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Phosphate fertiliser residues in wheat-growing soils of the Western Downs, Queensland

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Abstract

Effects of repeated annual application and residual effects of past phosphorus (P) applications were studied at Billa Billa and The Gums, Queensland, on 2 Vertisols representative of a large cropping area in this region. Phosphorus was applied annually at 0, 4, 8, 12, and 25 kg/ha at sowing to each wheat crop between 1978 and 1988. Phosphorus was also applied at 25, 50, 100, 200, or 400 kg/ha as a once-only application, before wheat was sown in 1978, and was incorporated by tillage.

Pot experiments were conducted each year with soil (6 kg/pot) gathered from field plots in May before wheat sowing to determine the residual value (RV) of previously applied P fertiliser under standard conditions of frequent watering. In 1979 the RV was determined in a second series of pots with a water deficit to simulate conditions of plant moisture stress that were to dominate the field experiments. The RV of P fertiliser was reduced to one-third that determined under well-watered conditions. Low residual values (8–47%) determined in the field in 1979 for P rates 25 and 50 kg/ha applied in 1978 were probably due to reduced P uptake from dry topsoil throughout which P residues were incorporated by tillage. By contrast, P applied annually at a low rate (4 or 8 kg/ha) in a band close to seeds created profitable responses when evaluated over the sequence of successive wheat crops.

The bicarbonate-extractable soil test value (P_{bf}) on either soil fertilised annually for n years with P at a rate R (kg/ha·year) was described by the model

$$P_{bf} = P_{bu} + 0{\cdot}29R\sum 5\{5 + (n-1)\}^{-1}$$

where P_{bu} is the soil test value (mg/kg) of unfertilised soil.

Additional keywords: P soil test, P uptake, Vertisol, sodic subsoil, predicting soil test.

Introduction

Many experiments with phosphorus (P) fertilisers have been conducted throughout the northern cereal region of Australia (Strong *et al*. 1978; Holford and Doyle 1992, 1993) since responses with wheat crops were first documented (Colwell and Esdaile 1966). Most experiments have demonstrated highly profitable responses to P fertilisers (Strong *et al*. 1978; Holford and Doyle 1993). Nevertheless, there is still uncertainty about the responsiveness of many soils to applied P, related mainly to unreliability of rainfall throughout this region (Holford *et al*. 1985, 1988), as well as to unsuitability and/or accuracy of the soil test (Holford and Cullis 1985; Holford *et al*. 1985, 1988; Holford and Doyle 1992).

On the Western Downs, Queensland, where winter rainfall is extremely unreliable, knowledge of the residual effectiveness of P applications could influence the strategy and quantity of P applied for long-term profitable fertilisation of

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wheat crops. Effects of repeated (annual) application, and residual effects of the single P application at the start of the experiment were studied at 2 sites, Billa Billa and The Gums, between 1978 and 1988 on Vertisols representative of a large cropping area in the region.

Materials and methods

Field experiments

Sites

Experiments were conducted at The Gums, about 30 km west of Tara (27° 16′ S, 150° 08′ E), and at Billa Billa, about 40 km north of Goondiwindi (28° 06′ S, 150° 17′ E). Both sites originally supported predominantly brigalow (*Acacia harpophylla*) and belah (*Casuarina crestata*) vegetation.

Table 1. Soil profile analysis to 1·2 m for experimental sites for pH (1:10 soil to water, w/v), bicarbonate-extractable P (P_b; Colwell 1963), acid-extractable P (P_a; Kerr and von Stieglitz 1938), and exchangeable sodium percentage (ESP)

Soil layer	The Gums			Billa Billa			
(m)	pH	P_b	P_a	pH	P_b	P_a	ESP
0–0·1	7·2	9	6	7·3	11	26	4
0·1–0·3	8·1	3	2	8·1	3	2	10
0·3–0·6	8·5	2	1	8·1	1	2	18
0·6–0·9	7·3	2	1	6·4	1	2	27
0·9–1·2	5·4	2	1	4·9	1	1	24

Soil at The Gums belongs to the Kupunn Series (Dawson 1972); it is a gilgaied, very deep, very dark grey cracking clay. Soil at Billa Billa belongs to the Calingunee soil type (Thwaites and Macnish 1991); it is a self-mulching, dark or grey cracking clay, sloping, and melonholed. Some properties of the soils are presented in Table 1. The soils are very similar in chemical and physical properties, having a similar particle size distribution in the top 10 cm layer (50% sand, 16% silt, 34% clay), and both are sodic below 0·4 m with an acid subsoil below 0·9 m.

