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ABSTRACT

Results obtained using a simple model for computing the residual effect of applied fertilizer P were compared with results of long-term field trials with maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench], and rice (*Oryza sativa* L.), carried out in Brazil, Australia, and Madagascar, respectively. The calculated and experimentally found residual effects of fertilizer P were in close agreement, provided the applications rates were not too high and seasonal effects not too strong. At all locations the same values for the time constants of P transfer between the labile and stable pools could be used, irrespective of the method of application and the type of fertilizer. As a consequence, the residual effect of fertilizer P is directly related to the first-year recovery fraction. For given recovery fractions, the residual effects are calculated for different types of P fertilizers.

Additional index words: Fertilizer trials, Maize, Phosphate rock, Phosphorus uptake, Rice, Sorghum, Superphosphate.

MUCH of the work on soil P has emphasized the capacity of the soil to retain P and render it unavailable to plants. There is an extensive literature on the P sorption capacity of various soils, but relatively little attention has been given to the long-term availability of the sorbed P for plants grown on these soils. Few experiments have been designed specifically to measure the residual effect of applied fertilizer P over several cropping periods. Among others, Lathwell and Musgrave (1966), Young and Plucknett (1966), and Kamprath (1967) have reported the results from such experiments, and they found very substantial residual effects of applied fertilizer P on soils of widely differing properties. Experimental results suitable for computing the residual effect of applied fertilizer P using the model developed by Wolf et al. (1987) are very scarce. Major problems arise in using the reported long-term trials, because P uptake is seldom measured continuously, and seasonal effects have often affected the results in such a way that it is difficult to find a regular pattern in the residual effects of applied fertilizer P. In this paper data from long-term trials in Brazil, Australia, and Madagascar are used to test the model of Wolf et al. (1987).

EXPERIMENTAL DESIGNS

Brazil

The experiment was established in 1972 at the Cerrado Center (CPAC) in the Federal District near Brasilia on a Dark Red Latosol (isohyperthermic, fine, kaolinitic Typic Haplustox) as part of a collaborative project with Cornell University, North Carolina State University, and the Agricultural Research Service of Brazil (EMBRAPA). The study measured the effects of P rates and methods of application on maize (*Zea mays* L.) yields and soil chemical properties. Results from this experiment have been reported by Lathwell (1979) and Yost et al. (1979; 1981), and in the annual reports of CPAC from 1976 through 1982 (Centro de Pesquisa Agropecuria dos Cerrados, 1976; 1978–1982). The data discussed in this report have been gathered from all these sources. Yield data were collected for 11 crops of maize grown between 1972 and 1981, and the results of P analyses have been reported for the first four crops.

The experimental site was cleared of regrowth from a previously cleared area of cerrado vegetation. This site had not received fertilizer P previously, and, as is characteristic of most soils of this region, the soil was extremely deficient in available soil P. In addition the soil was strongly acidic (pH 5.0) and extremely low in bases (87% Al saturation).

In four treatments all the fertilizer P (triple superphosphate; TSP), at rates of 70, 140, 280, and 560 kg P ha^{-1}, was broadcast before planting the first crop and no further P was applied. In a second set of three treatments the fertilizer P was applied as a band application at planting to each of the first four crops, at rates of 35, 70, and 140 kg P ha, with no further application from the fifth crop onward.

Australia

The trial was executed at Katherine, NT, and its results have been reported by Arndt and McIntyre (1963). The objectives of the experiment were to verify whether residual effects of superphosphate found by other Australian scientists could also be obtained in this part of Australia, and to compare initial and residual effects of phosphate rock and of superphosphate.

The trial was conducted on a newly cleared land of red-brown, sandy-clay loam, developed on Cambrian limestone (probably either a Trophrept or a Ustalf based on the description). Available phosphorus (0.005 *M* H_2SO_4) and total P contents (0–0.1 m) were 6 and 70 mg P kg^{-1}, respectively, and pH was 6.5 (0–0.2 m). The crop used was sorghum [*Sorghum bicolor* (L.) Moench]. The P fertilizers were broadcast. Treatments were initial applications of 12, 24, and 60 kg P ha^{-1} as single superphosphate (SSP) and about 40, 80, and 200 kg P ha^{-1} as *milled* phosphate rock. Yields were recorded for 7 yr. For details on experimental design, statistical treatment, and adjustment for the effect of season on yields, the reader is referred to Arndt and McIntyre (1963).

Madagascar

The trial was carried out on a P-rich, hydromorphic soil, probably an Aquept, at Mahitsy, between 1964 and 1973 (Velly and Roche, 1974). The crop was irrigated rice (*Oryza sativa* L.). Fertilizer P was applied once at the start of the trial in 1964, at rates of 0, 44, 87, 131, 174, and 437 kg P ha^{-1}. Fertilizer N and K were applied yearly at rates of 120 kg N ha^{-1} and 100 kg K ha^{-1}.

