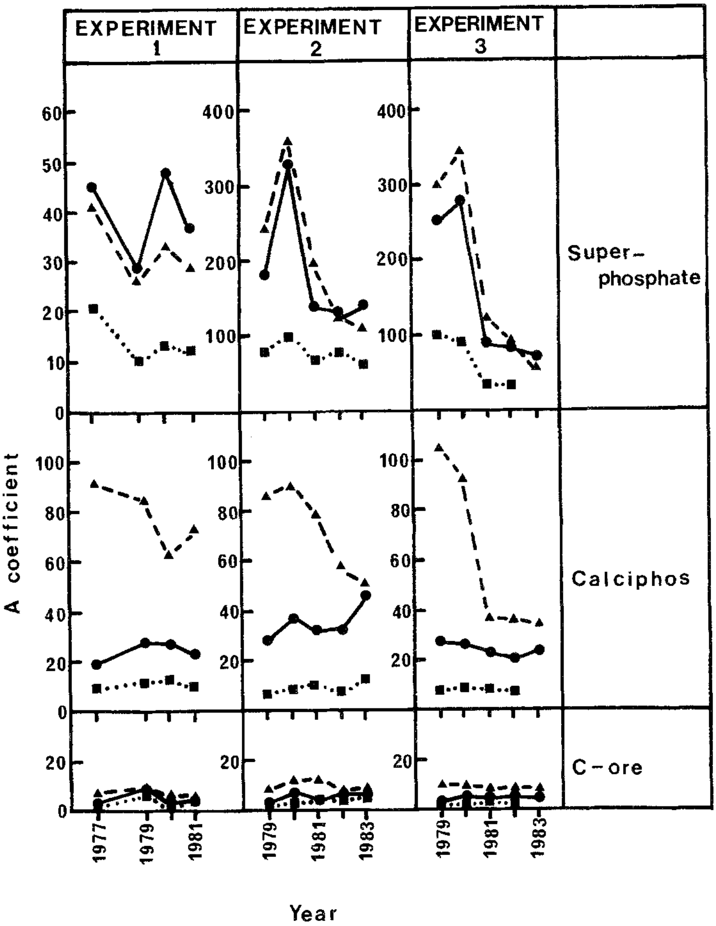


Fig. 6. Values for the A coefficient calculated for equation (1) for Colwell, Olsen and Bray soil tests for fertilizer applied in May 1976. Standard errors for the A coefficient varied between 5–20% of the mean values. For clarity values of the A coefficient for both the apatite rock phosphates in experiment 3 are not shown, but they were similar to the values shown for C-ore. In each case: ● Colwell, ■ Olsen and ▲ Bray.

soil test for experiment 1 and highest for the Bray test for experiment 2 (Fig. 7). Thus for superphosphate, the relationship between soil test values and the level of P applied was rarely exactly linear (i.e. B = 1), indicating that the level of applied P influenced the proportion of P that was extracted for all extractants. The wide range in values of B indicate that both negative and positive feedback mechanisms operated depending on soil, soil test and period of fertilizer-soil contact. The trends in B value for superphosphate over time were similar for all soil tests for experiments 2 and 3 but different trends occurred for the different soil tests for experiment 1. We can offer no

