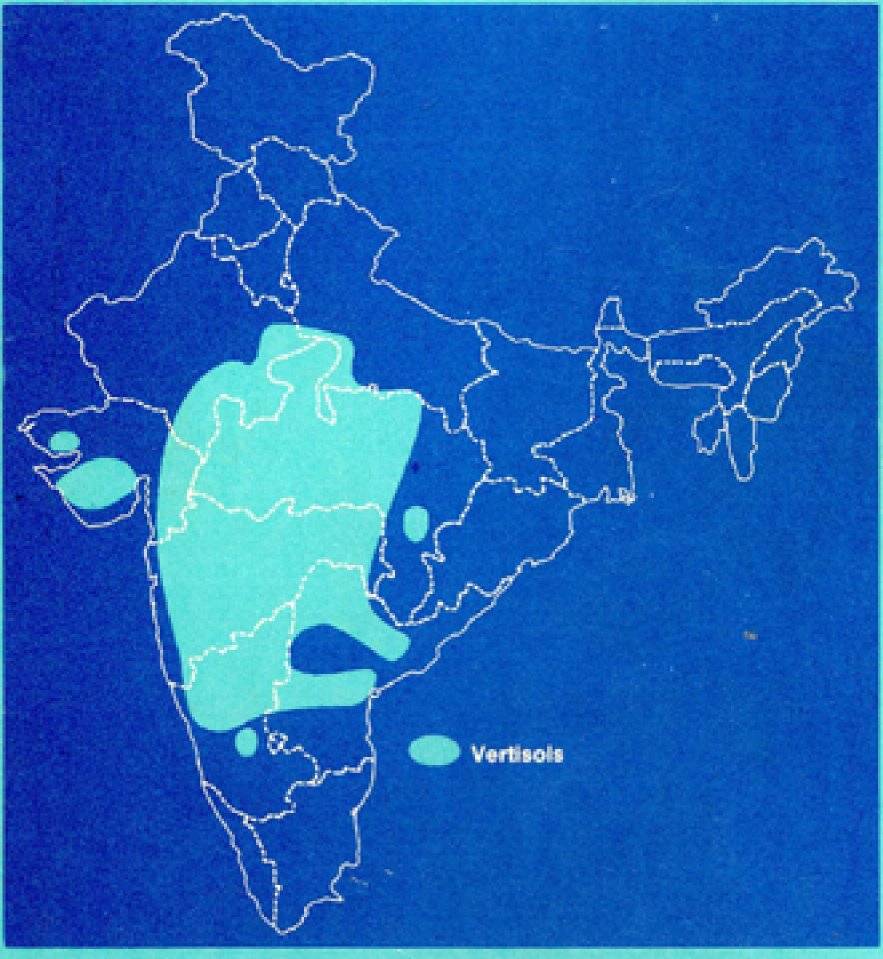
Phosphorus in Indian Vertisols



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Phosphorus in Indian Vertisols:

Summary Proceedings of a Workshop, 23-26 Aug 1988, ICRISAT Center

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics
Patancheru, A.P. 502 324, India.

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Purpose of the Workshop

In recent years, scientists and extension agencies have become much more aware of the high potential productivity of Vertisols and associated soils. However, one gap in current knowledge is how best to assess the phosphorus status of these heavy black clay soils. Crops on Vertisols have appeared to be less responsive to phosphorus fertilizers than those grown on other soils. This difference has been explained by various hypotheses, notably high fixation of fertilizer phosphorus and poor prediction of soil-available phosphorus by the Olsen test. As yet no hypothesis has been unanimously accepted. Part of the difficulty lies in the fact that much of the information is scattered. By bringing together scientists who have actually studied some aspect of phosphorus in Vertisols, this workshop aimed to develop a better understanding of past work and future research needs.

Note on Use of Elemental Phosphorus

Phosphorus applied as P_20_5 has been converted to elemental P throughout this report.

Introduction

Inaugural Address

I.P. Abrol

Deputy Director General (Soils and Agronomy), Indian Council of Agricultural Research, New Delhi

I am happy to be with your group for two reasons. One, I will have an opportunity to acquaint myself with current research efforts on the important subject you are discussing; and two, I consider the holding of this meeting an important step towards the goal of generating site-specific technologies for improving India's agricultural productivity. It is my pleasure to be associated with your efforts.

Both agriculturally and ecologically, Vertisols are important. According to estimates by the National Bureau of Soil Survey and Land Use Planning, India has about 72 million ha of true Vertisols and related black soils constituting nearly 22% of the country's geographical area. Vertisols are concentrated in the states of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, and Karnataka, which account for roughly 36, 23, 12, 10 and 9% respectively of India's total area under Vertisols. Nearly 84% of Maharashtra, 44% of Gujarat, and 38% of Madhya Pradesh are occupied by these soils.

Vertisols and related soils are subject to a wide range of climatic conditions, annual rainfall ranging from 500 mm to 1500 mm. Their depth varies from less than 50 cm (shallow) in about 5 million ha, between 50 and 100 cm (medium) in about 44.8 million ha, to more than 100 cm (deep) in 17.8 million ha. The soils have a high clay content (30 to 70%) and high water-holding capacity. Runoff can be high—40% and more depending on rainfall volume and intensity, vegetation cover, and soil slope. Vertisols are highly prone to erosion, soil loss having been estimated at 6 to 80 t ha^{-1} a^{-1} under present agricultural practices.

At present, India's cropped area under Vertisols is about 38 million ha, or nearly 27% of the country's total cropped area. The future holds very little scope for expanding the total cropped area, including that of Vertisols. Instead, efforts are needed to return presently cultivated soils with ecological constraints to permanent vegetation, using grassland and forestry. This is particularly true for shallow, erosion-prone Vertisols where productivity is fast deteriorating.

Of the area under Vertisols, 5.86 million ha or about 15% are irrigated, compared to a figure of 30% for the country's cropped area as a whole. Since the mid-1960s increases in India's overall production of food grains have largely come about through increased productivity and increased cropping intensity in irrigated areas, following the introduction of high-yielding varieties and increased fertilizer use, and the development of relevant infrastructures.

However, our experience with canal irrigation in the Vertisol regions is not one of unqualified success. In high-rainfall areas, the introduction of irrigation, as for instance in the Tawa project, has not had the desired impact on production. Waterlogging has adversely affected the yield of postrainy-season crops without increasing that of rainy-season crops. In the low-rainfall areas, when canal water is made available, it is used mainly for cash crops such as cotton and sugarcane. Overapplication of water, poor on-farm management, and inadequate drainage have resulted in large areas going out of production in the command area of several projects. In the Chambal command area in Rajasthan and Madhya Pradesh, production in 20% to 30% of the irrigated area has been sharply reduced. Waterlogging and salinity are already serious problems in the Jai Kwadi command area in Maharashtra, in the Malprabha area in Karnataka, and in several other projects. Future efforts in irrigated areas will need to concentrate on consolidating production gains through improved on-farm water management and the provision of drainage, rather than on expanding the area under irrigation.

A large proportion of Vertisols will continue to be farmed under rainfed conditions. Rainfed Vertisols contribute significantly to the production of coarse grains, cotton, oilseeds, and pulses. Black soil regions of Gujarat produce nearly 25% of India's groundnut crop. Madhya Pradesh contributes nearly 80% of the total soybean production. Together the black soils contribute nearly 79% of sorghum, 60% of cotton, 45% of pigeonpea, and 4 1 % of groundnut production in India. At present the productivity of these crops is very low. Improving productivity, particularly of oilseeds and pulses, is a major challenge of the coming decade.

In shallow black soils cropping is possible only during the rainy season, as soil moisture is insufficient in the postrainy season. In deep black soils with low and unreliable rainfall, monsoon fallowing is practised and a postrainy-season crop is grown on stored soil moisture, since this is less risky than attempting a crop during the rainy season.

In deep soils in medium- and high-rainfall areas, both rainy-season and postrainy-season crops can be grown. Deep black soils with reliable rainfall (> 750 mm) cover large portions of Andhra Pradesh, Karnataka, and Maharashtra. These areas have the widest gap between actual and potential crop yields of any rainfed farming region in the country. They hold substantial promise for increased production, provided farmers are supplied with appropriate technologies. I am aware of the significant advances made by national and ICRISAT scientists in the past decade in understanding how better to manage these soils. Efforts will need to be further strengthened in order to develop technologies that are more finely tuned to the needs of each crop in each area. Only then will a quantum leap in production from these areas be possible.