EXPERIMENTAL RESULTS

Brazil

Yields decreased from the beginning for the broadcast treatments and from the fifth crop onward for the banded applications, but the pattern was rather irregular (Table 1). At the same rates of total P application, total yields, accumulated over the eleven crop periods,

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were not different for the two methods of application, although the first four crops yielded higher when all the fertilizer P was applied before the first crop. The low yields of the third crop were caused by drought during the growing season. The second and fourth crops, which were irrigated and grown during the dry sunny season, were high yielding. All other crops were grown in the wet season without supplementary irrigation. Values for the P uptake by the first four crops are given in Table 2. For subsequent crops, actual uptake values were not available. Therefore, uptake was estimated by dividing yield figures by 450, the average yield/uptake ratio for the first four crops.

Australia

The sorghum yields presented in Table 3 are the averages corrected for seasonal fluctuations by Arndt and McIntyre (1963). The response to 80 and 200 kg P ha^{-1} applied as phosphate rock was less in the first year than in the second, third, and fourth years. The yields indicated in the footnote of Table 3 would be better estimates of the first-year yields than those presented in the table. An irregularity in the yield pattern was observed in the 24 kg P ha^{-1} (SSP) treatment during the sixth and seventh years. The data of these years were obtained from a reduced number of replicates that in previous years had shown a constant bias in favor of the 24 kg P ha^{-1} treatment. Actual values for the P uptake were not given by Arndt and McIntyre (1963). A sorghum grain yield/P uptake ratio of 300 was derived from the literature and was used to estimate P uptake.

Madagascar

The rice yields showed strong fluctuations (Table 4). Exceptionally high yields were obtained in the third year, while in the sixth year yields were low as a result of an infestation by Pyricularia. The control yields gradually declined, indicating a decrease in available soil P. The strong yield responses at the highest two fertilizer rates during the later years are striking. Uptake of P was determined for five crops (fourth–eighth) only (Table 5), and these figures were used to find the relationship between yield and P uptake. Estimated yield/P uptake ratios were 366 and 383 for yields less than and greater than 5600 kg ha^{-1}, respectively.

Table 1. Brazil, maize grain yields.

Crop no.	One broadcast application				Four banded applications		
	kg P ha⁻¹						
	70	140	280	560	4 × 35	4 × 70	4 × 140
	kg ha⁻¹						
1	5 235	6 275	6 795	7 960	2 415	3 855	4 795
2	3 [illegible]	5 640	7 480	8 540	5 080	6 575	8 430
3	880	2 210	2 975	3 870	3 080	3 415	4 190
4	1 785	3 425	8 440	9 035	6 030	8 075	9 040
5	1 650	3 000	4 820	6 250	4 490	5 860	6 890
6	660	1 890	3 890	6 190	2 270	4 370	6 910
7	450	885	2 555	4 670	1 335	2 710	4 855
8	700	1 300	2 500	4 800	1 500	3 000	5 100
9	1 600	1 800	3 200	4 900	2 400	3 500	5 400
10	350	550	1 470	3 980	880	1 900	4 090
11	160	490	700	2 340	400	970	2 400
Sum 11 crops	16 740	27 465	42 825	62 535	29 880	44 230	62 100
Calculated sum 11 crops	16 515	28 930	50 080	76 090	30 375	52 940	83 830
Sum last 7 crops	5 570	9 915	19 135	33 130	13 275	22 310	35 645
Calculated sum last 7 crops	4 865	8 350	19 030	36 690	14 425	25 760	48 180

Table 2. Brazil, P uptake by maize.

Crop no.	One broadcast application				Four banded applications		
	kg P ha⁻¹						
	70	140	280	560	4 × 35	4 × 70	4 × 140
	kg P ha⁻¹						
1	12.1	16.5	21.0	25.0	5.2	8.4	7.8
2	7.2	11.5	19.0	21.6	12.0	16.7	21.4
3	4.2	6.4	12.1	15.2	10.6	12.1	15.7
4	3.4	6.2	13.3	20.8	10.4	14.2	20.3

Table 3. Australia, grain sorghum yields.

Crop no.	Fertilizer application						
	kg P ha⁻¹						
	Control	Single superphosphate			Phosphate rock		
	0	12	24	50	40	80	200
	kg ha⁻¹						
1	639	1 195	1 555	1 995	1 028†	1 146†	1 503†
2	660	936	1 176	1 522	994	1 247	1 718
3	682	904	1 173	1 469	978	1 289	1 624
4	695	791	899	1 124	889	1 249	1 569
5	640	692	858	906	890	1 068	1 514
6	731	807	1 005	823	888	979	1 689
7	713	742	951	843	935	1 249	1 421
Sum 7 crops	4 760	6 067	7 617	8 682	6 602	8 208	11 038
Calculated sum 7 crops		6 235	7 595	10 495	6 555	8 170	11 545

† Better estimates for these yields were 1000, 1210, and 1625 kg ha^{-1}, respectively (Arndt and McIntyre, 1963).

Table 4. Madagascar, rice grain yields.