Design and treatments

On an area of about 1 ha at each site, 10 P treatments were laid down in a randomised block experiment of 4 replicates. Phosphorus was applied at 0, 4, 8, 12, 25, 50, or 100 kg/ha at the time of sowing to each wheat crop between 1978 and 1985 (1988 at Billa Billa). Triple superphosphate, containing 19% P, was applied using a cone distributor to deliver a weighted quantity of fertiliser over a plot 30 m long and 1·7 m wide through seeding tines with 25-cm spacings (17 cm in 1978). Phosphorus was also applied once only at 25, 50, 100, 200, or 400 kg/ha at each site using the same equipment before the 1978 crop was sown. These heavy applications were incorporated by several tillage operations before sowing.

Crop and soil management

Wheat (cv. Cook 1978–84, cv. Hartog 1985–1988) was sown in rows 25 cm apart each year, except in 1978, when the rows were 17 cm apart. Crops were sown at The Gums on 16 May 1978 and 21 May 1979, and at Billa Billa on 8 June 1978 and 22 May 1979. Later crops were sown in late May or June except in 1983 and 1984 when wet conditions delayed sowing until August. Wheat was not harvested in 2 years at each site because of unsuccessful crop establishment due to excessive weed growth (1983 at The Gums) or due to drought (1986 at The Gums, 1980 and 1982 at Billa Billa).

During the fallow (December–April), 2–4 tillage operations with tined implements were carried out with farm equipment. Each year before sowing, 50 kg N/ha was applied as urea in bands 25 cm apart and at the depth of seed placement to each site within treated areas.

Crop measurement and analysis

Crops were harvested by machine at grain maturity between late October and early December from the central 7 rows, and grain yield was estimated from a measured plot length (~25 m) with adjustment to a 12% water content. Grain was analysed for its P concentration in a Kjeldahl digest using an autoanalysis method of Technicon (1976, 1977) modified with the colorimetric procedure of Murphy and Riley (1962).

Rainfall

Similar total rainfall (mm) and patterns of rainfall were received at the 2 sites over the trial period, annual rainfall varying between 323 and 940 mm, of which 112–448 mm was received between May and October.

Soil measurement and analysis

Each plot was sampled in May before sowing by taking nine 50-mm-diameter cores to a depth of 100 mm, one from each of 9 equal areas within the plot. Cores were composited for each plot, dried at 35±5°C in a forced draught oven, and ground to <2 mm for P determinations using bicarbonate (Colwell 1963) and acid (Kerr and von Stieglitz 1938) extraction.

Pot experiments

Soil collection

From 1979, each year in May prior to sowing, ~8 kg of soil from The Gums and 4 kg at Billa Billa was gathered from the surface 100 mm layer of each plot and was bulked for each treatment at each site. Extra soil was gathered from control (nil P) plots to establish a response curve for freshly applied P. After air drying, soil was sieved to <10 mm and weighed into 2- or 6-kg quantities for 100- and 200-mm-diameter pots, respectively.

Phosphorus treatments

For The Gums soil, duplicate pots of each treatment were prepared for 2- and 6-kg pots. To a duplicate series of each pot size, control soil was fertilised with sieved triple superphosphate (19·2% P) to supply P levels of 0, 5, 10, 20, 30, 40, 50, 60, 80, 100, 120, 160, 200, 240, 300, and 400 mg/kg soil. Fertiliser was placed in a band at the depth of the seed, ~50 mm below the soil surface.

Management of pot experiments

Wheat seeds (cv. Cook 1979–84 and cv. Hartog 1985–88) were presoaked and sown into moist soil at field capacity between late May and early August in a glasshouse in Toowoomba, and thinned to 4 plants per pot after emergence.

Pots were watered regularly to field capacity by weight when plants had used approximately one-third to one-half of the calculated available water; 2 or 3 waterings per week were required until the late tillering stage, after which daily watering was necessary.

A pot experiment was conducted in 1979 to confirm the effect of watering regime on the residual value of P fertiliser applied in 1978 at The Gums. Two watering regimes were imposed: for one regime, 'high', wheat plants were watered regularly to the field capacity soil water content; for the other regime, 'low', a moisture stress was imposed on wheat plants by rewatering pots less frequently to a water content equivalent to one-third of the available soil water contained in the high regime

Nutrients other than P were applied before sowing each year. Three solutions were prepared: solution A contained Mg, Cu, Mn, Zn, and S as $MgSO_4 \cdot 7H_2O$, $CuSO_4 \cdot 5H_2O$, $MnSO_4.H_2O$, and $ZnSO_4 \cdot 7H_2O$; solution B contained B and Mo as $Na_2B_4O_7 \cdot 10H_2O$ and $Na_2MoO_4 \cdot 2H_2O$; and solution C contained K and N as KNO_3 and $Ca(NO_3)_2 \cdot 4H_2O$. Aliquots of the above solutions were applied to supply the following rates (mg/kg soil) of each element: 24 Mg, 5·3 Mn, 5·6 Cu, 11·7 Zn, 44 S, 2·8 B, 0·3 Mo, 102 K, 155 Ca, and 145 N. At the late tillering growth stage (large pots) a second application of N was done at 40 mg/kg soil as Ca $(NO_3)_2.4H_2O$.