It is well known that in many irrigated areas of India, there has been a direct relationship between fertilizer consumption and crop production. At present, fertilizer use is extremely limited in the rainfed areas. However, there is now considerable evidence that economic responses to fertilizers can be obtained from rainfed crops grown on Vertisols. Indian work on this subject was recently summarized. Farmers hesitate to use fertilizers because of the risk involved, and because the required inputs are frequently unavailable or too expensive. While research efforts will therefore need to focus on the development of low-input technologies, these will have to be combined with management practices that ensure maximum efficiency in the use of inputs. This means understanding soil-water-nutrient-plant relationships better than we do at present.

We need to develop more reliable criteria for assessing fertilizer phosphorus (P) deficiency, better methods of placement, and application frequencies that are better matched to the cropping system, including intercropping practices, soil water storage, previous history, and so on. The group here, is well aware of the complex nature of the interactions governing the short- and long-term availability of P in Vertisols. The basic mechanisms controlling the solution phase in relation to soil physico-chemical properties need to be understood. Rhizosphere biology and how the rhizosphere affects nutrient dynamics is another research area that needs more attention. Broad recommendations on the use of fertilizer must, in time, give place to recommendations tailored to individual crops or production systems. I consider the meeting of this group most timely, and an important step in this direction. I am grateful for the opportunity to be with you.

Overview of Research on Phosphorus in Vertisols[1]

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Introduction

Vertisols are potentially some of the most productive soils under dryland farming in the semi-arid tropics (SAT), primarily because their high water-holding capacity sustains crops better during drought periods than other soils. However, in contrast to their high potential productivity, their actual productivity is usually low under traditional production systems. Achieving substantial increases in productivity requires the introduction of an improved management system which has four main components: improved cultivars and cropping systems, nutrient inputs, improved agronomic practices, and improved water management.

Nutrient inputs play a particularly important role in the improved management system. They are *as* important as improved cultivars, and much *more* important than improved agronomic practices and water management (El-Swaify et al. 1985). Of the nutrient deficiencies (nitrogen, phosphorus, and zinc) known to be important in Indian agriculture, phosphorus (P) is second in importance to nitrogen (N); its deficiency is widespread.

This paper discusses the present status and scope of research on the behavior of P in Vertisols in relation to the agronomic response of crops to P in these soils, and examines future research needs.

Phosphorus deficiency in India

The extent of P deficiency in India has been assessed in the past by extensive surveys, either of the available P status of the soils or of the responses of crops to added P. The most recent survey of available P status showed that, in the 372 districts covered by the survey, the soils in 45% of them were low in available P, 50% were medium, and only 5% were high (Tandon 1987).

Such surveys, though useful, have limited value because P responses vary not only with crop but also with soil type (Goswami and Sahrawat 1982; Venkateswarlu 1987). One of the hindrances to the full use of survey data, and to the study of associations between soil type and available P, has been the failure of researchers to fully characterize the soil at experimental and sampling sites.

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This uncertainty is further complicated in the case of Vertisols. The response of different crops to P varies even more on Vertisols than it does on other soils. It is usually greater at higher potential productivity where P becomes limiting (Venkateswarlu 1987). Additionally, when grown on Vertisols some leguminous crops (e.g., chickpea and pigeonpea) appear to be much less responsive to fertilizer P than are such cereals as sorghum and pearl millet (ICRISAT 1981). The responses of crops to added P in Vertisols are generally reported to be lower than those obtained in other soil types under similar agroclimatic conditions (Kanwar 1986; Probert et al. 1987). In his recent literature survey, Kanwar (1986) suggested that the response of crops to P fertilizer diminished with soil types in the following order : Alfisol > Entisol > Vertisol. This followed earlier suggestions by Arakeri (1979) that responses to P were much less likely on Vertisols than on Alfisols and Entisols.

Responses to Phosphorus in Vertisols

Although cereals such as sorghum and pearl millet respond almost universally to N fertilizer on Vertisols, responses to added P are unpredictable. In India, it is generally thought that if the 0.5 M $NaHCO_3$ extractable P is less than 5 mg kg^{-1} soil, a response to applied P is likely (Indian Society of Soil Science 1979). However, recent research at ICRISAT Center has shown that these critical limits are unlikely to hold true for grain sorghum grown on Vertisols, which responded little to applied P unless the level of 0.5 M $NaHCO_3$ extractable P was less than 2.5 mg kg^{-1} soil. In contrast, a substantial response to added P was obtained on nearby Alfisols when the Olsen's P was less than 5 mg kg^{-1} soil (ICRISAT 1985).

The apparent lack of P responses on Vertisols has been attributed to their high fixation (adsorption) of added P, caused by their high clay content (Venkateswarlu 1987). It was implied that lack of response may reflect an inadequate amount of added P, and that Vertisols may require higher rates of fertilizer P than other soils. However, this hypothesis is not borne out by ICRISAT's (1985) results showing—from a Vertisol (Typic Chromostert) low in Olsen's P (2.5 mg kg^{-1})—a high yield of sorghum grain (5 t ha^{-1}), high P uptake (15 kg P ha^{-1}), yet barely detectable response to P applied at rates of up to 40 kg P ha^{-1}.

These results show clearly that soil P in Vertisols at ICRISAT Center is more freely available to crops than is indicated by the soil test widely used in India (Olsen). They also indicate the need to reexamine the critical limits of extractable P in Vertisols for different crops.

However, the results were obtained on just one soil type, the benchmark Kasireddipally series (Typic Chromustert). One of the purposes of this meeting is to determine whether similar results have been obtained on other Vertisols in India.

Behavior of Phosphorus in Vertisols

There have been very few studies on the behavior of P in Vertisols. P adsorption and desorption are the key processes governing the availability of P to crops. The relative sorption capacity of different clay minerals, such as kaolinite, illite, montmorillonite, and others, have been characterized fairly satisfactorily (Indian Society of Soil Science 1979). Most of the soil clay in the Indian Vertisols is of the swelling 2:1 lattice type; the dominant clay mineral is usually montmorillonite, which does not adsorb appreciable amounts of P (El-Swaify et al. 1985). The only other soil constituents that could adsorb P are $CaC0_3$ and the oxides of iron and aluminium. However, little attention has been given to these sesquioxides, and the effective sorption by $CaC0_3$ is not well understood. It has been found that P sorption is not always closely related to $CaC0_3$ content (Goswami and Sahrawat 1982); perhaps the critical factor is the quality of $CaC0_3$: that is, its fineness of subdivision and crystal structure.

Recent work at ICRISAT suggested that, contrary to the existing belief, Vertisols do not have high P adsorption capacity (Warren and Sahrawat, this workshop). Further, all the adsorbed P is easily exchangeable by ^{32}P and little P is adsorbed in a non-exchangeable form. The benchmark Vertisol and Alfisol tested at ICRISAT Center differed only a little in their P adsorption behavior, except that high adsorption occurred in the B horizon of the Alfisol, whereas adsorption in the Vertisol changed little with depth. The amount of fertilizer P to be added to obtain 0.2 mg L^{-1} equilibrium P concentration after incubation for 6 days at 25° C varied between 28 and 38 mg P k g^{-1} soil to a soil depth of 160 cm. The surface (0-15 cm) soil required only 30 mg P kg^{-1} (ICRISAT 1985). Such results clearly indicate that P adsorption is not a major problem in the Vertisols studied.

However, there is an urgent need to expand studies of this kind to include Vertisols of different pedogenic histories. Together with agronomic research on the P responses of crops, such studies would greatly assist in developing a sound P management strategy for Vertisols.

Chemical characterization of different forms of P in four benchmark Vertisols, with a range of extractable (0.5 M $NaHC0_3$) P levels, showed that these soils have similar amounts of the different forms of P to other Vertisols in India (Indian Society of Soil Science 1979). These results indicated, as expected, that Ca-P was the dominant form, followed by Fe-P, with very low amounts of Al-P. Interestingly, the levels of Fe-P in the Vertisols were similar to those found in the Alfisols (ICRISAT 1985).