Crop no.	Fertilizer application					
	kg P ha⁻¹					
	0	44	87	131	174	437
	kg ha⁻¹					
1	5 842	6 173	6 513	6 852	6 681	6 854
2	5 502	5 728	6 413	6 489	6 714	7 088
3	7 361	7 337	7 500	7 742	7 694	7 679
4	3 973	4 574	4 294	5 111	5 128	6 067
5	5 680	5 992	5 959	6 523	6 158	6 914
6	3 542	3 664	3 589	3 768	3 885	4 148
7	4 607	4 792	5 246	5 521	6 181	7 203
8	2 670	2 606	3 037	3 083	4 239	5 318
9	3 373	3 410	3 951	3 626	5 836	6 427
Sum 9 crops	42 490	44 276	46 502	48 715	52 516	57 698
Calculated sum 9 crops	42 400		47 250		51 125	57 825

Table 5. Madagascar, P uptake by rice.

Crop no.	Fertilizer rate					
	kg P ha⁻¹					
	0	44	87	131	174	437
	kg ha⁻¹					
4	10.0	11.3	12.9	14.3	15.4	22.6
5	14.9	16.0	17.2	19.3	19.3	24.0
6	10.3	11.5	10.6	12.5	14.4	16.9
7	8.3	9.4	9.7	10.5	14.4	18.4
8	7.0	6.7	7.4	8.3	12.3	12.9

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RESULTS OF MODELING

Brazil

No grain yield was obtained when no P was applied (Yost, 1977). Assuming that there must have been some uptake of P but not enough to produce grain, this uptake was estimated to be 0.3 kg P ha^{-1} for each season in the trial period. The net input of P from chemical and physical processes (Wolf et al., 1987) was assumed to be 0.3 kg P ha^{-1} yr^{-1}. For the lowest rate of the broadcast treatments, the recovery fraction of fertilizer P was (12.1 − 0.3)/70 = 0.169. Hence, the uptake fraction of the labile pool was calculated to be 0.169/0.8 = 0.21 (fraction of labile P in TSP is 0.8; see Table 1 in Wolf et al., 1987), and the estimated size of the labile pool of the unfertilized soil was 0.3/0.21 = 1.43 kg P ha^{-1}. The labile pool size after application of 70 kg ha^{-1} of fertilizer P was calculated as 1.43 + (0.8 × 70) = 57.4. Similarly, the estimated labile pool sizes were 113.4, 225.4 and 449.4 kg ha^{-1} P, after application of 140, 280, and 560 kg P ha^{-1}, respectively. For the banded treatments the sizes of the labile pools were 29.4, 57.4, and 113.4 kg P ha^{-1}, respectively.

To calculate the size of the stable pool, time constants of transfer of P between the labile and stable pools should be known. For that purpose the model was run a number of times using estimated fertilizer recovery and substituting various values for the constants. Values of 5 and 30 yr were chosen for time constants of transfer from the labile to stable pool and from the stable to labile pool, respectively. The transfer from the labile pool to the stable pool is secondary only to the uptake coefficient. A time constraint of transfer for 5 yr resulted in closest agreement with actual uptake from the minimally P-treated soil.

Hence, the estimated transfer of P from the labile to the stable pool in the unfertilized soil was 1.43/5 = 0.29 kg P ha^{-1} yr^{-1}, and the reverse transfer was this value plus the value of the net input of P: 0.29 + 0.3 = 0.59 kg ha^{-1} yr^{-1} P. The size of the stable pool in the unfertilized soil, initially, is then 30 × 0.59 = 17.6 kg ha^{-1} P. Upon application of fertilizer P, the stable pool increases by 20% of the quantity of fertilizer P applied.

The first-year recovery fraction of fertilizer P decreased with increasing P application rates (Table 2). It was 0.169 for the 70 kg P ha^{-1} rate and 0.063, 0.032, and 0.014 for the 70 to 140, 140 to 280, and 280 to 560 kg P ha^{-1} rate intervals, respectively. This decrease could have resulted from either of two possibilities. It is possible that at higher P rates there is a more rapid shift to the stable pool from the labile pool, resulting in a smaller labile pool than estimated by our calculations. More likely, in our estimation, crop demand relative to the size of the labile pool at very high fertilizer P application rates was decreased. In principle then, all labile P was assumed to be equally available to the crop but it was not able to exploit a very large labile pool as intensively as a smaller labile pool. Support for this assumption is derived from the fact that after the fifth crop, differences between the 560 kg P ha^{-1} rate and the other rates increased indication that the labile pool was only then being completely exploited (Tables 1 and 2).

Thus, in the model calculations, rather than use a constant uptake fraction, decreasing uptake-fractions of the labile pool with increasing labile pool size were used in the following way. If the labile pool was smaller than 57.4 kg P ha^{-1} (corresponding with the rate of 70 kg ha^{-1} fertilizer P), the crop was assumed to be able to take up annually a fraction of 0.21. If the labile pool size was between 57.4 and 113.4 kg P ha^{-1}, the pool was subdivided into a part of 57.4 kg with an uptake fraction of 0.21, and another part with an uptake fraction of 0.063/0.8 = 0.079. In a similar way the pools were subdivided into three and four parts, if the pool sizes were between 113.4 and 225.4, and between 225.4 and 449.4 kg P ha^{-1}, respectively. The uptake fractions of the third and fourth parts were calculated from the corresponding recovery fractions as 0.040 and 0.018, respectively. This again may be evidence that the large labile pools contained more available P than could be exploited by crops.