Plants were harvested from 2-kg pots 8 weeks after sowing. Plants in larger pots were harvested at grain maturity between early November and mid December.

Plant measurements and analysis

After drying, plant material from smaller pots was ground before P analysis by using the same methods as for field samples. For larger pots, grain was separated from straw, before grinding.

Treatment of data

Phosphorus uptake (mg/pot) each season was normalised with respect to the average P uptake for all seasons from unfertilised soil, by multiplying by the following correction factor: average P uptake (mg/pot) from unfertilised soil over all seasons/P uptake (mg/pot) from unfertilised soil for the season.

Each year, normalised P uptake (y mg/pot) by wheat was described in terms of rate of freshly applied P (x mg/pot) according to the model

$$\ln y = a + b \ln x$$

From this function was estimated the quantity of freshly applied P to which the wheat response was equal to that of residues of previous applications. Therefore, the residual value (RV) for any previous P application is the fraction of the original application that would be needed as a fresh application to achieve an equivalent crop response (grain yield or P uptake) in the second and subsequent years.

Results

Grain yield

At each site, the largest yield response (~1 t/ha) to applied P occurred with the 1978 crop, when >300 mm of rainfall was recorded between May and October. Similarly high grain yields of ≥4 t/ha were achieved with high levels (25, 50, or 100 kg/ha) of P applied either at sowing or incorporated by tillage before sowing (Fig. 1)

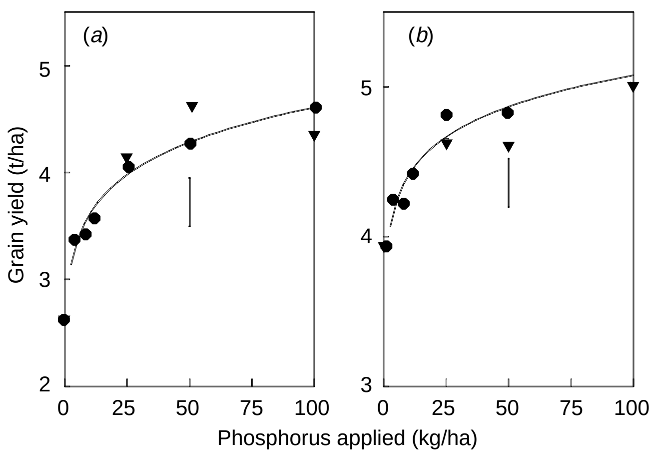

Fig. 1. Grain yield response of wheat in 1978 at (*a*) The Gums and (*b*) Billa Billa, on the Western Downs, Queensland, where P was applied at sowing (●) or incorporated by tillage prior to sowing (▼). Vertical bars denote l.s.d. at $P = 0{\cdot}05$.

Despite the much lower grain yields (1–1·5 t/ha) achieved at the 2 sites in subsequent years, 1979–1985, wheat usually responded ($P < 0 \cdot 05$) to P applied at sowing and to residues of P applied in 1978 at The Gums (Fig. 2). Wheat fertilised with a modest annual P rate of 4, 8, or 12 kg/ha usually outyielded that where a heavy rate of fertiliser was applied in 1978. At the Billa Billa site, small responses ($P < 0 \cdot 05$) to applied P were detected in only 2 (1979, 1983) of 8 wheat crops grown between 1979 and 1988.

