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Response of sorghum to fertilizer phosphorus and its residual value in a Vertisol

K.L. Sahrawat[1], T.J. Rego, J.R. Burford, M.H. Rahman, J.K. Rao & A. Adam[2]
International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Patancheru P.O., Andhra Pradesh, India. [1]*Present address:* [2]*West Africa Rice Development Association (WARDA), 01 BP 2551 Bouake 01, Côte d'Ivoire, West Africa*

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Abstract

The response of crops to added P in Vertisols is generally less predictable than in other soil types under similar agroclimatic conditions. Very few studies have considered the residual effects of P while studying responses to fresh P applications. Field experiments were conducted for three years to study the response of sorghum to fertilizer P applied at 0, 10, 20 and 40 kg P ha^{-1}, and its residual value in a Vertisol, very low in extractable P (0.4 mg P kg^{-1} soil), at the ICRISAT Center, Patancheru (near Hyderbad), India. In order to compare the response to fresh and residual P directly in each season, a split-plot design was adopted. One crop of sorghum (cv CSH6) was grown each year during the rainy season (June–September).

The phenology of the sorghum crop and its harvest index were greatly affected by P application. The days to 50% flowering and physiological maturity were significantly reduced by P application as well as by the residues of fertilizer P applied in the previous season. In the first year of the experiment, sorghum grain yield increased from 0.14 t (no P added) to 3.48 t ha^{-1} with P added at the rate of 40 kg P ha^{-1}. Phosphorus applied in the previous year was 58% as effective as fresh P but P applied two years earlier was only 18% as effective as fresh P.

Introduction

Under rainfed cropping in India, it is generally understood that if the extractable P by 0.5 *M* $NaHCO_3$ is less than 5 mg kg^{-1} soil, a response to P is likely and an application of about 15 kg ha^{-1} is recommended (El-Swaify *et al.*, 1985). However, a review of P fertilizer requirements in the semi-arid region of India (Kanwar, 1986) concluded that the response to P of cereal crops, such as sorghum, varies across soil types and follows the order: Alfisol > Entisol > Vertisol and that to obtain similar yield responses, Vertisols require higher application of P than other soil types.

Recent research at the ICRISAT center to investigate these differences showed that large responses to P occurred in Alfisols when the extractable P (0.5 *M* $NaHCO_3$) was less than 5 mg kg^{-1}. On the other hand, sorghum responded little to applied P on Vertisols unless the extractable P was less than 2.5 mg kg^{-1} (ICRISAT, 1985). The cause of low response in Vertisols is not known, but is often attributed to phosphate sorption (Murthy, 1988). However, recent work on the behaviour of P in Indian Vertisols indicated that the Vertisols have low phosphate sorption capacity compared to other tropical soils (such as Ultisols and Oxisols). The data on P desorption indicated that the Vertisols studied sorb P in an easily desorbable form (Sahrawat and Warren, 1989; Shailaja and Sahrawat, 1990).

The response of crops to added P on Vertisols is generally less predictable than other soils such as Alfisols under similar agroclimatic conditions. One reason is the uncertainty of the availability of natural and residual P. However, very few studies have considered the effects of residual fertilizer P relative to fresh P applications. The objective of the present work was to study the response of sorghum to P and

Table 1. Soil characteristics of the experimental site

Soil characteristic	Value
pH (1:2 water)	8.28
Organic C (mg kg^{-1})	3300
Total N (mg kg^{-1})	401
(NH_4+NO_3-N) (mg kg^{-1})	8.2
Total P (mg kg^{-1})	150
Extractable P, 0.5 *M* $NaHCO_3$ (mg kg^{-1})	0.4
CEC (cmol kg^{-1})	49.2
Extractable Zn, DTPA (mg kg^{-1})	5.8
Exchangeable K, 1 *N* NH_4OAC (mg kg^{-1})	232
$CaCO_3$ (%)	5.6
Clay (%)	53
Sand (%)	21
Silt (%)	26

its residual effect in a Vertisol very low in extractable P under rainfed cropping.