The same pool sections and uptake fractions were used to calculate the uptake of P in the following years. For example, at the beginning of the second year the size of the labile pool of the 560 kg P ha^{-1} treatment was 338.9 kg P ha^{-1}, according to the model calculations, and hence the uptake of P in the second year was calculated as:

$$0.210 \times 57.4 + 0.079 \times (113.4 - 57.4) + 0.040 \times (225.4 - 113.4) + 0.018 \times (338.9 - 225.4) = 23.0 \text{ kg P ha}^{-1}.$$

The recovery of banded P was lower than that of broadcast P, possibly due to the restriction in root growth the first year, which did not occur subsequent to mixing the bands in the soil. As such differences were not found in the following years, for both sets of treatments the same uptake fractions of the labile pool were used.

Figure 1 shows the courses of the calculated sizes of the labile and the stable pools. In the case of a single initial broadcast application, the labile pool rapidly declines, while the stable pool builds up till a maximum is reached at the sixth and eighth crops. The higher the application rate, the later the stable pool reaches its maximum. In the case of four repeated banded applications, the labile pool reaches its maximum after the fourth application, and the stable pool after 8 to 10 crops.

Grain yields calculated with the model are in good agreement with the actual yields, except for the highest application rates of 560 and 4 × 140 kg P ha^{-1} (Fig. 2). At these high application rates, the amount of available P is higher than the crop demand. The P concentration of the grain increases, and the yield/P uptake ratio is lower than the 450 assumed in the calculations.

The measured uptake by the third crop, which had suffered from drought, was considerably lower than the calculated uptake. Higher yields than calculated were observed for the ninth crop (again with an exception for the rates of 560 and 4 × 140 kg P ha^{-1}), probably because of very favorable weather conditions. The model does not account for these seasonal fluctuations.

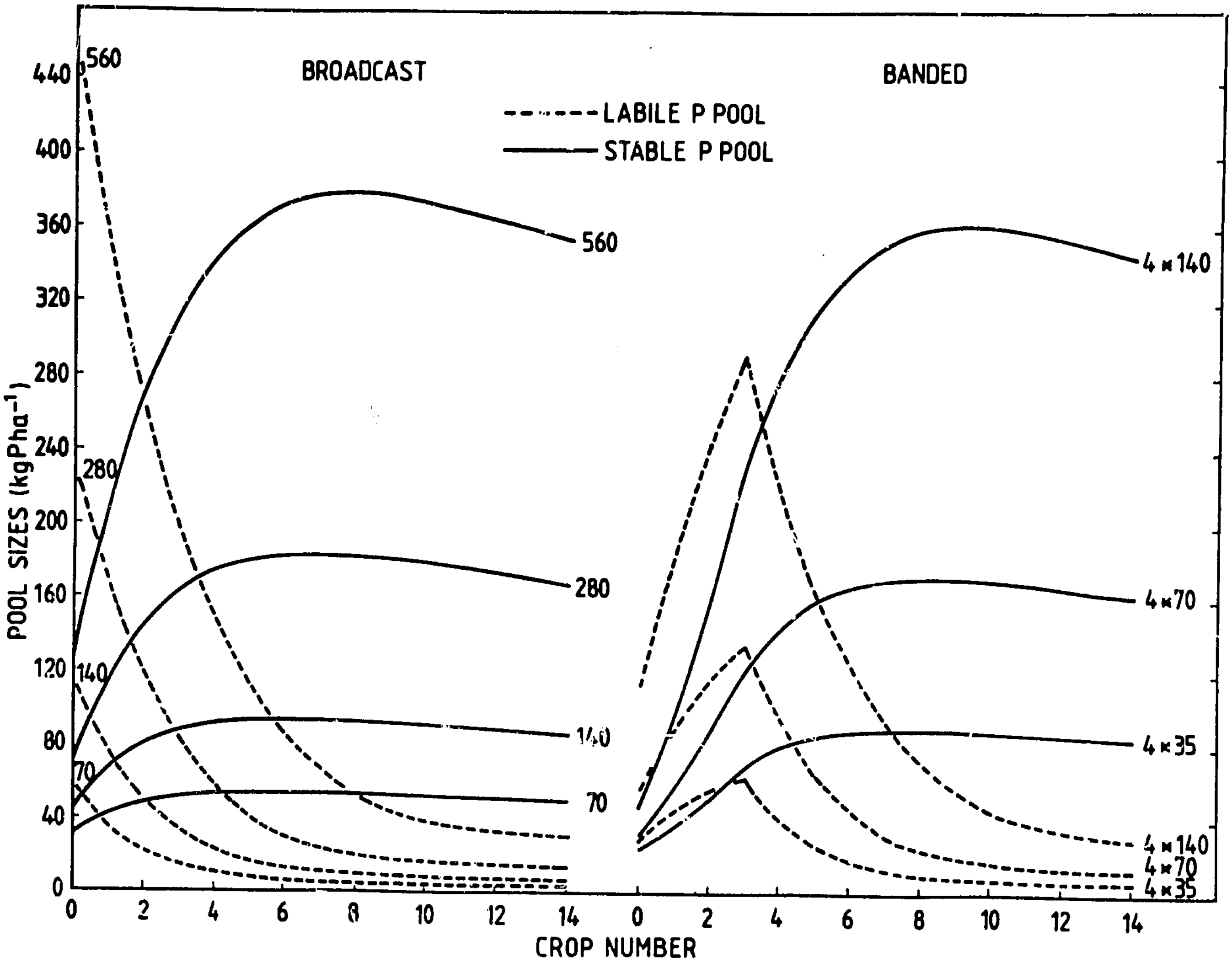

Fig. 1. Course of calculated pool sizes of labile and stable P for the broadcast and banded application treatments in the Brazilian trial. Numbers indicate application rates in kg P ha^{-1}. Curves begin assuming application of fertilizer P applied before first crop and pools established prior to first crop as native pools approached zero.