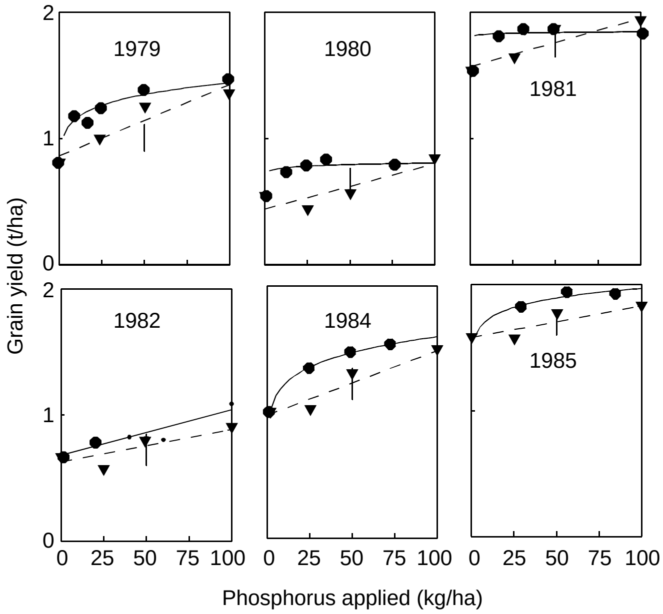

Fig. 2. Grain yield response of wheat at The Gums between 1979 and 1985 where P was applied in 1978 (▼ --- ▼), and where P was applied to each crop at sowing (●—●) at 4, 8, 12, or 25 kg/ha. Accumulative P application rates are shown. No crop was sown in 1983. Vertical bars denote l.s.d. at $P = 0 \cdot 05$.

Soil test value

Effect of P applications on the bicarbonate-extractable (P_b) soil test value

Soil analysis each year in May showed an increasing P_b soil test value where P was applied to each crop. The soil test value increased with increasing annual application rate, with similar rates of increase in P_b at the 2 sites (Fig. 3).

Similarly, heavy P applications (25–400 kg/ha) in 1978 substantially increased the P_b soil test value in May 1979, after which the value in May declined with each successive year, with similar rates of decline at the 2 sites (Fig. 4).

The soil test P_b value relative to that in May 1979 over the 3 years 1980–82 was 0·94, 0·75, and 0·53 for soil at The Gums, and 0·89, 0·80, and 0·59 for soil at Billa Billa.

Availability of P fertiliser residues in the field

Repeated annual application of P to successive wheat crops could affect residual values estimated for the field experiments; previously applied P may increase crop response over that to the freshly applied P. In 1979, RVs for 25 and 50 kg/ha P applications in 1978 were estimated relative to crop response to cumulative fertiliser P, applied annually. For The Gums, soil RVs were 8 and 47% respectively, and for the Billa Billa soil, 46 and 30%.

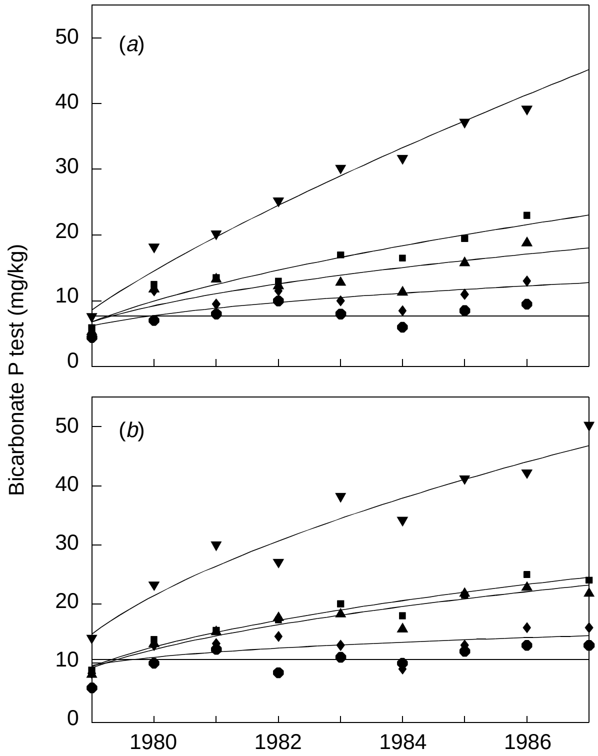

Fig. 3. Increase in bicarbonate-extractable P soil test value at (*a*) The Gums and (*b*) Billa Billa, with repeated P application at 0 (●), 4 (◆), 8 (▲), 12 (■), and 25 (▼) kg P/ha to successive wheat crops between 1978 and 1987.

Availability of P to wheat grown in pots with P-fertilised soil gathered from field plots

Repeated application of P to successive wheat crops, or high P rates applied in 1978, increased P uptake of wheat plants each year in 6-kg quantities of soil gathered from field plots at The Gums (Figs 5 and 6). The quantity of P available for wheat plants increased with successive P application (Fig. 5) but declined with each successive wheat crop following single applications in 1978 (Fig. 6). Over 8 years following P application in 1978, P availability declined from 0·57 to 0·18 that of a fresh P application (Fig. 7).

Water stress had greater impact on the response to residues of fertiliser P applied in 1978 than on the response to freshly applied P (Fig. 8). This is revealed by the calculated RVs in Table 2. Under well-watered conditions, the RV ranged from 0·30 to 0·66 (mean 0·57), whereas under water-stress conditions, the RV ranged from 0·06 to 0·24 (mean 0·17).