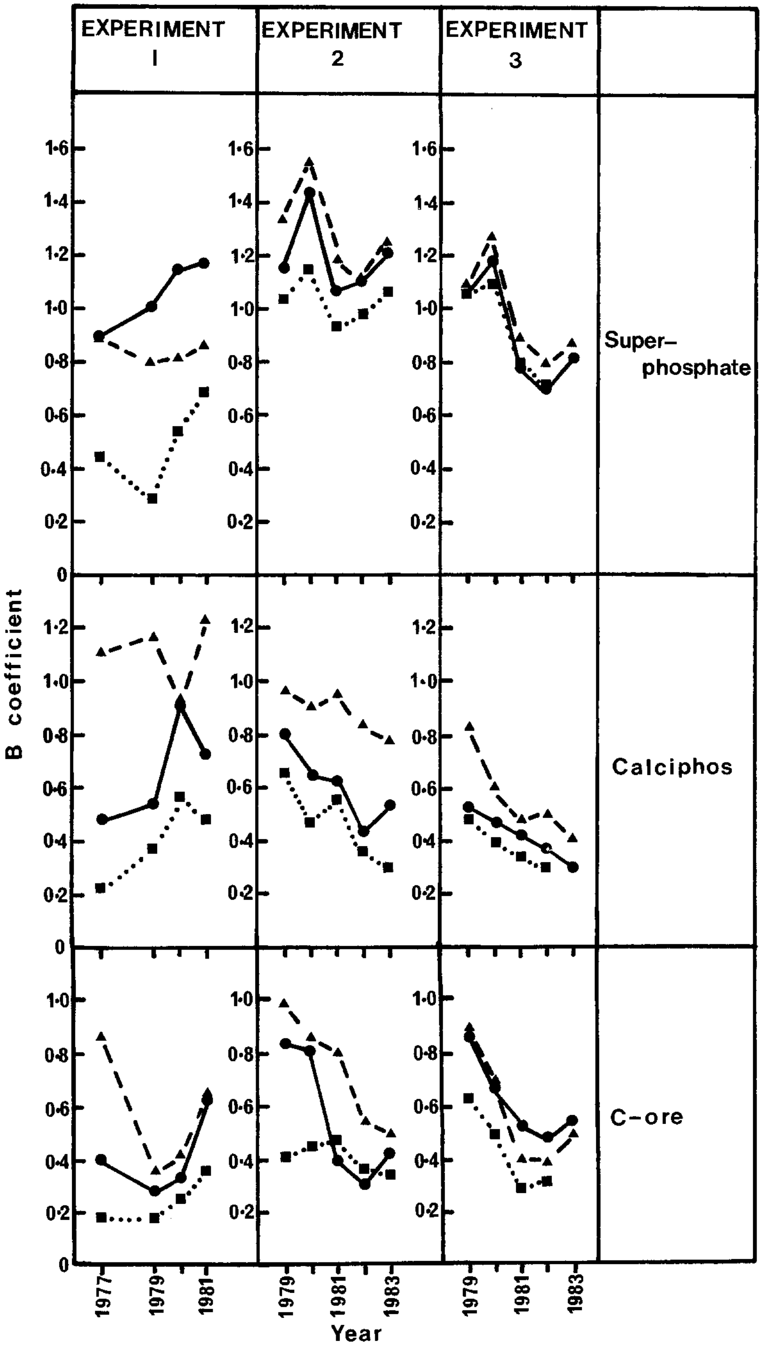
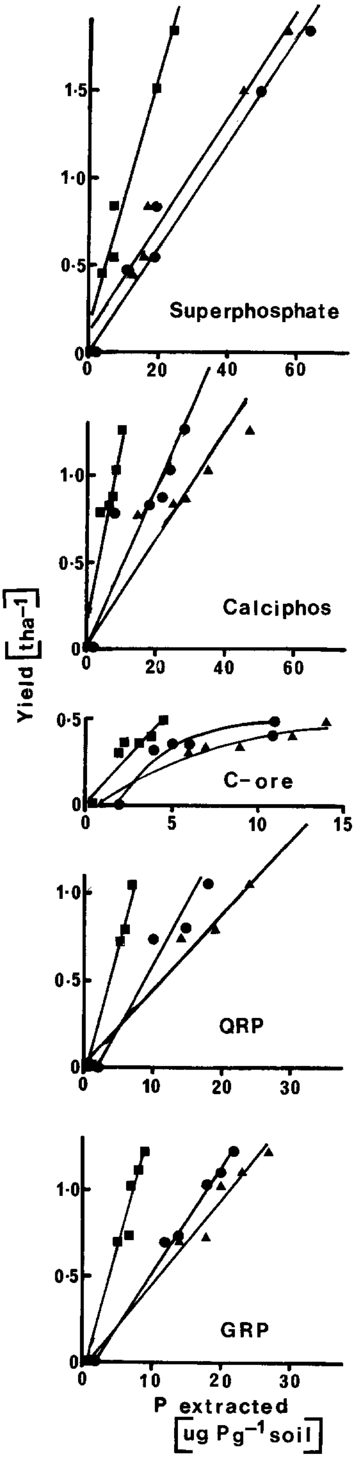