Some Questions for this Workshop

To conclude my presentation, I would like to pose the following questions to my fellow participants in order to gauge our understanding of P behavior in the Vertisols of the different regions of India :

1. Do crops (both cereals and legumes) grown on Vertisols in your region respond to added P? If so, are their responses of similar magnitude to those obtained on other soils?
2. What are the critical P levels for different crops grown on Vertisols?
3. Do the P responses of crops on Vertisols differ ? If so, can this be attributed to differences in pedogenic histories?

4. Do Vertisols fix (adsorb) appreciable amounts of P? Is there enough research evidence to support this view or is it merely a hypothesis?

Several more questions could be added to this list, but those I have given are enough to convey the problems currently facing research. I hope these questions will be answered, at least in part, during this meeting, using our present knowledge of P in Vertisols. Where they cannot be, we will need to define the unresolved issues more closely so as to identify future research needs.

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Summaries of Presented Papers

Session I. Soil Chemistry

Isotopically Exchangeable P in an ICRISAT Vertisol

G.P. Warren and K.L. Sahrawat

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The phosphate adsorption properties of Vertisols have rarely been measured, although adsorption isotherms provide a means of soil characterization that can be related to fertilizer requirement and other soil properties. Phosphate adsorption isotherms were therefore determined for a Vertisol (Kasireddipalle series) and an Alfisol (Patancheru series) from ICRISAT Center.

Eleven rates of added P (including a zero) were chosen so that final P concentrations in supernatant solutions ranged from 0 to approximately 2 mg L^{-1}. For each rate of P, samples of soil were shaken gently with KH_2P0_4 solution in 0.01 M $CaCl_2$ for 22 h at 30 °C. Carrier-free labelled P, as ^{32}P in orthophosphate, was then added in a small volume. Shaking of the suspension continued for another 22 h, then soil and solution were separated by centrifugation and filtration. Total P and radioactive P in solution were measured. Isotopically exchangeable P was calculated using the dilution principle. Non-exchangeable P, i.e. P taken up during the first equilibration period but not exchanging with labelled P during the second period, was calculated using the following relationship:

$$P_a = \Delta P_l + \Delta P_e + \Delta P_n$$

Subscript a = added,

1 = liquid (i.e. remaining dissolved),

e = exchangeable and

n = non-exchangeable P.

Previous work on acid soils of the humid tropics showed that much P was adsorbed non-exchangeably, and was therefore unlikely to be available to plants. In both the Alfisol and the Vertisol in the current experiment, all adsorbed P remained exchangeable, so none of the added P fraction was very strongly sorbed. This result shows that, for this Vertisol at least and possibly for others, added P is not fixed permanently, but could all be recovered, given a sink for desorbed P.

Fitted isotherms for total adsorbed P in a range of tropical soils were examined, and the adsorption capacity of the Vertisol was found to be modest by comparison with the Oxisols and Inceptisols investigated. However, the sorption capacity (at 1 mg P L^{-1}) of the Vertisol was about twice that of the Alfisol, so the Vertisol would require larger additions of fertilizer P to raise dissolved P to the same concentration.

Exchangeable P remaining after some desorption was examined. After decantation of the supernatant, labelled soil was redispersed in a $CaCl_2$ solution, shaken for another 22 hours, and again separated from the supernatant. Desorption was then repeated. In both soils, after the second desorption, exchangeable P exceeded total adsorbed P, suggesting that labelled P was becoming equilibrated with a fraction of native soil P.

These results are consistent with the hypothesis that fertilizer P is not permanently fixed by this Vertisol. As in the Alfisol, it remains available for desorption, but there is a larger capacity for sorption. It is impossible, on the basis of a single experiment, to draw any conclusions regarding critical limits for Olsen's extractable P. Nevertheless, these data suggest that, for the same amount of chemically extractable P, there would be more plant-available P in the Vertisol than in the Alfisol.

Soil Phosphorus in some Vertisols and Crop Responses to Phosphorus in these Soils

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Phosphorus (P), next to nitrogen, is regarded as the most limiting nutrient element in Vertisols. However, analysis of 100 surface samples collected from each of six soil series—three Chromusterts: Sarol (from Madhya Pradesh), Shendvada (from Maharashtra), and Noyyal (from Tamil Nadu); and three Vertic Ustochrepts: Kamaliakheri (from Madhya Pradesh), Pithvajal (from Gujarat), and Pemberty (from Andhra Pradesh)—showed that only Pemberty was low, while Noyyal and Kamliakheri were medium, and Sarol, Pithvajal and Shendvada were high in Olsen's extractable P. The analysis also showed that Oisen's extractable P varies widely in these soils, both between and within soil series.

Calcium phosphate is most abundant in these soils, although Fe-P and reductant-soluble P are also present in substantial amounts.

The desorption of P in these soils differs, indicating differential rates of P supply to crops at similar amounts of extractable P. Hence, P desorption rates should be taken into consideration when the critical limits of P availability for crop growth are defined.

Adsorption studies indicated that the curve of added P plotted against equilibrium concentration is hyperbolic, such that a proportionately larger amount of added P is adsorbed with small increments. P adsorption in these soils essentially follows a linear Langmuir adsorption pattern. Two of the six soils showed two distinct patterns of P adsorption, which may be resolved into two separate Langmuir adsorption isotherms. The widely differing adsorption of P in these soils suggests that, at identical amounts of extractable P, different amounts of fertilizer P may have to be added to obtain the same crop response. More work is needed to characterize the properties which distinguish different Vertisols in terms of their adsorption and desorption capacities.

Crop responses to P vary considerably with different soils and crops. Field trials conducted in Vertisols on farmers' fields showed that rice grown in Maharashtra and Madhya Pradesh, sorghum in Madhya Pradesh, Maharashtra, Andhra Pradesh and Karnataka, cotton in Maharashtra, pigeonpea in Andhra Pradesh and Gujarat, groundnut in Gujarat and Maharashtra, soybean in Madhya Pradesh and linseed in Maharashtra all showed very good responses to added P. However, pearl millet in Gujarat and Maharashtra, cotton in Gujarat, black gram and mung bean in Maharashtra and Karnataka and sesame in Andhra Pradesh did not show much response. Matching data on P availability in these soils would have greatly increased the value of this information.

Session II. Soil Tests and Crop Responses

Calibration of Phosphorus Soil Tests for Targeted Yields of Crops Grown on Indian Vertisols

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Soil testing is essential for increasing fertilizer use efficiency. The soil-testing service in India started in 1956/57. Today, there are more than 450 soil-testing laboratories in the country, with an annual capacity to analyze about 6 million samples. The All India Coordinated Soil Test Crop Response Correlation Project provides the necessary research backing for this advisory service. The project has developed the concept of soil-test-based fertilizer application for targeted yields (FATY) of crops. The FATY approach ensures balanced nutrition. It takes into account the relationships not only between soil nutrients and fertilizers but also among nutrients themselves. This paper discusses soil test calibrations for phosphorus (P) together with those for nitrogen (N) and potassium (K).

The relationship between grain yield and nutrient uptake is linear within certain conditions. Thus, to obtain a specific yield, a specific quantity of nutrients must be taken up by the crop. Once this nutrient requirement for a given yield is known, the fertilizer needed can be estimated taking into account the percentage contribution of soil-available nutrients as well as that of the fertilizers themselves. The required fertilizer dose of a given nutrient can be calculated from the following equation:

$$Fd = \frac{NR}{CF} \times 100\,T - \frac{CS}{CF} \times STV$$

where Fd = fertilizer dose, kg ha^{-1}; NR = nutrient amount required to produce unit quantity of economic produce, kg kg^{-1}; CS = percentage contribution from soil-available nutrient to total uptake; CF = percentage contribution from applied fertilizer nutrient to total uptake; T = yield target, kg ha^{-1}; and STV = soil test value, kg ha^{-1}.

Crops differ in their requirement of P to produce a unit quantity of grain. Oilseeds need more, pulses less, and cereals less still. The average requirements are 0.98 kg P 100 kg^{-1} seed for oilseed crops (mustard, safflower, linseed, niger, soybean, and groundnut), 0.70 kg P 100 kg^{-1} seed for pulses (pigeonpea, chickpea, black gram, and mung bean) and 0.44 kg P 100 kg^{-1} grain for cereals (rice, wheat, sorghum, pearl millet, and maize). Among other crops, the requirements are 1.85 kg 100 kg^{-1} of banana, 1.50 kg 100 kg^{-1} of dry chilies and 0.07 kg 100 kg^{-1} of sugarcane. The nutrient requirement is a crop characteristic and does not depend on the soil type.