Materials and methods

Field experiments were conducted during the rainy seasons of 1987, 1988 and 1989 at the ICRISAT Center, Patancheru (near Hyderbad) India (17.5° N, 78.5° E, 545 m altitude) on a Vertisol. The Vertisol belongs to the Kasireddipalle series and is a Typic Pellustert developed on basaltic alluvium. A cover crop of maize was grown at the experimental site before initiating the experiment.

Some characteristics of the soil at the experimental site are given in Table 1. Soil samples were taken before starting the experiment. They were air-dried, ground and sieved through a 2-mm screen before analysis. For the analyses reported in Table 1, pH was measured by a glass electrode using a soil to water ratio of 1:2. Organic C was determined as described by Walkley and Black (1934) and total N was determined as described by Dalal *et al.* (1984). Carbonate (expressed as $CaCO_3$) content was determined by acid neutralization as described by Allison and Moodie (1965) and particle size by the hydrometer method (Gee and Bauder, 1986). The total P content in soil was determined by digestion with perchloric acid (Olsen and Sommers, 1982), and extractable P was determined with 0.5 *M* $NaHCO_3$ (Olsen and Sommers, 1982). Exchangeable K (Jackson, 1967), cation exchange capacity (Chapman, 1965) and extractable Zn (Lindsay and Norvell, 1978) were also determined.

In order to compare the response of sorghurn to fresh and residual P directly in each season, an experiment of a split-plot design with four replications was adopted. Diammonium phosphate (DAP) was applied at four rates of 0, 10, 20 and 40 kg P ha^{-1} in May 1987. In the 1988 cropping season, each plot was split into 4 sub-plots and the 4 rates of fresh P applied in the sub-plots. In the 1989 cropping season, the sub-plots were further split in the same manner to give sub-sub-plots for the application of fresh P in 1989. The area of each sub-sub-plot was 4×4 m^2. One sorghum crop (cv CHS6) was grown each year in the rainy season from June to September under rainfed conditions. The crop was seeded using 50 cm $\times$ 16 cm spacing giving a population of 125,000 plants ha^{-1}. All plots received uniform rates of N, K and Zn application. Nitrogen was applied at a rate of 120 kg N ha^{-1}, 36 kg at seeding and the rest at 3 weeks after emergence of the crop. Nitrogen application rate by DAP at seeding was balanced by applying urea in treatments that received 0, 10 and 20 kg P ha^{-1}. Nitrogen was top dressed as urea. Potassium chloride and zinc sulfate were applied at the rates of 170 and 40 kg ha^{-1} respectively to supply K and Zn.

During the growing season, the sorghum crop was hand-weeded twice. The crop was protected from shoot fly (*Atherigone soccata*) by spraying 0.2% metasystox. The sorghum crop was harvested at maturity using a net harvest area of 3×2 m^2 (gross area 4×4 m^2). Ten plants were taken randomly from each plot, dried and ground for plant analysis. The harvested crop was separated into seed and stalk after drying for 3–4 days. The separated parts were again oven-dried at 60°c for moisture correction.

During the growing season, from sowing to harvest of the crop, 604 mm of rainfall was received in 1987, 941 mm in 1988 and 583 mm in 1989.

The following Mitscherlich equation described in Barrow and Mendoza (1990) was employed to describe the P response surface fitted to sorghum grain yield data obtained in 1987, 1988 and 1989 considering both fresh P and the residues from applications made in 1987 and 1988 years:

$$Y = A - B\exp(-C_1.P_{87} - C_2.P_{88} - C_3.P_{89}) \quad (1)$$

where Y is the grainy yield (t ha^{-1}) and P_{87}, P_{88} and P_{89} are the levels of fertilizer P (kg ha^{-1}) applied in 1987, 1988 and 1989. C_1, C_2 and C_3 are the coefficients that indicate how effective the fertilizer P is after two, one

Table 2. Effect of applied P on days to flowering and physiological maturity of sorghum in 1987

P rate kg ha^{-1}	Days to 50% flowering	Days to physiological maturity
0	99	133
10	65	100
20	61	100
40	60	100
F test	Significant at ($p < 0.001$)	Significant at ($p < 0.001$)

or in the current year of applications, and A and B are constants.