Fig. 7. Values for the B coefficient calculated for equation (1) for Colwell, Olsen and Bray soil tests for fertilizer applied in May 1976. Standard errors for the B coefficient varied between 10–30%. For clarity values of the B coefficient for both the apatite rock phosphate in experiment 3 are not shown, but they were similar to the values shown for C-ore. In each case: ● Colwell, ■ Olsen and ▲ Bray.

explanation for these variations in B coefficients for superphosphate during the experiments but they may be a consequence of changes with time in the partitioning of soil P between different forms. These forms will differ in solubility for each of the three soil tests. The distribution of P between these forms (i.e. adsorbed, precipitated, occluded, organic, residual fertilizer) may differ for different levels of fertilizer application and for different periods since application. For rock phosphates, the value of B was generally less than one for all three extractants indicating that proportionally less P was extracted for each incremental addition of fertilizer. The decline in B values with time for experiments 2 and 3 for Calciphos and C-ore indicates that the influence of level of application in decreasing the proportion of extractable P increased with time. For experiment 1 after 1979 the value of B for the three soil tests generally increased with time for both rock phosphates whereas there was a consistent decrease for Experiments 2 and 3. The reasons for this difference in behaviour between the experiments is not known but is presumably a reflection of differences in the extent and rate of dissolution of Calciphos and C-ore in the different soils.

Soil tests as predictors of yield

For each experiment and each soil test the relationship between yield and soil test values was well described (R^2 greater or equal to 0.80) by equations (2) or (3). Data were first fitted to the quadratic equation (2), and if the C coefficient was not significantly different from zero, the data were refitted to the linear equation (3). Most of the data were best described by equation (3). For the data that were curvilinear and which were best described by equation (2), some curves for C-ore were sigmoidal in shape so that the B coefficient was negative and the C coefficient positive. However, most data that were best described by equation (2) had a positive B coefficient and a negative C coefficient. These curves were also adequately described by an exponential equation, e.g. Mitscherlich equation. Use of equations (2) and (3) rather than an exponential equation was preferred because they provided greater flexibility in the description of data since all data could be adequately described by the different forms of the same equation [12]. Data were adequately described by the linear equation (3) where the data all fall on the intial responsive part of the relationship. With the exception of C-ore this applies to the present experimental data despite very large applications of all fertilizers (Table 3). For C-ore the relationships for the alkaline extractants (Colwell, Olsen) were curvilinear (Fig. 8) and were best described by equation (2). This marked curvilinear trend occurs for yield and soil test values that are within the linear regions of the data for other fertilizers and may indicate that the alkaline extractants dissolved some of the C-ore that


Superphosphate
1·5
1·0
0·5
0
0
20
40
60
Calciphos
1·0
0·5
0
0
20
40
60
C-ore
0·5
0
0
5
10
15
QRP
1·0
0·5
0
0
10
20
30
GRP
1·0
0·5
0
0
10
20
30
Yield [tha⁻¹]
P extracted [ug Pg⁻¹ soil]

remained in the soil and so included some P that would not be readily available to plants.