Crop species and varieties also differ significantly in their ability to use both available and applied P. Except for long-duration crops, the percentage contribution of P from soil was around 50%, the average values being 48.2% for cereals, 50.9% for pulses, and 50.0% for oilseeds. For long-duration crops it was 193.5% for sugarcane, 181.0% for banana and 90.0% for cotton. The P contribution from fertilizer was around 25% for cereals, pulses, and oilseed crops. However, it was more in the case of sugarcane (71.8%), followed by cotton (44.8%), chilies (28.3%) and banana (9.0%). Fixation of added P in soil, which may reach levels as high as 81%, is one of the main criteria limiting more efficient use of fertilizer P.

Olsen's method has been suitable for estimating the available P status of the black soils of India. This method was calibrated to provide fertilizer prescriptions for targeted yields of a large number of crops, including rice, sorghum, pearl millet, maize, wheat, pigeonpea, chickpea, mung bean, black gram, soybean, groundnut, mustard, linseed, safflower, niger seed, cotton, chilies, banana, and sugarcane grown in black soils at Coimbatore (Tamil Nadu), Nandyal, Hyderabad, Rudrur, Amaravati and Guntur (Andhra Pradesh), Rahuri and Yawal (Maharashtra), Jabalpur, Indore, Powerkheda, Chindwara, Sehore and Raipur (Madhya Pradesh). P application rates based on soil testing for targeted crop yields proved distinctly superior to general recommendations as they resulted in a saving of not less than 20%.

The residual effect of P, the differential availability of P during cold and warm seasons, the ability of different crops to use soil and fertilizer nutrients, and the different P fractions are some of the important criteria in the selection of suitable crops and P management practices in crop rotations. A basis for calculating P fertilizer schedules for whole cropping sequences has been developed, by predicting postharvest soil-test values. The latter were predicted from initial soil P levels, crop yields obtained, and quantities of fertilizer added.

Soil Phosphorus Fractions in Vertisols as Influenced by Fertility Gradients and Yield Targets for Mung Bean-Sorghum Sequential Crops

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Experiments were separately conducted at Rahuri on mung bean (cv S8) and postrainy-season sorghum (cv CSH 8R) on a Vertisol. The experiments used a fertility gradient approach, and fertilizer adjustment equations were calculated for subsequent use in a follow-up mung bean-sorghum sequence trial.

The soil belonged to the Otur series (Typic Chromustert) and its properties were: pH, 8.2; organic carbon, 0.52%; Olsen's P, 12.4 mg kg^{-1} soil; phosphorus (P) fixation capacity, 152 kg ha^{-1}; texture, silty clay.

Fertilizer applications for the standard field experiments were (N:P:K): 0:0:0, 50:22:42, 100:43:83, 200:87:167 and 400:174:333 kg ha^{-1}. In the follow-up trial, the yield targets for mung bean were 600, 900 and 1200 kg ha^{-1}, with fallow and control for comparison. Crop yields were recorded and P uptakes determined. After harvest of mung bean, soil samples were collected and analyzed for available N, P, and K. Each harvested plot was then divided into four subplots and postrainy-season sorghum was grown with control, and yield targets of 4000, 5000, and 6000 kg ha^{-1}. Sorghum yields and P uptake were recorded.

Soil samples collected as part of the standard field experiments, before sowing mung bean and sorghum, were analyzed for different fractions of P, and coefficients of correlation and regression with the yield and P uptake of the respective crop were determined.

P fractionation studies showed that more than 95% of total P was present in inorganic forms, of which 5 to 12% was present in active P fractions (Al-P , Fe-P, and saloid P), while Ca-P was the major form (55%) of inorganic P. Except for residual P and occluded P, all fractions of P were significantly correlated with mung bean and sorghum yields, P uptake and Olsen's P. The partial regression coefficients showed that A1 -P made a significant positive contribution towards mung bean yield, P uptake and Olsen's P. Saloid P and Ca-P contributed significantly to sorghum yield, while saloid P contributed significantly to both P uptake of sorghum and Olsen's P. The Al-P fraction was found to be highly correlated with Olsen's P.

Problems of Phosphorus Availability in Vertisols of the Semi-Arid Region

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Vertisols are often deficient both in available phosphorus (P) and in nitrogen (N). Experiments at the Bellary Research Centre showed that the combined use of both nutrients increased crop yields in general and improved the efficiency with which each nutrient was used. In the absence of sufficient P, response to applied N could not be obtained. Maize yields in particular (10 years'data) improved from 1.54 t ha^{-1} with N alone to 4.43 t ha^{-1} with P and N.

The availability of applied P varied with the type and amount of clay mineral in the soil. The soils tested ranged from 0.22 to 15.45 mg P kg^{-1} soil, as determined by Olsen's extractant. The percentage availability of added P was [100-(clay %)] for black soils, whereas it was [100-2(clay %)] for red and alluvial soils. The reliability of this relationship was corroborated by measurements obtained from an irrigated black paddy soil near Nandyal. This relationship helps when soil P has to be adjusted to a predetermined level.

Other aspects such as response to applied P, together with its residual effects, were also studied at Bellary under rainfed and limited irrigation conditions with sorghum as test crop. Under rainfed conditions, response was found to be associated with the initial level of P available in the soil. Under restricted rainfall conditions, when available P was less than 2.15 mg P kg^{-1} soil, yields did not continue to rise in response to applied P beyond a level of 4.3 mg P kg^{-1} soil. However, in a wet year, when sufficient rainfall continued till flowering, responses were observed up to a level of 13 mg P kg^{-1} soil. The source of P was not found to have a significant effect on P utilization and crop response.

The application of P to a sorghum crop in a pearl millet-sorghum rotation under limited irrigation showed that residual effects of P persisted only for about 2 years, with sorghum benefiting more than pearl millet.

Evaluation of Soil Test Methods for Phosphorus in the Vertisols of Maharashtra for Wheat

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A pot experiment was conducted on 16 Vertisols and Vertic Inceptisols with wheat (cv HD 2189) as a test crop to identify a suitable extractant for determining available soil phosphorus (P) and critical soil P levels. Each pot contained 5 kg of soil in which four wheat plants were grown. Fertilizer P was applied at four rates equivalent to 0, 21.7, 43.5 and 65.2 kg ha^{-1}. Nitrogen and potassium were applied at rates equivalent to 200 and 100 kg ha^{-1} respectively to all pots. Soil properties were: pH, 8.2-8.7; organic carbon, 0.34-0.78%; calcium carbonate equivalent, 5.0-8.8%; Olsen's P, 8.5-19.5 mg P kg^{-1} soil; and texture, sandy clay loam to clay.

Six different extractants were used: Olsen (0.5 M $NaHCO_3$, pH 8.5), Soltanpour (1M NH_4HCO_3 + 0.005 M DTPA, pH 7.6), Morgan (10% NaOAc, pH 4.8), Bray (0.03 N NH_4F + 0.025 N HC1), Truog (0.002 N H_2SO_4, pH 3) and Nelson (0.05 N HCl + 0.025 N H_2SO_4). The Truog method extracted the highest quantity of P from the soils, due to its use of sulfuric acid, which dissolves more Ca-P than other extractants. The lowest quantity of P was extracted by Nelson's extractant, which dissolves Fe-P. The extracting power of different methods was in the following order: Truog P > Olsen P > Morgan P > Bray P > Soltanpour P > Nelson P.

The percentage grain yield of wheat [(yield without P/yield with P) x 100] varied from 19.40 to 71.8. The soils containing high P recorded higher percentage grain and straw yields, indicating more efficient utilization of P in low-P soils than in medium- and high-P soils. Percentage P uptake [(P uptake without added P/P uptake with added P) x 100] in wheat grain varied from 13.3 to 67.3% and in wheat straw from 13.0 to 66.5%, increasing with the available P content of soils.