The Equation 1 was fitted using a computer program to locate the values of the parameters that gave the smallest value for the residual mean square.

The grain and stalk samples of sorghum were analysed for P content. The plant materials were digested using a digestion block and P in the digest was determined by an autoanalyzer procedure (Technicon Industrial Systems, 1972). The data were statistically analysed using the analysis of variance procedure.

Results and discussion

Effect of P on flowering and maturity

In this vertisol, very low in available P, the phenology of the sorghum crop was greatly affected by P application. In the 1987 season, P application significantly reduced the days to 50% flowering as well as days to physiological maturity (Table 2). For example, the unfertilized crop took 99 and 133 days respectively for 50% flowering and physiological maturity and the application of P at the rate of 10 kg ha^{-1} reduced the time taken to flowering and maturity by 34 and 33 days, respectively. Further increasing the rate of P application beyond 10 kg P ha^{-1} did not significantly affect the days to 50% flowering or physiological maturity.

In the 1988 season, the phenology of the sorghum crop was significantly affected by P applied in the current season but not by the residues of fertilizer P applied in the 1987 season (data not shown). However, as in the first year there was a response to P application, though not to the increasing rates of P on the phenology of the crop. In the 1989 season, the days to 50% flowering were significantly affected by the residues of the fertilizer P applied in 1988 but not by the residues of fertilizer P applied in 1987. However, the days to physiological maturity were not significantly affected by the residues of fertilizer P applied in either 1988 or 1987 (Table 3).

These results provide the first field data on the effects of fertilizer P on the phenology of the sorghum crop in a soil very deficient in available P. These results indicate that the effects of P on the days to flowering and physiological maturity merit consideration for crop growth modelling. These results were generally con-

Table 3. Flowering and physiological maturity of sorghum in 1989 in response to residues of fertilizer P applied in 1987 and 1988

P applied in 1987 (kg ha^{-1})	P applied in 1988 (kg ha^{-1})			
	Days to 50% flowering[a]			
	0	10	20	40
0	78	74	74	69
10	75	74	71	70
20	77	75	72	70
40	73	72	71	69
	Days to physiological maturity[b]			
0	111	111	111	111
10	118	111	111	104
20	111	111	104	104
40	111	111	104	104

[a]F test significant at $p < 0.001$ for 1988 P treatment, but not significant for 1987 and 1987 × 1988 P treatments; SE for comparing 1988 treatments = ± 0.43.
[b]F test not significant.

Table 4. Sorghum grain and stalk yields, and total P uptake of grain and stalk in response to applied P in 1987

P rate (kg ha^{-1})	Grain (t ha^{-1})	Stalk	Total P uptake (kg ha^{-1})
0	0.14	2.10	1.88
10	1.87	4.11	4.29
20	2.62	4.78	6.19
40	3.48	4.68	10.17
SE±	0.189	0.100	0.153

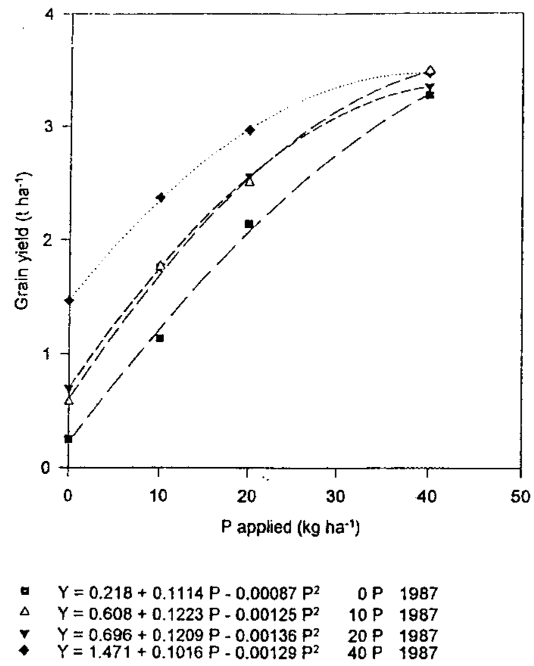

Fig. 1. Phosphorus response of sorghum grain to fresh P applied in 1988 as influenced by the residues of P applied in 1987.