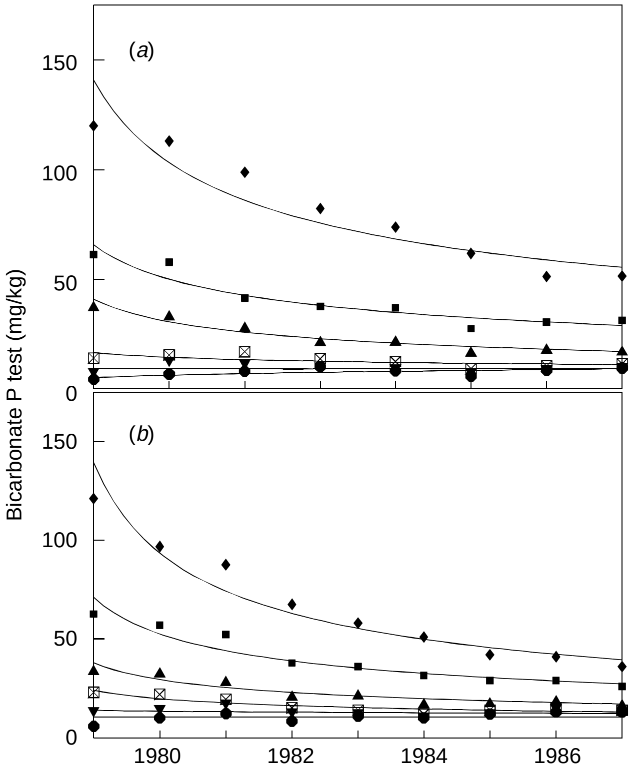

Fig. 4. Decline in bicarbonate-extractable P_b soil test value at (*a*) The Gums and (*b*) Billa Billa, in May each year prior to sowing successive wheat crops between 1978 and 1987 and following heavy applications of P applied at 0 (●), 25 (▼), 50 (⊠), 100 (▲), 200 (■) and 400 (◆) kg P/ha before the 1978 crop.

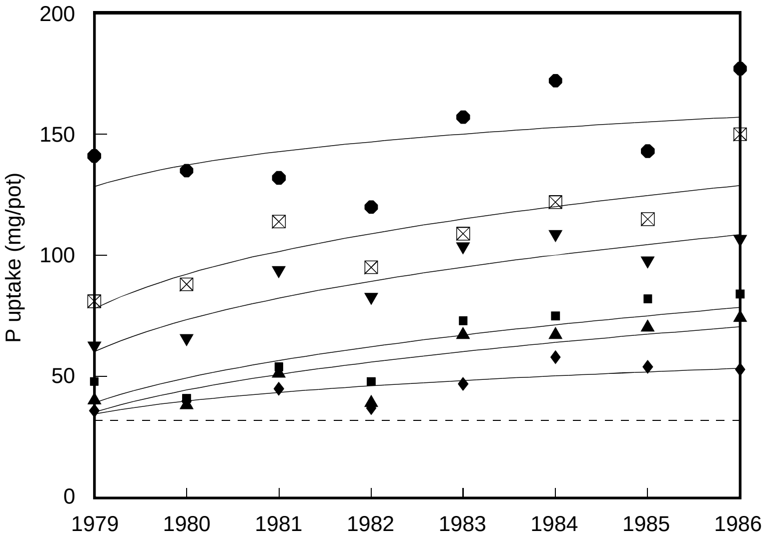

Fig. 5. Increase in P availability (mg P/pot) to wheat grown in pots of soil from The Gums fertilised with P annually at 0 (——), 4 (◆), 8 (▲), 12 (■), 25 (▼), 50 (⊠), or 100 (●) kg P/ha. Soil was gathered in May each year from the surface 10 cm of field plots.