The highest correlation coefficients were observed between Olsen's P and percentage grain and percentage straw yields of wheat (r = 0.91 and 0.89 respectively), and between Olsen's P and percentage P uptake by wheat grain and straw (r = 0.89 and 0.91). These results indicate that Olsen's method is the best for predicting the response of wheat to applied P on Vertisols and associated soils; the critical limit of soil P for wheat was found to be 14 mg P kg^{-1} soil.

Crop Responses to Phosphorus in Vertisols of Central India under Rainfed Conditions

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Vertisols and associated soils, also known as black soils and black cotton soils, cover about 40% of the total geographical area (44.3 million ha) of the state of Madhya Pradesh. Deep (>100 cm), medium (30 to 100 cm), and shallow « 30 cm) black soils occupy 3.5, 37.0 and 7.1% respectively of the total geographical area of the state. Rainfed farming is practised on the major portion of these soils.

Available phosphorus (P) content in these soils is usually low to medium; only in very few is it high. Wide variations in crop responses to P application have been observed, particularly under rainfed conditions. The limited crop response to applied

P is attributable to the high P-fixation capacity (about 69.5 kg P ha^{-1}), the deficiency of other elements, and limiting soil moisture. The development of shrinkage cracks, that damage plant roots, checking their growth and limiting the efficiency with which they extract nutrients and moisture, may also affect crop growth.

Studies have been carried out at various locations on Vertisols and associated soils to evaluate the response of various crops to applied P. Available P (determined by the Olsen method) at the locations used ranged from 8 to 14 kg P ha^{-1}. The response of rainfed hybrid maize and sorghum was observed to be around 7.1 and 17.5 kg grain kg^{-1} of P applied through single superphosphate at the rates of 43.5 kg P ha^{-1} for maize and 21.7 kg P ha^{-1} for sorghum. Although the grain yield of sorghum was increased by 15.7, 23.4 and 33.6% over the control by the application of 43.5, 65.2, and 87 kg P ha^{-1} respectively, the response was only about 9.9 kg grain kg^{-1} of applied P.

In another study, higher doses of P, ranging from 47.8 to 143.5 kg P ha^{-1}, resulted in 18 to 25% increases in sorghum yield, but the response decreased from 12.7 to 5.8 kg grain kg^{-1} of P with the increasing rate of fertilizer application.

The response of wheat, chickpea and safflower under receding soil moisture conditions at 17.4 kg P ha^{-1} fertilizer application was only 5.8, 7.4 and 3.0 kg grain kg^{-1} of applied P. The very low response of these postrainy-season crops to applied P was probably due to inadequate soil moisture.

Good responses of rainy-season oilseeds and pulses were observed, however. Soybean seed yield responses of 16.6 and 12.7 kg kg^{-1} of applied P were obtained at added P levels of 8.7 and 17.4 kg P ha^{-1} applied as fertilizer in Vertisols at Indore. A higher dose of P (34.8 kg ha^{-1}) gave an additional yield increase of 8.3% compared with that at 17.4 kg P ha^{-1}, but the response was only 9.7 kg seed kg^{-1} of P applied.

Application of farmyard manure (FYM) alone at the rate of 4 t ha^{-1} enhanced sorghum yield by 27% and recovery of P from soil by 141% over the control. Combined use of FYM at the rates of 3.5 to 41 ha^{-1} together with 47.8 and 21.7 kg P ha^{-1} as fertilizer resulted in about 12% and 27% more sorghum grain and 35% and 74% more uptake of P from the soil, compared with the same levels of P applied as fertilizer but without FYM. Increasing levels of P fertilizer application in the range 0-34.8 kg P ha^{-1} increased the land-equivalent ratio (land-use efficiency) from 1.38 in the control to 1.63 at 34.8 kg P ha^{-1}. The total productivity of a soybean/pigeonpea intercropping system rose by 36.4%.

Applying P as fertilizer at the rate of 21.8 kg P ha^{-1} improved the water use efficiency of rainfed sorghum by 13.6%, which was further enhanced to 45% with combined use of FYM at the rate of 41 ha^{-1}. Application of P at a rate of 17.4 kg ha^{-1} increased the water use efficiency by 5 to 20% in soybean, 10% in chickpea and 21% in safflower under rainfed conditions.

Crop Responses to Applied Phosphorus in Vertisols

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Pot culture studies were carried out to investigate the reasons for lack of response to applied phosphorus (P) in six black soils (Vertisols) that were representative of the semi-arid tropical regions of India and had low available P (2.8 to 7.0 mg P kg^{-1} soil). Studies with pearl millet and sorghum in two different seasons suggested that these soils did in fact need additional P. From regression analysis, the optimum doses were found to be above 30 mg P kg^{-1} soil. For most soils, the responses were linear in the range of 0 to 43 mg applied P kg^{-1} soil.

The requirement of high doses of P for optimum yields was attributed to the high P fixation capacities of these soils, ranging from 43 to 75% of the amount of P applied. The effect of single superphosphate and diammonium phosphate as sources of P was not consistent over crops or soils. Two consecutive applications of large quantities of P did not result in any buildup of soil-available P.

Critical Level of Phosphorus in Vertisols in Relation to Crop Responses

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Vertisols and associated soil groups in India extend over 70 million ha. These soils have a high productive potential which is seldom met at present. One of the problems preventing their optimal use is phosphorus (P) deficiency.

To evaluate the long-term effect of continuous use of various fertilizers and/or manures on soil productivity and health, field experiments were designed during 1970/71 at 11 research stations representing the major soil groups of India, including Vertisols. The experiments, which formed part of a project on long-term fertilizer use organized by the Indian Council of Agricultural Research (ICAR), are still in progress. The experimental details are documented in the project's Research Bulletin No. 1. Critical soil levels of P for given crops were determined following the Cate-Nelson approach.

Quadratic response functions were fitted between yield and available soil P (Olsen's extractable P) for soybean, wheat, and maize fodder crops in a Chromustert at Jabalpur, and finger millet, maize, and cowpea in a Vertic Ustocrept at Coimbatore during 1985/86. The quadratic functions were as follows:

Soybean: $y = 1058 + 75.01\,P - 0.632\,P^2$ ($R^2 = 0.80^{**}$)
Wheat: $y = 142 + 167.45\,P - 1.740\,P^2$ ($R^2 = 0.69^{**}$)
Maize fodder: $y = 548 + 64.48\,P - 0.324\,P^2$ ($R^2 = 0.71^{**}$)
Finger millet: $y = -1281 + 728.57\,P - 24.656\,P^2$ ($R^2 = 0.82^{**}$)
Maize: $y = -468 + 543.10\,P - 15.905\,P^2$ ($R^2 = 0.88^{**}$)
Cowpea: $y = -453 + 174.60\,P - 7.642\,P^2$ ($R^2 = 0.81^{**}$)

Where y = grain or fodder yield in kg ha^{-1}
P = available P (Olsen's) in kg ha^{-1}

Yield responses were quite high in both the Vertic Ustocrept and the Chromustert, but higher in the former than in the latter. In the Chromustert, the highest grain yield response was noted for wheat, followed by soybean and maize fodder. The highest grain yield response in the Vertic Ustocrept was noted for finger millet, followed by maize and cowpea.

The increase in grain or fodder yield per kg increase in available P was about 75 kg for soybean, 167 kg for wheat, and 64 kg for maize fodder in the Chromustert at Jabalpur, while it was 729 kg for finger millet, 543 kg for maize, and 175 kg for cowpea in the Vertic Ustocrept at Coimbatore. Thus the highest response to P application was noted in the latter soil.

The critical soil levels of P were 11 mg kg^{-1} for soybean and 15 mg kg^{-1} for wheat on the Chromustert, and 6.5 mg kg^{-1} for finger millet, 6.5 mg kg^{-1} for maize, and 6.0 mg kg^{-1} soil for cowpea on the Vertic Ustocrept. Critical P levels thus vary between crops. The P release behavior also seems to vary, even within a taxonomic soil class.

Scope and Limitations of Phosphorus Fertilizer Use in Vertisols and Associated Soils in the Semi-Arid Tropics of India

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Vertisols and associated soils occur in the arid, semi-arid, and subhumid zones of India. Our dryland research work is spread over 22 experimental stations, including Akola, Bellary, Bijapur, Indore, Kovilpatti, Rajkot, Rewa, Solapur, and Udaipur (now Arjia), where Vertisols and associated soils are represented. Most of these stations grow crops during the southwest monsoon (Jun-Sep), except at Bellary and Kovilpatti, where crops are raised during the northeast monsoon (Oct-Jan).