Australia

The yield of unfertilized sorghum was set at 680 kg ha^{-1}, being the average of the control yields given in Table 3. As control yields did not decline during the 7 yr of the experiment, it was assumed that there was a continuous net input of P (by weathering of minerals, etc.) equal to the crop uptake on the unfertilized soil, being 680/300 = 2.27 kg P ha^{-1}. The values for the uptake fractions of the labile pool were derived from the first-year results of the SSP treatments. Since recovery fractions decreased as application rate increased, rather than use a constant recovery fraction, various recovery fractions of 0.154, 0.100, and 0.041 were used for the intervals 0 to 12, 12 to 24, and 24 to 60 kg P ha^{-1} applied, respectively. The corresponding uptake fractions of the labile pool were 0.193, 0.125, and 0.051 for labile pool sizes of 0 to 21, 21 to 30, and 30 to 59 kg P ha^{-1}, respectively (see under *Brazil* for explanation). For the phosphate rock trial the same values were used. The fractions of labile and stable P in the phosphate rock were set at 0.17 and 0.83, respectively, based on comparison of the yields for the phosphate rock and the SSP treatments during the first year. These fractions are in good agreement with results from Brazil where application of 85 kg P ha^{-1} as rock phosphate was about 20% as effective as equal amounts of P as superphosphate in increasing the yield of soybean [*Glycine max* (L.) Merr.] (Centro de Pesquisa Agropecuria dos Cerrados, 1982). For the time constants of transfer the same values were used as were used in the Brazilian trial, i.e., 5 and 30 yr, respectively.

The yields as predicted by the model (Fig. 3) agreed with the actual yields, except for the rate of 60 kg P ha^{-1}, applied as SSP, where the model predicted yields higher than those measured. At this relatively high application rate, the crop P concentration probably increased, and hence the yield/P uptake ratio was lower than the assumed value of 300.

Madagascar

Because in the Madagascar trial the control yields decreased in course of time, it could not be assumed that the net input of P was equal to the uptake of P in the control during the first year. For such non-steady-state situations, it is impossible to calculate the net input and the size of the stable pool. Therefore, model calculations were made for different values of the net