Table 5. Sorghum grain and stalk yields, and total P uptake of grain and stalk in response to fresh P applied in 1988 and by residues of fertilizer P applied in 1987

P applied in 1987 ($kg\ ha^{-1}$)	P applied in 1988 ($kg\ ha^{-1}$)			
	0	10	20	40
	Grain yield[a] ($t\ ha^{-1}$)			
0	0.24	1.14	2.14	3.27
10	0.58	1.77	2.50	3.49
20	0.70	1.77	2.56	3.35
40	1.47	2.37	2.97	3.47
	Stalk yield[b] ($t\ ha^{-1}$)			
0	1.34	3.55	5.28	7.01
10	2.05	4.50	5.57	7.12
20	2.56	4.73	6.05	7.46
40	5.05	5.96	6.79	7.36
	Total P uptake[c] ($kg\ ha^{-1}$)			
0	1.08	3.17	5.69	9.55
10	1.79	4.49	6.50	10.56
20	2.10	4.63	7.14	10.95
40	4.52	6.77	8.73	11.17

[a]F test significant for 1987 ($p < 0.05$), 1988 ($p < 0.001$) and 1987 × 1988 ($p < 0.001$) treatments; SE for comparing 1987 P treatment = ± 0.108, SE for comparing 1988 P treatments = ± 0.050 and SE for 1987 × 1988 = ± 0.138.
[b]F test significant for 1987 ($p < 0.05$), 1988 ($p < 0.001$) and 1987 × 1988 ($p < 0.001$) treatments; SE for 1987 treatments = ± 0.246, SE for 1988 treatments = ± 0.126 and SE for 1987 × 1988 = 0.328.
[c]F test significant for 1987 ($p < 0.001$), 1988 ($p < 0.001$) and 1987 × 1988 ($p < 0.05$) treatments; SE for comparing 1987 treatments = ± 0.307, SE for comparing 1988 treatments = ± 0.157 and SE for 1987 × 1988 treatments = ± 0.410.

sistent with regard to the effect of applied P on the sorghum crop phenology in the current season in the three years of study because it may not be uncommon to find such effects for sorghum grown in the field where little P fertilization takes place.

Effects of P on yield and P uptake

In the Vertisol studied which was very low in available P, sorghum grain yield responded to fertilizer P. In 1987, yield increased from 0.14 t (no P added) to 3.48 t ha^{-1} with P added at the rate of 40 kg ha^{-1}. The sorghum stalk yield more than doubled by application of P at the rate of 20 kg ha^{-1} but there was no further response to 40 kg ha^{-1} application. Total P uptake by biomass increased with the rate of P application (Table 4).

In the 1988 cropping season, the response to fresh P applied in 1988 was influenced by the residual effect of P applied in 1987 (Fig. 1 and Table 5). The residual effect of P depended on the rate of P applied in the first year; however, even the lowest rate of P, 10 kg ha^{-1}, applied in 1987 had significant residual effect on sorghum production and P uptake in 1988. The largest residual effect of P was from the 40 kg P ha^{-1} rate applied in 1987, which gave a sorghum grain yield of 1.47 t ha^{-1} without any fresh P application in 1988.

As in the first year, sorghum yield increased in response to fresh P application in 1988. However, the grain and stalk yields of sorghum were similar at the highest rate of P application in treatments both with and without the residual effects of P, indicating that the effects were mainly due to P (Fig. 1). The total P uptake was highest in the treatment that received 40 kg P ha^{-1} both in the current and the preceding seasons (Table 5).