All three soil tests were equally predictive of yield. This reflects the high degree of correlation between the yield and soil test values for each year. For each experiment, the relationship between yield (expressed as either absolute yield or as a percentage of the largest yield) and soil test value was different: (1) For each soil test, for the same fertilizer and year (Fig. 8, Table 4). (2) For each fertilizer, for the same soil test and year (Fig. 8, Table 4). (3) For different years, for the same fertilizer and soil test (Fig. 9). Thus for a single field experiment and for each of the three standard soil tests very different estimates of the current P status and therefore fertilizer requirements of the soil were indicated in different years. Consequently a different calibration relating yield to soil test values was required for different years for each fertilizer and site. In soil testing programs it is usually assumed that there is a single calibration for each soil type which relates yield (usually expressed as a percentage of the maximum yield each year) to soil test values. Thus soil testing procedures based on a single calibration curve may produce highly inaccurate estimates of the P requirements of crops and pastures. This may be illustrated by reference to Fig. 9 which shows that to obtain 50% of the maximum yield the required Colwell P values ranged from 8–38 $\mu g\,P g^{-1}$ soil (in 1982 and 1985 respectively) so that no single level of adequate soil P could be defined under these circumstances. It is understood that the different response curves shown in Fig. 9 are partly a consequence of factors other than P supply limiting plant growth and these factors exerted a different influence each year. However, all other plant nutrients that may also have limited yield were supplied at sufficient levels so that the different response curves must mostly reflect seasonal conditions which combined to produce different plant yield responses each year. Irrespective of whether yields are expressed in absolute units or as percentages of maximum yield it is evident that soil test values did not provide a single, definitive determination of the P status of these soils over the 10-year duration of these experiments.

Fig. 8. Relationship for experiment 3 between yield and soil test values for dried whole tops of Madden wheat harvested October 1981 for different fertilizers applied in May 1976. Lines are for statistical fits to equation (2) (quadratic) or to equation (3) (linear). In each case: ● Colwell, ■ Olsen and ▲ Bray soil tests on soil samples collected January 1981.

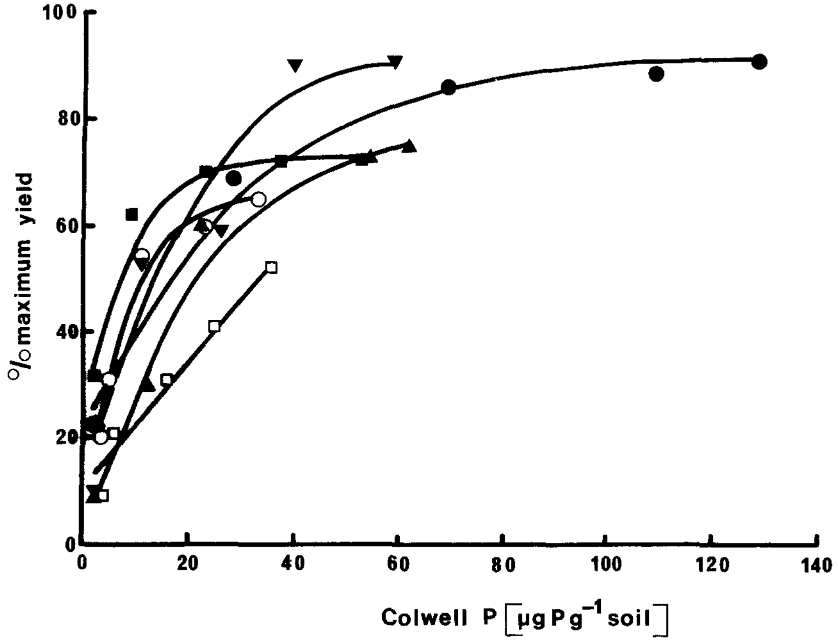


Fig. 9. Relationship for experiment 2 between percentage of maximum grain yield of wheat (y) and Colwell P values for superphosphate applied in May 1976 (x). Maximum yields were for freshly applied superphosphate applied across all plots each year. Maximum yields were as follows (t ha^{-1}): 1978, 3.0; 1979, 2.0; 1981, 3.0; 1982, 3.0; 1984, 3.2; 1985, 2.2. Lines are statistical fits to equation (2) (quadratic) or equation (3) (linear). In each case the coefficients are (values in parenthesis are standard errors):

● 1978, $y = 24 + 1.5x - 0.008x^2 (R^2 = 0.95)$
(80) (0.1) (0.0001)

▲ 1979, $y = 1.8 + 3.1x - 0.03x^2 (R^2 = 0.98)$
(41) (0.4) (0.0001)