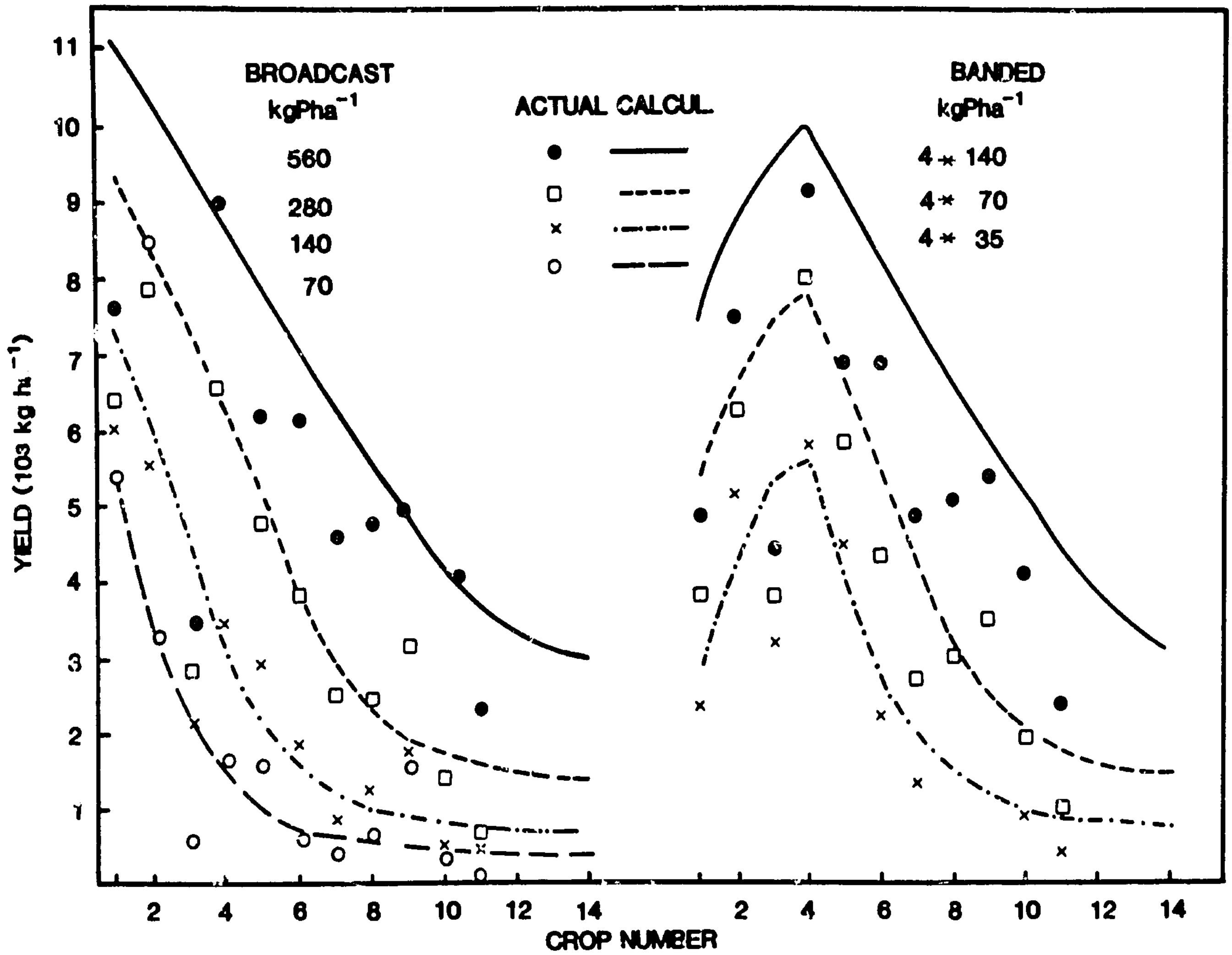

Fig. 2. Course of calculated and actual maize yields for the broadcast and banded application treatments in the Brazilian trial.

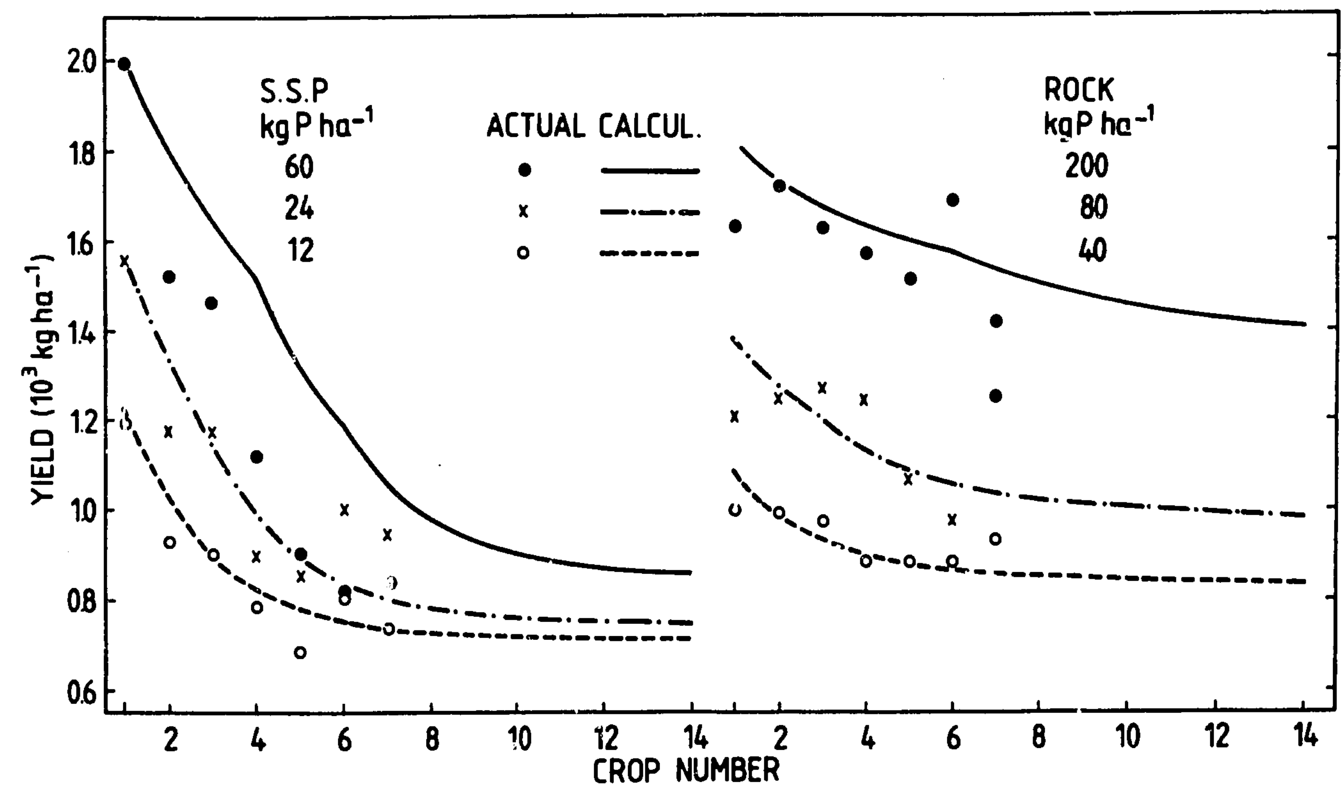

Fig. 3. Course of calculated and actual sorghum yields for the single superphosphate (SSP) and phosphate rock (ROCK) treatments in the Australian trial.