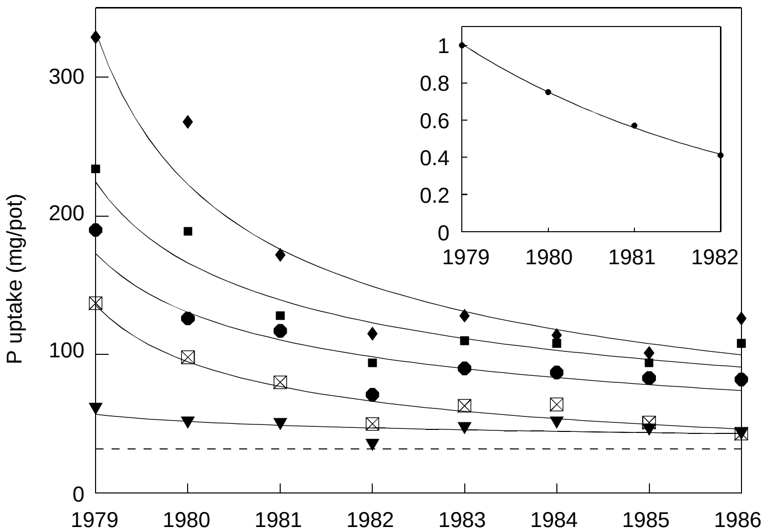

Fig. 6. Decline in P availability (mg P/pot) to wheat grown in pots of soil gathered each year in May from field plots at The Gums fertilised with 0 (——), 25 (▼), 50 (☒), 100 (●), 200 (■), or 400 (◆) kg P/ha. Inset shows decline in residual value relative to availability in 1979 for the first 4 years.

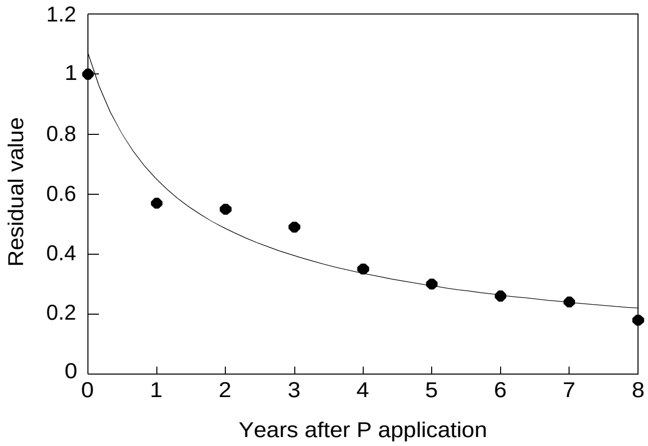

Fig. 7. Decline in residual value of P applied (mean 50, 100, and 200 kg/ha) in 1978 only, as indicated by recovery of P in grain of wheat grown in fertilised soil gathered each year from The Gums site. Decline in availability was described by

$$\ln(\mathrm{RV}) = 0{\cdot}068 - 0{\cdot}721\ln(x+1)$$

where x is number of years after application.

Soil P test (P_b) in fertilised soil

The bicarbonate-extractable soil P test (P_b) was monitored annually in both field trials where P was applied in a single application in 1978 or repeatedly with each wheat crop. The decline in the soil test value relative to that in 1979, a year after application, was described by a function that closely followed the line of best fit to these data (Fig. 9).

Table 2. Residual value (RV) of fertiliser P applied in 1978, to wheat grown in 1979 in pots, as affected by watering regime

Fractional values of these applications were derived from data shown in Fig. 7, grain P uptake for fertiliser P applied in 1978, and equations describing response to freshly applied fertiliser P

High, watered regularly to field capacity; low, watered less frequently to one-third water content of pots on high regime

Fertiliser P (kg/ha)	Watering regime High	Watering regime Low
25	0·30	0·06
50	0·66	0·19
100	0·61	0·24
200	0·45	0·09
400	0·32	0·10

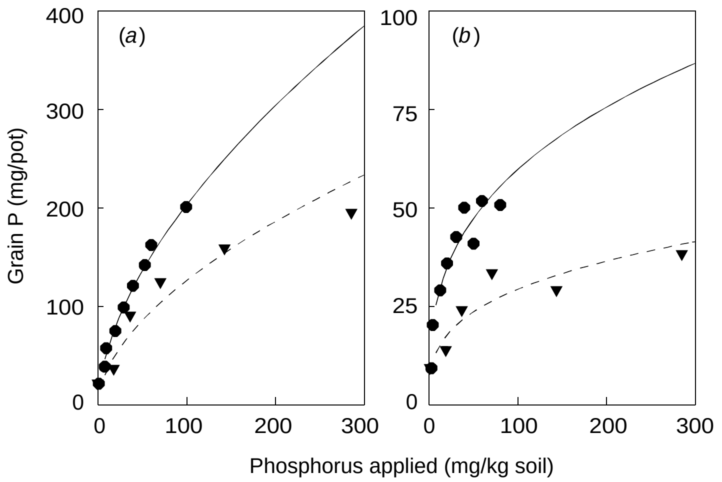

Fig. 8. Response of wheat in grain P (mg/pot) to freshly applied P (●—●) and to residues of P applied in 1978 (▼— ▼) for soil from The Gums at (*a*) 'high' and (*b*) 'low' watering regimes. Response (y mg P/pot) to freshly applied P (x mg P/pot) is described by