The soils range from shallow to deep and have a high clay content (over 30%). These soils are slightly alkaline (pH around 8) and low to medium in available phosphorus

(P), as determined by Olsen's method (ranging from 0.45 mg kg^{-1} soil at Rajkot to 6.50 mg kg^{-1} soil at Akola).

Experiments were conducted at different stations to determine the response of crops to P application. The results are inconsistent. No definite trend was observed, even when the P status of soils was low. Main rainy-season (Jun-Sep) crops tended to show some response to applied P, but more often than not the results were not statistically significant. Postrainy-season crops seldom responded at all to applied P. Application of P during the rainy season helped to build up soil P status, but this was not reflected in increased crop yields of postrainy-season crops grown on residual soil moisture. Different sources of P had little effect on crop yields.

The reason for this lack of responses was investigated at CRIDA headquarters. It was observed that the P fixation capacity of the soils ranged from 43 to 75%. The dose of applied P was adjusted accordingly. This approach showed promise under both controlled and field conditions. Addition of farmyard manure (FYM) together with P also helped to obtain higher responses.

From the studies made so far, it appears that we have yet to understand the P dynamics of Vertisols and associated soils. Until we do, the scope for effective P fertilizer use in dryland Vertisols will doubtless be limited.

Studies of P in Vertisols should be directed towards answering the following questions :

- What are the critical limits for available P in soils with different moisture regimes?
- What is the minimum amount of P required for different levels of biological productivity?
- Can we identify a more reliable extractant than Olsen's for determining available P in soils in dryland situations?
- What P management systems are needed to obtain optimum yields in different crops and cropping systems?
- What should be the long-term strategy for P fertilizer use to ensure sustainable production and productivity in dryland situations?

Session III. Non-legume Agronomy

Response to Phosphate Application in Sorghum-Wheat Cropping Sequences on Vertisols

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Phosphorus (P) in Vertisols has until recently been seen as unpredictable in its behavior. The response of traditional crop varieties to phosphate on these soils has been very erratic and often very low, even when P availability also appeared low. With the introduction of high-yielding hybrids and increased cropping intensity, the picture has changed: responses have become somewhat more predictable. The need for high yields has increased phosphate requirements.

Studies on responses to phosphate application were conducted at Mahatma Phule Agricultural University between 1977 and 1981 on a Vertisol with medium P availability (5.75 mg P kg^{-1} soil), in which sorghum-wheat sequences were grown on a fixed site. Response to phosphate was noted in sorghum, which yielded about 6.5 t ha^{-1} under irrigated conditions. The following wheat crop showed a marked response (cumulative) to the application of phosphate, which was thereby indicated as a critical input. The subsequent crops (both sorghum and wheat) showed practically no response to nitrogen (N), even at 120 kg N ha^{-1}, without an application of phosphate. With the application of 17.4 kg P ha^{-1}, response to N was substantial. However, increasing the P application to 34.8 kg P ha^{-1} did not show any advantage over 17.4 kg P ha^{-1}.

Phosphorus Management in Cropping Systems on Vertic Soils

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Experiments were conducted on farmers' fields in Koheda village (Andhra Pradesh) during 1978-81 to study the response of safflower to applied fertilizer nitrogen (N) and phosphorus (P) in sole and sequential cropping systems.

The soils were alkaline (pH about 8.2), low to medium in available P (Olsen's P being 3.6-7.9 mg kg^{-1} soil), and had a P-fixation capacity of 46 to 53% of the amount applied. The soil depth varied from 85 to 105 cm. The soil contained 39% coarse sand, 4% fine sand, 11% silt and 46% clay.

Safflower following rainy-season fallowing did not respond to P application, even when the available P content was 5 mg kg^{-1} soil or less and the moisture content of the soil was relatively high. However, safflower responded to applied P and had a higher P uptake when it followed sorghum. The lack of response in the fallow-safflower system is attributed to the level of soil P, which was adequate to support a safflower yield of about 1.1 t ha^{-1}. Depletion of the P reserve by sorghum (about 5 mg kg^{-1} soil) grown during the rainy season was offset by P application, which helped to increase the yield of safflower in the sorghum-safflower cropping system.

Deep placement (10-15 cm) of N and P increased safflower seed yield (by 56%) and P uptake (by 91%) over the yields (750 kg ha^{-1}) when fertilizers were placed in the seeding furrows.

It is evident from these studies that, at this site, a P application to safflower is needed, particularly when it follows sorghum. Deep placement of P (10-15 cm) gives a better return than the conventional shallow placement.

Estimation of Available Phosphorus in Vertisols in View of Root Effects on Rhizosphere Soil

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Olsen's bicarbonate extraction method is the generally recommended method in India for evaluating phosphorus (P) availability to crops in calcareous and alkaline soils. In the Vertisols at ICRISAT Center, chickpea and pigeonpea usually do not respond to P fertilizer application even though P availability is low according to Olsen's method (<5 mg P kg^{-1} soil). Moreover, in an irrigated field experiment, using a maize hybrid well supplied with nitrogen (N) and potassium (K) fertilizers, we have observed P-deficiency symptoms on an Alfisol but not on a Vertisol, even though the Olsen-extractable P was 9.0 mg kg^{-1} soil for the Alfisol while the Vertisol had only 6.2 mg P kg^{-1}.

In order to compare the P uptake of different crops grown on Alfisols and Vertisols at ICRISAT Center, we conducted a pot experiment in which soybean, pearl millet, sorghum, chickpea, and pigeonpea were each grown in 16 Alfisol samples and 19 Vertisol samples. The Vertisol samples were taken from a Vertisol at ICRISAT Center, at a depth of 5 to 15 cm. The Olsen P content ranged from 0.5 to 30.9 mg kg^{-1} soil. Essential nutrients other than P were applied and P uptake was measured. A regression of P uptake against the Olsen's P values indicated that P availability in the Vertisol as compared to the Alfisol was underestimated by the Olsen extraction method.

Vertisols have a major portion of their inorganic P in the form of Ca-P, and P can be solubilized by acidic extraction methods, such as the Truog, Bray No. 2, and Ca-lactate methods, or in the presence of chelating agents (as in Olsen's Ethylene Diamine Tetra-acetic Acid method). The major fraction of inorganic P in Alfisols is Fe-P.

Rhizosphere soil collected from each of the Vertisol pots had pH values 1.0 to 1.5 units lower than the bulk soil pH of 8.7. The rhizoplane pH, measured by an agar plate method, ranged from 3.8 to 5.4. The lower pH of the rhizoplane was associated with higher levels of available P adjacent to the root as compared with bulk soil in Vertisols. Solution P levels in Alfisols are less affected by the soil pH level than in Vertisols.

Using the agar plate technique, it was shown that chickpea roots exude organic acids, mainly as malic and citric acid, to a greater extent than do the roots of soybean, pigeonpea, groundnut, sorghum, or pearl millet. For this reason, there were better correlations between Truog P and P uptake for chickpea than for the other crops. The Truog method extracted five times as much P from the Vertisol as it did from the Alfisol, even though Olsen's method predicted the Alfisol to have more available P than the Vertisol.

Utilization of Mussoorie Rock Phosphate by Legume Sequences

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A pot culture experiment was conducted to determine the phosphorus (P) utilization from Mussoorie Rock Phosphate (MRP) by legume sequences involving five rainy-season crops, mung bean, black gram, horse gram, soybean, and groundnut, followed by two postrainy-season crops, chickpea and pea. In addition to a control(Po), single superphosphate (SSP) was used as a P source for comparison with MRP on an equal total P basis (11 mg kg^{-1} soil). The P sources were applied only to rainy-season legumes at sowing, and residual effects on postrainy-season legumes were studied. A lateritic soil (Ultisol, pH 5.7) and a calcareous medium black soil (Vertisol, pH 8.5) from Kolhapur district (Maharashtra) were used. Ten plants were grown in each pot for 50 days, after which they were harvested, dry matter(DM) was measured, and P uptake determined. Olsen's P in the soil of each pot was also determined after each harvest.