The data on sorghum grain and stalk in 1989 in response to the residues of fertilizer P in 1987 and 1988 are shown in Table 6. Sorghum grain yield was significantly affected by the residual effects of fertilizer P applied in 1988 but not by P applied in 1987 or the interaction between P applied on 1987 and 1988. The sorghum stalk yields were also significantly affected

Table 6. Sorghum grain and stalk yields and total P uptake of grain and stalk in 1989 in response to residues of fertilizer P applied in 1987 and 1988

P applied in 1987 (kg ha^{-1})	P applied in 1988 (kg ha^{-1})			
	Grain yield[a] (t ha^{-1})			
	0	10	20	40
0	0.31	0.38	1.04	2.30
10	0.48	0.79	1.09	2.26
20	0.32	0.94	1.38	1.99
40	0.82	0.97	1.78	2.68
	Stalk yield[b] (t ha^{-1})			
0	1.82	2.24	3.94	4.54
10	2.44	2.90	3.32	5.47
20	1.98	3.16	3.94	4.13
40	3.21	3.08	4.97	4.83
	Total P uptake[c] (kg ha^{-1})			
0	1.46	1.77	3.92	6.40
10	1.97	2.40	3.02	6.57
20	1.75	3.20	4.20	5.42
40	2.70	2.94	5.25	7.48

[a]F test significant for 1988 treatments ($p < 0.001$) but not significant for 1987 and 1987 × 1988 treatments; SE for comparing 1988 treatments = ± 0.090.
[b]F test significant for 1988 P treatemnts ($p < 0.001$) but not for 1987 and 1987 × 1988 treatments; SE for comparing 1988 treatments = ± 0.172.
[c]F test significant for 1988 P treatments ($p < 0.001$) but not significant for 1987 and 1987 × 1988 treatments; SE for comparing 1988 treatments = ± 0.229.

by the residual effects of P applied in 1988 but not by the residual effects of fertilizer P applied in 1987. However, the interaction between P applied in 1987 and 1988 significantly affected stalk yield (Table 6).

Similar to grain yield, the total P uptake by sorghum grain and stalk was significantly affected by the fertilizer P applied in 1988 but not by P applied in 1987 or by the interaction of P applied in 1987 and 1988 (Table 6). Analysis by multiple regression of the results for sorghum grain yield in 1989 showed that the residual effect of a previous P application is inversely proportional to the time since application:

Grain yield = 0.783 + 0.032 × 1988-P + 0.049 × 1989-P $r^2 = 63\%$, where 1988-P and 1989-P are the amounts of fertilizer P (kg ha^{-1}) applied in 1988 and 1989.

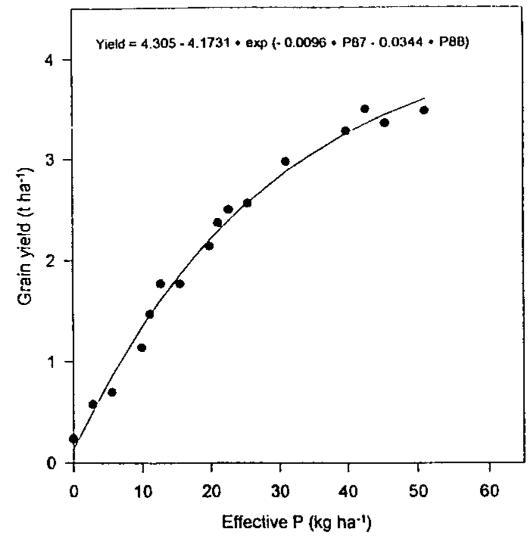

Fig. 2. Relationship between sorghum grain yield and "effective P" rates, considering fresh P applied in 1988 and the residues of P applied in 1987.