$$(a)\ \mathrm{Ln}\,\Delta y = 2\cdot643 + 0\cdot58\ln x$$

$$(b)\ \mathrm{Ln}\,\Delta y = 2\cdot533 + 0\cdot338\ln x$$

Two functions are necessary to predict the P soil test value n years after P application at a rate R (kg P/ha). Eqn 1 describes the soil test value 1 year after fertiliser application (P_{b1}) as a linear function of P rate R:

$$P_{b1} = P_{bu} + 0\cdot29R \quad (1)$$

Eqn 2 describes the subsequent decline in the P soil test value:

$$P_{bn} = P_{b1}[5\{5 + (n-1)\}^{-1}] \quad (2)$$

Eqns 1 and 2 were used to predict the P soil test value (P_{bf}) after annual P application for n years at a P rate R:

$$P_{bf} = P_{bu} + 0{\cdot}29R \sum 5\{5 + (n-1)\}^{-1} \quad (3)$$

where P_{bu} is the soil test value of the unfertilised soil. Good agreement was found between the observed soil test values at both field sites and the value predicted using Eqn 3 (Fig. 10).

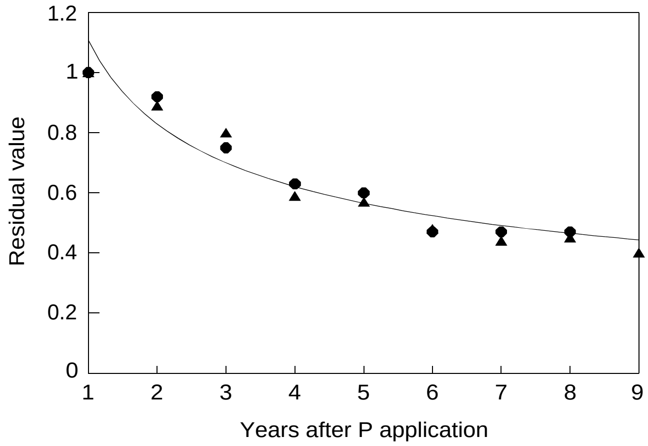

Fig. 9. Relative decline in soil P test (Colwell 1963) at (●) The Gums and (▲) Billa Billa, on the Western Downs, where P was applied in 1978.

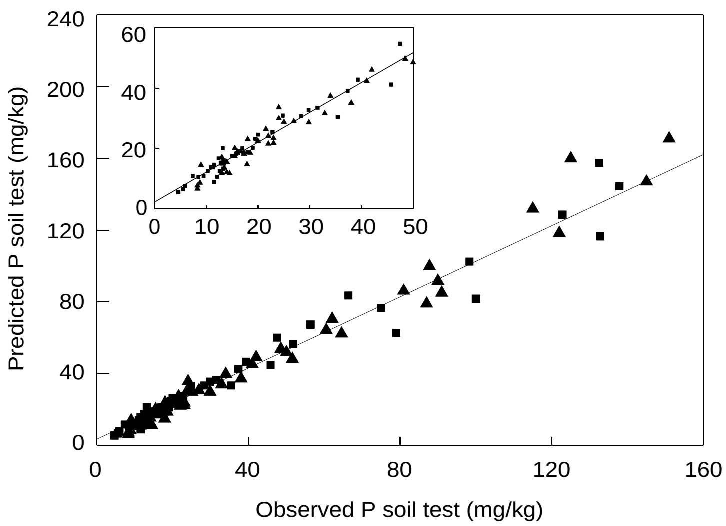

Fig. 10. Observed and predicted soil P test values (P_{bf}) for 2 P-fertilised soils from The Gums (■) and Billa Billa (▲). Soil test values were predicted where P fertiliser was applied to each crop in a sequence of wheat crops between 1978 and 1988. Eqn 3 was used to predict P_{bf}. The inset shows the relationship for low P application rates (4–25 kg/ha), where the rate has been discounted by 10% to allow for removal of fertiliser P in the year of application.

To obtain good agreement between observed and predicted soil test values for low P rates (<25 kg/ha), it was necessary to discount the rate of applied P by 10%. After making this quantitative adjustment, equivalent to the approximate uptake of fertiliser P by wheat in the year of application (Holford and Doyle 1993), there was extremely good agreement between observed and predicted P soil test values as shown in the inset of Fig. 10.

Discussion

Response to applied P

Holford and Doyle (1993) showed that more applied P was required to reach economic optimal wheat yields when soil moisture was adequate than when responses were affected by water deficits. Rainfall and stored soil moisture in 1978 (Fig. 1) were sufficient to exceed the lower yield ceilings of wheat crops between 1979 and 1985 (Fig. 2) due to water deficits. In spite of the low yield ceilings for wheat, which lowered P requirements substantially, routine application of a low P rate applied with seed at sowing was profitable management practice when evaluated over the 9 years of these experiments.