The lateritic soil was superior to the medium black soil in producing dry matter and promoting P uptake. For rainy-season legumes, SSP was a superior source of P to MRP, which was similar to the control in terms of DM production and P uptake. For postrainy-season legumes, however, the order was SSP > MRP > Po; that is, the rock phosphate was superior to the control. Among the rainy-season legumes, groundnut produced the most DM, followed by soybean, horse gram, mung bean, and black gram. The P uptake followed the same trend except that the values for soybean, horse gram, and mung bean were not significantly different from each other. Groundnut was superior to other legumes in using P from MRP in the lateritic as well as the medium black soil. For postrainy-season pea, application of MRP resulted in higher P uptake than the control on lateritic soil only. For chickpea, however, the soil x P source interaction was not significant for P uptake. Olsen's P values for both soils after the harvest of all legumes were in the order SSP > MRP > Po.

Response of Chickpea, Pigeonpea and Sorghum to Method of Phosphorus Application in a Vertisol

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The effect of either banding phosphorus (P) fertilizer at 5 cm or mixing it in the top 15 cm of soil was compared for chickpea (cv K 850), pigeonpea (cv C 11), and sorghum (cv CSH 5) in a Vertisol with low P availability (1.5 mg P kg^{-1} determined by Olsen's method) at ICRISAT Center. The P was applied as single superphosphate at a rate equivalent to 50 kg P ha^{-1}.

In the first season (postrainy season 1986/87), under irrigated conditions, mixing was more effective than banding in increasing total dry matter and grain yield of chickpea and pigeonpea over a control that did not receive fertilizer. However, the two application methods increased sorghum growth and yield to a similar extent. Without irrigation, all three crops showed virtually no response to P fertilizer application, clearly indicating that P fertilizer is only effective when soil moisture is adequate.

In the second season (for pigeonpea and sorghum, rainy season 1987, when the short-duration ICPL 87 was used instead of the medium-duration C 11; for chickpea, postrainy season 1987/88), the residual effects of different application methods were compared at the same site without irrigation. Mixing still resulted in a much higher grain yield than the control, and sorghum and chickpea yields were similar with mixing and banding. These results indicate that P fixation in this Vertisol does not seriously limit P availability for plant uptake.

In order to further investigate the effect of availability of P fertilizer in relation to placement depth and soil moisture, two banding depths (5 cm and 15 cm) were compared with the mixing treatment, for pigeonpea grown in the rainy season (1987) and chickpea in the postrainy season (1987/88). With irrigation, application by mixing resulted in highest grain yield for both crops. However, without irrigation, the deep banding treatment resulted in the highest grain yield, especially in the case of pigeonpea. Soil moisture at 15 cm depth remained reasonably constant and higher than at 5 cm throughout the growing season for both crops. This was thought to confer a yield advantage to the deep-banding treatment when irrigation is not used.

Responses of Chickpea to Phosphorus Application on a Vertisol in a Semi-Arid Environment

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Chickpea is an important pulse (grain legume) crop grown mainly on receding soil moisture in Vertisols of the Indian subcontinent, the Mediterranean region, and Ethiopia. Although the available P levels in these Vertisols are generally considered to be low, responses of chickpea to soil application of P are usually marginal compared to other crops, such as postrainy-season sorghum.

A series of experiments were carried out with chickpea at ICRISAT Center on Vertisols without addition of fertilizer and with soil-available P levels of 2 to 5 mg kg^{-1}, to determine the extent of P limitation by using different methods of P application in order to elicit a response to P.

In pot experiments, large responses to soil application of P fertilizers were observed in shoot mass and, to a lesser extent, in grain yield. However, no significant responses to soil-applied P were obtained in the field in a series of experiments conducted over several years. This lack of response does not seem to be due to the nonavailability of soil-applied P fertilizer in receding soil moisture conditions because there was no response either with or without the application of water.

Single superphosphate and/or rock phosphate dust applied to the foliage during the late vegetative and early reproductive stages of crop growth were also ineffective in increasing the seed yield under field conditions. The main objective was to examine the hypothesis that the highly acidic exudate on the foliage would solubilize large amounts of P even from the relatively insoluble rock phosphate. Some response to foliar spray applications of P was observed in a few genotypes. However, these responsive genotypes may not be of value because they do not outyield the nonresponsive types.

Chickpea has been reported to create a highly acidic rhizosphere, and has also been shown to develop a good vesicular arbuscuiar mycorrhizal colonization in Vertisols at ICRISAT. The lack of yield responsiveness to P in chickpea can be attributed to these factors, which result in efficient mobilization of P to the shoot. The P concentration in shoots of 30-day-old plants grown on the Vertisols which did not receive P fertilizers was > 0.6%. This is well above the critical minimum level reported for chickpea growth. This P concentration in shoots of chickpea is also quite high in comparison with other legumes. The concentration of P rapidly declined with advancing growth and was only 0.2% at the time of maturity.

Chickpea is not only efficient in mobilizing P to the shoot but is also very efficient in producing shoot mass and seed yield per unit of P taken up from the soil. For each kg of P taken from the Vertisol, it produced around 400 kg of shoot mass and 200 kg of seed yield. Both values are much higher than those obtained for other food legumes and cereal crops grown on Vertisols at ICRISAT Center.

Summary of Discussions and Recommendations

Group discussions were held following the presentation of each paper, and at the end of each session of the workshop. We present here the major points arising from these discussions.

Most of the previous research involving phosphorus (P) in soils has focused on irrigated production systems. As a result, little is known about the behavior of P under rainfed conditions, especially in Vertisols. From the research that has been done, responses to P have been shown to be highly variable and inconsistent.

That there is inconclusive evidence as to whether crops are more or less responsive to added P on rainfed Vertisols than on other soils is due largely to the difficulty encountered by researchers in excluding confounding factors. In future, crop responses must be considered in relation to soil tests that clearly establish the level of available soil P; differences between crops as well as between different Vertisols should be taken into account; the effect of moisture content of the soil will need to be considered; and response to added P will have to be isolated from the response to other inputs, including other soil nutrients.

Benchmark Approach

Because soils differ in their level of available P, comparisons between them must be made on the basis of a response in relation to available P status. Within Vertisols, the existing delineation of P-deficient soils is based on an inadequate sampling strategy involving the use of samples that may not be truly representative, and whose origins are sometimes unknown. More work is clearly needed to define which soil series are very deficient, moderately deficient, and sufficient in P. The use of a benchmark approach including accurate characterization is a prerequisite to such work.

Critical Limits

Participants were unable to provide concrete evidence that critical limits differed for different Vertisol soil series. The methods used for calculating and reporting critical limits varied. In addition, confusion was caused by attempting to extrapolate critical limits from pot experiments to field situations. However, one paper reported critical limits for individual crops at a single Vertisol site. This approach needs to be extended to other Vertisol sites, and then to other soil orders.

Soil Tests

There was general agreement that Olsen's test was a satisfactory basis for predicting responses to added P in Vertisols, although critical limits in Vertisols may differ from those on other soils. However, a few participants suggested that Olsen's was not the best method. One group of researchers proposed acidic extraction methods for

Vertisols. Nevertheless, elsewhere in the world, Olsen's method (or modifications thereof) has generally been found to be the most effective soil test method for alkaline soils. Further work is needed to determine the accuracy of different soil test methods, whose usefulness can then be compared with that of other, more sophisticated methods.

The concentration of P in soil solution—because it can be related to the concentration known to be optimal for plants growing in solution culture—has been suggested as a more reliable indicator of available P status than currently used soil tests. Measurements of the actual P concentrations in soil solutions are rare for the tropics, and more are needed, despite the apparent difficulty of measuring low concentrations.

Adsorption/Desorption

Evidence was produced that some benchmark Vertisol soil series differ very considerably in their adsorption and desorption of P. The Vertisol at the ICRISAT site fixes relatively little P, so that fixation cannot be considered as a mechanism explaining apparent lack of response to added P in this soil. However, work elsewhere in India has indicated that some Vertisols do fix appreciable amounts of P. The laboratory test commonly used in India for establishing levels of P fixation needs closer definition. Moreover, the concepts of fixation and adsorption may need to be differentiated, and more strategic research is required to improve our understanding of the timing and extent of P adsorption/desorption in relation to cropping needs. Percentage clay content has been widely used in India as an index of fixation capacity, but the type of clay minerals should also be taken into account.