Response to fresh and residual P

The Mitscherlich Equation 1 fitted using three years' grain yield data from 64 P treatments consisting of fresh P applied in 1989 (P_{89}) and the residues of P applied in 1987 (P_{87}) and 1988 (P_{88}) was described by the following equation:

$$Y = 4.1708 - 4.1811\exp(-0.0056 \times P_{87} - 0.0182 \times P_{88} - 0.0313 \times P_{89}), R^2 = 0.98 \quad (2)$$

The effective P levels from fertilizer P added in different years were calculated proceeding as follows:

$$\text{Effective P} = (P_{89} + 0.0182/0.0313 \times P_{88} + 0.0056/0.0313 \times P_{87})$$

$$\text{or effective P} = (P_{89} + 0.5814 \times P_{88} + 0.1789 \times P_{87}) \quad (3)$$

The Equation 3 shows that the fitted values of the C coefficients are such that the residual value in 1989 of the P added in 1987 was 17.9% and that of the P applied in 1988 was 58.1%.

The grain yield data with one year residual was also fitted to the Mitscherlich Equation 1. The data pertain to P response in 1988 to fresh P application as influenced by residues of P applied in 1987. The relationship (Fig. 2) was described by the following equation:

$$Y = 4.305 - 4.1731 \times \exp(-0.0096 \times P_{87} - 0.0344 \times P_{88}), R^2 = 0.98 \quad (4)$$

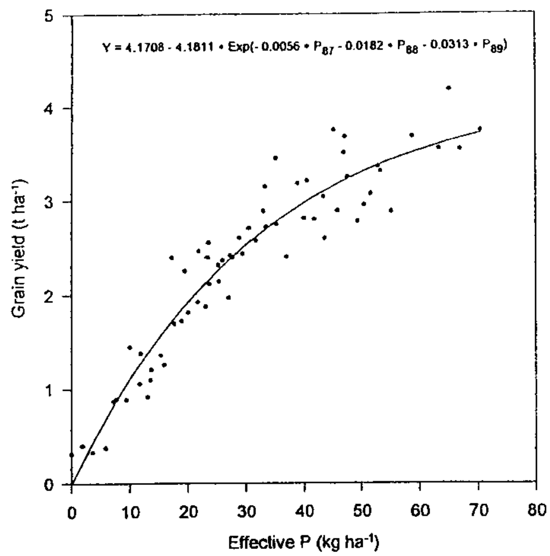

Fig. 3. Relationship between sorghum grain yield and "effective P" rates, considering fresh P applied in 1989 and the residues of P applied in 1987 and 1988.

Table 7. Effect of added P on harvest index (%) of sorghum during three years under rainfed conditions

Year	Harvest index at different rates of added P (kg ha^{-1})				
	0	10	20	40	Mean
1987	6.3	31.3	35.2	42.3	28.8
1988	15.2	24.3	28.8	31.8	25.0
1989	14.5	31.6	33.6	38.6	29.6
Mean	12.0	29.1	32.5	37.6	

The effective P calculated as described above showed that the residual value in 1988 of the P added in 1987 was 28%.

The results show that the residual value of P differed, because when cumulative residual value of P from two years application were considered, the residual value in 1989 of the P applied in 1988 was 58.1%, while the residual value in 1988 of the P applied in 1987 was only 28.0%.

The relationship between sorghum grain yield and effective P rates is shown in Figure 3 using the data derived from 64 P treatments which received P levels varying from 0 to 120 kg P ha^{-1}. The data showed that the grain yield response of sorghum continued up to 70.5 kg effective P ha^{-1}, consisting of 40 kg P ha^{-1} applied in 1989 and the residues of 40 kg P ha^{-1} of fertilizer added each in 1987 and 1988. The relationship between effective P rates and sorghum grain yield (Figs. 2 and 3) also show that quite large levels of P have to be applied to get near maximum yields, although the residual effects of previously applied P are large especially in the immediate succeeding season. This is due to high P buffering capacity of the Vertisol (Sahrawat and Warren, 1989).