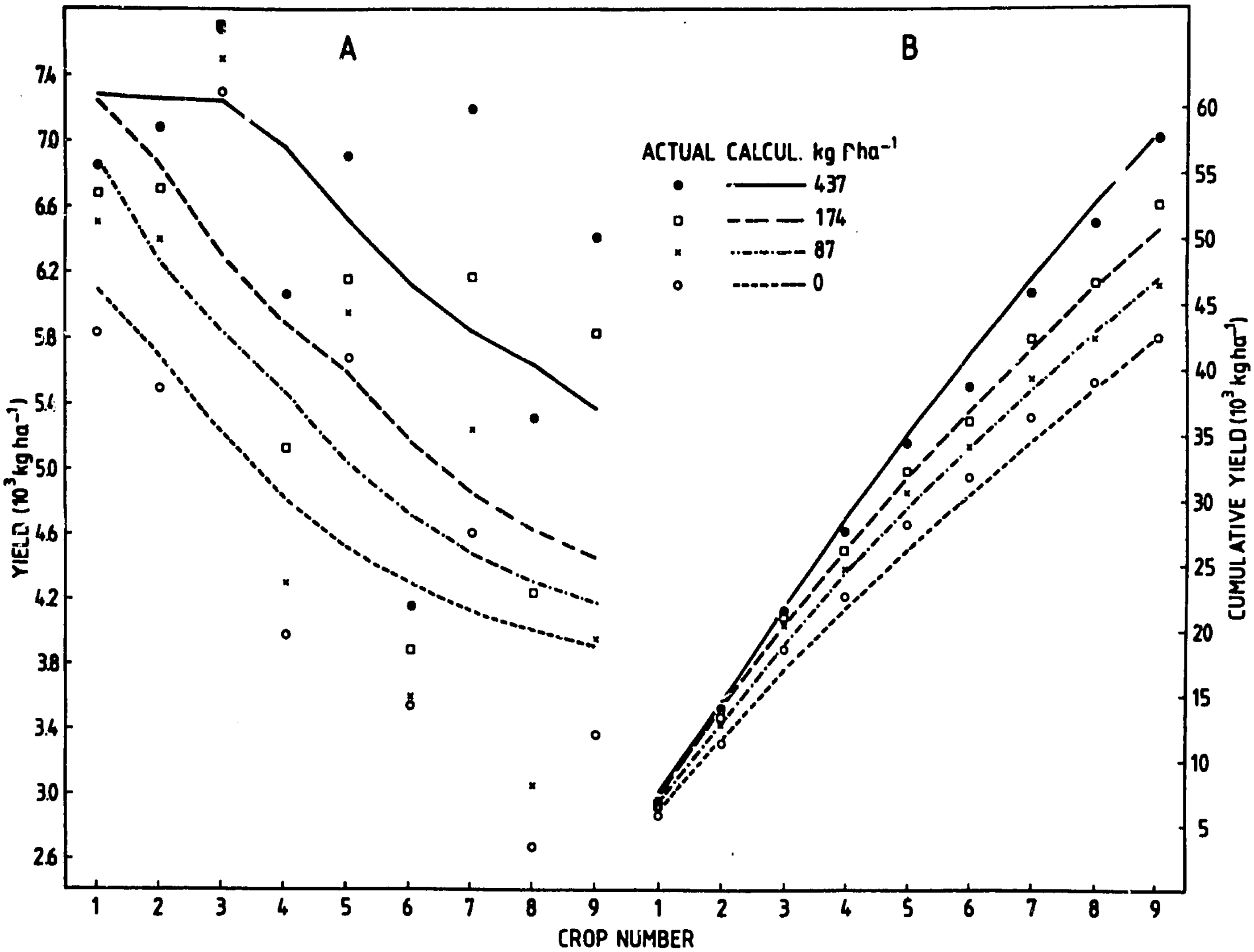

Fig. 4. Course of calculated and actual rice yields for four P application rates in the Madagascar trial (A); sum of cumulative yields (B).

input of P and the size of the stable pool, until a reasonable fit with the measured control yields was obtained. The best combination proved to be a net input of 3 kg P ha^{-1} yr^{-1}, and a stable pool size of 1250 kg P ha^{-1}. Time constants for the transfers between the labile and stable pool were again set at 5 and 30 yr. The recovery fractions of fertilizer P were calculated from the first-year crop yields, taking into account the irregularities of the yields obtained at the rates of 131 and 174 kg P ha^{-1} (Table 4). The resulting values for the recovery fractions were 0.048, 0.024, and 0.008 for the intervals of 0 to 87, 87 to 174, and 174 to 437 kg P ha^{-1} applied, respectively (see under *Brazil* for explanation). The corresponding uptake fractions of the labile pool were 0.060, 0.030, and 0.001 for labile pool sizes of 0 to 370, 370 to 440, and 440 to 1088 kg P ha^{-1}, respectively (see under *Brazil* for explanation).