Residual Effects

Residual effects of fertilizer P attracted relatively little discussion during the workshop, though it was widely agreed that further research on this topic was needed. Of particular importance is the characterization of residual effects for the different benchmark Vertisols. This needs to be achieved by the use of systematic, well-planned experiments, specifically designed to investigate residual effects both on yields of different crops as well as on the forms and behavior of P in the soil.

Soil Phosphorus Fractionation

A number of papers touched on the different forms of P found in the soil—Ca-P, Fe-P, Al-P, etc, among which Ca-P is the dominant form. The Ca-P compounds usually found in Vertisols are relatively insoluble because of the high pH of these soils. Little research has been done on the effect that this may have on the availability of P to plants.

Interactions

Plant response to P is often confounded by the interaction of other environmental factors. In particular, moisture affects both the demand of a crop for P and its availability, and also the ability of roots to explore for P. Participants agreed that there will be different soil-test/crop-response relationships for Vertisols with an assured moisture regime compared with those on which crops are grown under a receding moisture regime. The relationships for irrigated, rainfed, and receding soil moisture regimes would all be different. There was strong support for further research in this area.

Problems in the nutrition of crops grown on a receding moisture regime attracted several comments. Because the availability of nutrients will be less as the soil dries out, the role of nutrients (including P) in subsurface soil layers will become increasingly important. One paper presented at this workshop, as well as other work reported elsewhere, showed that deep placement of P can be highly advantageous under such conditions.

We do not know the extent to which limited responses to P are linked with other soil factors. Interactions with other nutrients, particularly nitrogen and zinc, have been identified. Several participants reported that the addition of farmyard manure promoted the response to P. Little attention was given at the meeting to the influence of agronomic practices, such as time of sowing, disease and pest control, and so on, although all these factors were deemed to be important. Major yield-reducing events or factors in experiments testing responses to P should always be reported.

Agroclimatic factors which influence plant growth, and therefore the demand for P, include light and temperature, as well as moisture. These should be studied over the full range of climate in a region, and not just at one or two benchmark sites.

Rhizosphere Research

Central to the need for more research on plants is the exploration of root form and function. The rhizosphere is known to have properties different from those of bulk soil, including a lower pH, which would increase solubility of the Ca-P and other P compounds. In the case of chickpea, the roots exude organic acids (malic or citric) which dissolve P, making it more accessible to the plant.

Fertilizer Strategies

A combination of plant and soil studies is needed as the basis for developing a strategy for the use of P fertilizer in both intercrops and crop sequences. This strategy will specify the different P requirements of different crops in relation to the availability of residual P in the soil. It will focus largely on rainfed systems, taking into account both assured (rainy-season) and receding (postrainy-season) soil moisture regimes.

Experimental Approach

Participants agreed that, in designing and reporting their experiments, scientists working on phosphorus (P) in Indian Vertisols should adopt a degree of standardization in experimental approach in order to make it easier to compare their results and to draw overall conclusions. Particular attention should be given to planning the conditions under which experiments are conducted, and presenting them completely and accurately when results are written up. The materials and methods section of the write-up should include:

- accurate soil classification (using Soil Taxonomy[1]), general soil properties (clay percentage, N percentage, pH, depth, cation exchange capacity, etc), and measurements specific for P (Olsen's P, equilibrium P concentrations, Chang and Jackson fractionation, P fixation or adsorption/desorption characterization);
- definition of crops grown (cultivars), and whether grown sole, or as intercrops, or in sequence (together with sowing date and all agronomic operations);
- details of agroclimate, including rainfall (average, actual, and seasonal distribution), temperature, and evaporation;
- irrigation (protective, full or nil), and/or any other relevant details of moisture regime.

Some additional points on methods and data should also be noted:

- pot experiments may be used to explore certain mechanisms in soil-nutrient relationships, but not for predicting critical limits, which should be determined under field conditions;
- the percentage relative yield used in establishing critical limits needs to be specified, and preferably a standard value should be adopted;
- the availability of P in the soil should be expressed as mg kg^{-1} soil, not extrapolated to kg P ha^{-1} using an assumed bulk density of soil;
- added P applied as fertilizer (or in soil) should be expressed as elemental P in kg P ha^{-1}, not as pentoxide, kg P_2O_5 ha^{-1};
- any method used for establishing P fixation capacities should be clearly described;
- any major yield reducing factors should be reported, together with their effect on the interpretation of results.

[1]USDA (United States Department of Agriculture), Soil Conservation Service, Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook No.436. Washington, D.C., USA: U.S. Government Printing Office. 754 pp.

Program Proposal

At a general group discussion, participants agreed on the need to formulate a collaborative research approach to study the phosphorus problems identified in the discussions. The following program is proposed, based on suggestions put forward by representatives of various institutions.

Title

Characterization of the behavior of phosphorus (P) in Vertisols and associated soils in India and implications for the response of crops to P applied under dryland farming conditions.

Objectives

- To characterize the status and behavior of P in the important Vertisol benchmark soil series found in India
- To study the P requirements of major crops on Vertisols, especially in relation to their phenology and to other environmental factors
- To understand the mechanisms operating in Vertisols to control P supply and crop demand for both
    - assured moisture regimes (rainy season), and
    - receding moisture regimes (postrainy season)
- To identify the best predictive soil test and associated critical limits as a basis for P fertilizer strategies for Vertisols under dryland farming conditions
- To develop P fertilizer strategies for the main crops and cropping systems of the agriculturally important benchmark Vertisols of India.

Collaborating Institutions

Institutions that have already indicated a major interest in collaborative research are CRIDA (Central Research Institute for Dryland Agriculture) and ICRISAT (Resource Management Program). CRIDA's representatives indicated that their plans for networking activities included collaborative research at Mahatma Phule Agricultural University's research stations at Rahuri and Sholapur, Jawaharlal Nehru Agricultural University (JNAU) at Indore, University of Agricultural Sciences (UAS) Dharwad at Bijapur, two stations (Jabalpur and Coimbatore) provided by the Long-Term Fertilizer Experiments (LTFE) project, and one provided by the Soil-Test Crop Response (STCR) coordinated research project. ICRISAT plans collaborative strategic research at ICRISAT Center, drawing on the specialized knowledge of a number of other institutes, including the Potash Research Institute of India (Gurgaon).

Completion of planning

Participants agreed that initial emphasis will be given to soil characterization, and studies on crop uptake and mechanisms determining responses. These studies will be conducted at CRIDA and ICRISAT, which will develop hypotheses on crop responses and critical limits for testing in field experiments at collaborating research stations of the national programs in India.

Progress will be quicker for rainy-season crops than for postrainy-season ones, since several years' research will be needed before an adequate understanding can be gained of the interactions between nutrients, moisture, crops and soils, under receding moisture conditions.

Participants agreed that a future meeting would be held to finalize the project details, including an action plan.

Annex

Crop Names used in this Report

Common name	Latin binomial
Banana	*Musa* spp
Black gram	*Vigna mungo* (L.) Hepper
Chickpea	*Cicer arietinum* L.
Chilies	*Capsicum frutescens* L.
Cotton	*Gossypium* spp
Cowpea	*Vigna unguiculata* (L.) Walp.
Finger millet	*Eleusine coracana* (L.) Gaertn.
Groundnut	*Arachis hypogaea* L.
Horse gram	*Macrotyloma uniflorum* (Lam.) Verdc.
Linseed	*Linum usitatissimum* L.
Maize	*Zea mays* L.
Mung bean	*Vigna radiata* (L.) Wilczek
Mustard	*Brassica* spp
Niger seed	*Guizotia abyssinica* (L.f.) Cass.
Pea	*Pisum sativum* L.
Pearl millet	*Pennisetum glaucum* (L.) R. Br.
Pigeonpea	*Cajanus cajan* (L.) Millsp.
Rice	*Oryza sativa* L.
Safflower	*Carthamus tinctorius* L.
Sesame	*Sesamum indicum* L.
Sorghum	*Sorghum bicolor(L.)* Moench
Soybean	*Glycine max* (L.) Merr.
Sugarcane	*Saccharum officinarum* L.
Wheat	*Triticum* spp

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