▼ 1981, $y = 10 + 3.0x - 0.03x^2 (R^2 = 0.92)$
(168) (1.2) (0.0003)

■ 1982, $y = 30 + 2.5x - 0.033x^2 (R^2 = 0.82)$
(135) (1.2) (0.0004)

○ 1984, $y = 11 + 4.2x - 0.080x^2 (R^2 = 0.94)$
(60) (1.5) (0.001)

□ 1985, $y = 9.5 + 1.2x (R^2 = 0.95)$
(3.3) (0.2)

Table 4. Regression coefficients, with standard errors in parenthesis, for experiment 3 for the relationship between yield and soil test values for fertilizer applied in may 1976, when data were fitted to $y = A + Bx + Cx^2$, where y is the yield ($kg\,ha^{-1}$) and x is the soil test value ($\mu g\,P\,g^{-1}$ soil), and A, B and C are regression coefficients. When the C coefficient was not significantly different to zero ($P > 0.05$), data were re-fitted to $y = A + Bx$. Data were constrained to pass through the yield and soil test values measured for the unfertilized P treatment; no yield was produced for the nil P treatments and Colwell P was 2 $\mu g\,P\,g^{-1}$ soil, Olsen P was 0.6, and Bray P was 1.0.

Year	Fertilizer	B	C	r^2
Colwell soil test				
1978	Superphosphate	25(6)	0.07(0.006)	0.92
	Calciphos	90(24)	−1.8(0.17)	0.93
	C-ore	156(20)	–	0.80
	QRP	126(38)	−3.4(3.04)	0.92
	GRP	24(14)	–	0.80
1979	Superphosphate	22(3)	–	0.93
	Calciphos	49(4)	–	0.90
	C-ore	105(68)	3.7(6.00)	0.83
	QRP	98(8)	–	0.93
	GRP	114(7)	–	0.91
1981	Superphosphate	30(1)	–	0.97
	Calciphos	45(4)	–	0.80
	C-ore	73(412)	−3.02(4.27)	0.87
	QRP	63(5)	–	0.94
	GRP	60(8)	–	0.94
1982	Superphosphate	8(3)	–	0.80
	Calciphos	35(23)	−0.73(0.05)	0.95
	C-ore	33(3)	–	0.89
	QRP	25(1)	–	0.99
	GRP	20(10)	−0.05(0.03)	0.97
Olsen soil test				
1979	Superphosphate	106(77)	−0.97(0.09)	0.96
	Calciphos	158(8)	–	0.95
	C-ore	251(72)	−22.50(11.00)	0.92
	QRP	47(26)	30.00(14.10)	0.99
	GRP	243(14)	–	0.91
1981	Superphosphate	80(5)	–	0.96
	Calciphos	127(10)	–	0.86
	C-ore	110(8)	–	0.87
	QRP	144(6)	–	0.98
	GRP	132(6)	–	0.96
1982	Superphosphate	27(5)	–	0.80
	Calciphos	101(44)	−6.12(1.61)	0.97
	C-ore	138(97)	−13.86(8.00)	0.89
	QRP	56(4)	–	0.97
	GRP	55(2)	–	0.98

Year	Fertilizer	B	C	r^2
Bray soil test				
1979	Superphosphate	19(2)	-	0.92
	Calciphos	9(2)	-	0.81
	C-ore	69(44)	−1.52(0.06)	0.93
	QRP	63(3)	-	0.98
	GRP	36(10)	-	0.80
1981	Superphosphate	34(2)	-	0.97
	Calciphos	30(3)	-	0.82
	C-ore	67(17)	−2.24(1.09)	0.95
	QRP	144(6)	-	0.94
	GRP	47(2)	-	0.96
1982	Superphosphate	8(2)	-	0.80
	Calciphos	23(2)	−0.33(0.05)	0.98
	C-ore	42(10)	−1.23(0.18)	0.97
	QRP	20(1)	-	0.97
	GRP	25(7)	−0.26(0.01)	0.98

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