Because the seasonal effects on yield were of the same order of magnitude as the yield increases brought about by the application of fertilizer P, or even larger, Fig. 4A is confusing. To circumvent the annoyance of the seasonal effects, Fig. 4B presents the cumulative yields. There is a good agreement between measured and calculated data, except for the control yields between the third and seventh years. This is due to the exceptionally high yield of the third crop.

DISCUSSION

Evaluating the performance of a model describing the residual effects of fertilizer P is difficult due to the scarcity of results from long-term field experiments. Even when such experimental data are available, often only the yields and not the crop uptake of P are measured. Moreover, seasonal effects may play such a dominant part that a regular course of residual P recovery can hardly be found. Therefore, model performance should be considered satisfactory, if the cumulative effect of applied fertilizer over a number of years is correctly described. The model of Wolf et al. (1987) meets this requirement as shown in Tables 1, 3, and 4 where the cumulative measured yields and the calculated yields are given for the same number of crops. Correlation coefficients ranging from 0.95 to 0.99, between cumulative observed and calculated yields, attest to the usefulness of the model. The model overestimated the cumulative yields for 11 crops at the highest P application rate for the Brazil site. This is not surprising as the labile pool contained more available P than could reasonably be taken up by the first few crops. Moreover, the productivity of these soils improves with time after first being brought into cultivation (Goedert, 1985), so that the nutrients are more nearly utilized to their maximum by the later

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Table 6. Residual recovery fraction (× 100) in successive years and accumulated over 9 yr, as dependent on the initial recovery fraction.

Initial recovery fraction†	Years after application						
	2	3	4	5	7	10	Total‡
Superphosphate							
4.0	3.0	2.3	1.8	1.5	1.0	0.7	13.2
8.0	5.7	4.1	3.0	2.3	1.4	0.9	21.5
12.0	7.9	5.3	3.7	2.6	1.6	1.0	26.5
16.0	9.7	6.1	3.9	2.7	1.5	1.0	29.3
20.0	11.2	6.4	3.9	2.5	1.4	1.0	30.4
Phosphate rock§							
1.0	0.9	0.8	0.7	0.7	0.6	0.6	6.2
2.0	1.7	1.4	1.3	1.2	1.0	0.9	10.6
3.0	2.4	1.9	1.7	1.5	1.3	1.2	13.7
4.0	2.9	2.3	1.9	1.7	1.5	1.3	15.9
5.0	3.4	2.6	2.1	1.8	1.6	1.4	17.5

† Fraction of applied fertilizer phosphorus, recovered first year after application (× 100).
‡ From second year to tenth, inclusive.
§ It is assumed that the phosphate rock does not contain an inert P fraction.

crops. The model predicted very well the total yield of the last seven crops of the experiment. In addition, the residual effect of P application was demonstrated both by experiment and the model. We suggest that the model can be very useful in projecting the long-term effects of fertilizer P. The model, however, cannot be used to predict crop uptake of P and yield for a specific year as weather and climate variables are not included in the model.

This is illustrated by the data from the Madagascar (Fig. 4) site; cumulative yields are predicted extremely well by the model, but yields from individual years deviate widely from the predicted curve. Uptake and yield do vary, however, uniformly from treatment to treatment in a given crop (Tables 1,2,3,4).

The attractiveness of the model is its simplicity. Only three parameters need to be known for calculating the residual effect of applied fertilizer: (i) the initial (i.e., the first-year) recovery fraction of fertilizer P and, thus, (ii) the recovery fraction of the labile pool, and (iii) the time constants of P transfer between the labile and the stable pools.

The initial recovery fraction undoubtedly will be site specific, although for similar soils and similar crops, it may be possible to pool data from several experiments to develop a common recovery fraction. For different values of the initial recovery fraction, residual recovery fractions over a number of years after fertilizer application were computed with time constants of 5 and 30 yr, and for superphosphate and phosphate rock, respectively (Table 6). Table 6 shows that the reduction in recovery fraction is relatively larger, the higher the initial P recovery fraction.

For superphosphate the residual recovery fractions are practically equal in the tenth year, irrespective of the initial recovery fraction. For an initial recovery fraction of 0.04 the total residual recovery fraction (second–tenth year) for superphosphate is about three times the initial fraction, and for an initial recovery fraction of 0.20 it is about 1.5 times the initial fraction. The absolute value of the total recovery fraction, however, increases with increasing values of the initial recovery fraction. The total fraction recovered in 10 yr changes from 0.17 to 0.50 for superphosphate when the initial recovery fraction increases from 0.04 to 0.20, and changes from 0.07 to 0.23 for phosphate rock when the initial recovery fraction increases from 0.01 to 0.05. At an identical initial recovery fraction, e.g., 0.04, the residual recovery fraction is higher for phosphate rock than for superphosphate, which is due to the larger stable pool built up after application of phosphate rock.

Extra data are required only for the combination of very high application rates and a non-steady state in the unfertilized soil, as in the Madagascar trial. In the three examples treated in this paper, all from tropical areas, time constants could be set at 5 and 30 yr. Apparently, the effects of soil and climate were taken into account sufficiently via the value for the initial recovery fraction. Further testing is necessary to find out if the time constants need modification for other climates and soils. If there is not such a need, the only factor required for calculating the residual effect of applied fertilizer is the initial recovery fraction.

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