At Billa Billa, a root disease, crown rot, was evident in some wheat crops by the presence of deadheads and/or coloration of tiller bases. At a nearby site, G. B. Wildermuth (unpublished data) found increased disease incidence with management practices that increased water deficits. Thus, an even lower yield ceiling may have been imposed on some wheat crops by the presence of this disease.

Root densities of wheat crops were determined at anthesis in 1978, a high rainfall year, and in 1979, when lower rainfall created high water deficits for wheat crops (W. M. Strong, unpublished data). The ability of wheat roots to respond to freshly applied P placed in bands even at a low application rate (8 kg/ha) would suggest that very high P fertiliser efficiency should be achievable in the year of fertiliser application. Increased root densities in fertilised soil, even in the presence of a high water deficit in 1979, is further evidence that P applied routinely to deficient wheat should benefit the large majority of systems with continuous wheat cropping on such soils.

Residual value of P fertiliser

Across a range of different soils from various countries, Barrow (1980) found that the RV of applied P to subclover grown in pots varied between 30 and 80%. One year after P application, we found a similar RV to wheat grown in pots to that of Sahrawat *et al*. (1995) for field-grown sorghum in an Indian Vertisol (58%). They found that the RV fell to 18% 2 years after application, whereas we found a higher RV (~40%). We believe that the lower value found by Sahrawat *et al*. (1995) is likely to be a more accurate estimate of RV in the field, particularly in a semi-arid climate when the topsoil is infrequently re-wet by rainfall.

Effect of water deficit on residual value of P fertiliser

The effect of water deficit for the majority of wheat crops grown between 1979 and 1985 reduced the apparent availability of P fertiliser residues. Standard watering of plants in pots does avoid the problem of determining the RV of P fertiliser where water deficit dominates wheat-growing seasons, as for this region. Residual values of fertiliser P of 60–40% that of freshly applied P during the 3 years after P application were determined under these well-'watered' conditions. Similarly high residual values of P fertiliser were found by Holford and Crocker (1991) for clover-based pastures on the Northern Tablelands of New South Wales, and by Bolland (1992) for legume-based pastures on soils of Western Australia. For neither of those pasture systems would water deficit be as frequent an occurrence as for wheat grown in this region.

It is unlikely that P fertiliser residues, after their incorporation through the surface layer by tillage, are fully accessible to the wheat crop during periods of water deficit. The residual value of fertiliser P applied in 1978 to wheat grown under water deficit in pots in 1979 was reduced to approximately one-third the value for well-watered plants. Smaller root extension and infrequent water recharge of surface soil during dry seasons are likely to reduce plant availability of residues. By contrast, P applied freshly may remain available to wheat plants even in the presence of a water deficit (Strong and Barry 1980), particularly if fertiliser P is placed in a band in close proximity to the seed row.

Predicting P soil test value

With continued P fertilisation, the availability of P in soil is increased by consequence of the accumulated fertiliser residues. We monitored the annual change in P soil test values at both sites where P was applied as a single application in 1978 or was applied repeatedly with successive wheat crops. Using the decline parameters of the P soil test value observed for single P rates applied in 1978, we predicted the values for repeated P applications. Very good agreement between observed and predicted P soil test values, as shown in Fig. 10, suggests that this approach may be valuable to estimate P soil test values of similar soils after P fertiliser practices have been adopted. The approach may also be of value in predicting the decline in the P soil test where high P rates are applied in the form of organic wastes. However, the rate at which organic P in the waste is mineralised to inorganic P would need to be known or estimated to apply the correct R term to Eqn 3.

For low levels of P ($<$25 kg/ha), it was found necessary to discount the rate of applied P (R) by 10%. It is reasoned that this quantitative adjustment to the rate of applied P accounts for the approximate utilisation of fertiliser P by the wheat crop in the year of application (Holford and Doyle 1993). Residues of P fertiliser may remain more available in systems of reduced tillage where fertiliser bands may remain intact longer in the absence of disruptive tillage effects (Rudd and Barrow 1973).

Conclusions

The availability of residues of P fertilisers applied in systems of continuous cropping in the northern wheatbelt may be reduced due to water deficits.

Continued P fertilisation of these heavy clay soils will eventually increase soil P test values, even with very low P application rates (4–8 kg/ha). Soil test values (bicarbonate-extractable) can be reliably predicted, even with such low P application rates, by a method that discounts the P applied by 10% utilisation in the year of application. The decline in soil P test values is accurately described as a function of time after P application; the soil P test declines after 5 years to 50% of the value 1 year after application.

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