Effect of P on harvest index

The effect of added P during the three years of study for selected treatments given in Table 7 shows that the harvest index (ratio of grain yield to grain plus stalk yield) of the sorghum crop was greatly affected by P application. The harvest index increased with added P and the first rate of P application had the greatest effect. Evidently grain formation was more strongly affected than biomass production. The effect of P is similar to the effect of P on the phenology of the crop.

Conclusions

These results indicate spectacular effects of fertilizer P on sorghum growth, yield and P uptake in the current season. The effects of fertilizer P residues were strong and significant on sorghum in the immediate preceding season of P application. The results are of particular significance due to the lack of data on the residual effects of P in the Vertisols of the semi-arid tropical regions under rainfed conditions (Kanwar, 1986; Probert *et al.*, 1988). The effects of P application on the phenology and harvest index of sorghum are large and significant, and need to be considered for crop growth modelling.

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References

Allison L E and Moodie C D (1965) Carbonate. *In*: Black C A (ed.) Methods of Soil Analysis, part 2. Agronomy 9: 1379–1400. Am. Soc. Agron., Madison, WI

Barrow N J and Mendoza R E (1990) Equations for describing sigmoid yield responses and their application to phosphate responses by lupins and by subterranean clover. Fert. Res. 22: 181–188

Chapman H D (1965) Cation exchange capacity. *In*: Black C A (ed.) Methods of Soil Analysis, part 2. Agronomy 9: 891–901. Am. Soc. Agron., Madison, WI

Dalal R C, Sahrawat K L and Myers R J K (1984) Inclusion of nitrate and nitrite in the Kjeldahl nitrogen determination of soils and plant materials using sodium thiosulphate. Commun. Soil Sci. Plant Anal. 15: 1453–1461

El-Swaify S A, Pathak P, Rego T J and Singh S (1985) Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. Adv. Soil Sci. 1: 1–64

Gee G W and Bauder J W (1986) Particle-size analysis. *In*: Klute A (ed.) Methods of Soil Analysis, part 1. Agronomy 9: 383–409. Am. Soc. Agron., Madison, WI

ICRISAT (1985) International Crops Research Institute for the Semi-arid Tropics. Annual Report for 1984: 256–258. Patancheru, Andhra Pradesh 502 324, India

Jackson M L (1967) Soil Chemical Analysis. Prentice-Hall, New Delhi: 498

Kanwar J S (1986) Crop production techniques and fertilizer management areas: ICRISAT experience. *In*: Crop Production Techniques and Fertilizer Management in Rainfed Agriculture in Southern Asia. Proceedings of the second regional IMPHOS seminar, 22–25 January 1986. Institut Mondial du Phosphate (IMPHOS) and Fertilizer Association of India, New Delhi, India

Lindsay W L and Norvell W A (1978) Development of DTPA soil test for zinc, iron, manganese and copper. Soil Sci. Soc. Am. J. 42: 421–428

Murthy A S P (1988) Distribution, properties and management of Vertisols of India. Adv. Soil Sci. 8: 151–214

Olsen S R and Sommers L E (1982) Phosphorus. *In*: Page AL *et al.* (eds.) Methods of Soil Analysis, part 2. Agronomy 9: 403–430. Am. Soc. Agron., Madison, WI

Probert M E, Fergus I F, Bridge B J, McGarry D, Thompson C H and Russell J S (1987) The Properties and Management of Vertisols. CAB International, Wallingford, Oxon, UK

Sahrawat K L and Warren G P (1989) Sorption of labelled phosphate by a Vertisol and an Alfisol of the semi-arid zone of India. Fert. Res. 20: 17–25

Shailaja S and Sahrawat K L (1990) Adsorption and desorption of phosphate in some semi-arid tropical Indian Vertisols. Fert. Res. 23: 87–96

Technicon Industrial Systems (1972) Technicon Autoanalyser II Manual. Industrial method no. 218-72A. Technicon Industrial Systems, Tarrytown, New York

Walkley A and Black I A (1934) An examination of the Degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Sci. 37: 29–38