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Strategies for Maximizing the Efficiency of Phosphorus Utilization in Cropping Systems Involving Chickpea and Pigeonpea

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Abstract

This chapter summarizes current knowledge on phosphorus (P) fertilizer requirements of chickpea and pigeonpea in different cropping systems and suggests means of maximizing efficiency of P fertilizer use in both traditional and evolving cropping systems. In many of the P fertilizer trials conducted for both of these crops in India, mostly under dryland conditions, significant responses occur up to application rates of 15-30 kg P ha^{-1}. With the evolution of new cropping systems with higher potential yields and biomass production, and hence demand for P, fertilizer P requirements based on studies of traditional systems need to be reexamined. More rational and combined use of soil maps, soil analysis, plant analysis, pot trials, and field trials is suggested for diagnosis of P deficiency and determination of P fertilizer response functions.

As chickpea and pigeonpea are usually grown in complex cropping systems, an integrated approach to determining P requirements of the entire system, rather than those of the individual crops alone, through modeling of the P cycle is recommended. A major impediment to this approach is inadequate knowledge of the residual value of P fertilizer in the soils and cropping systems of concern. In increasing efficiency of P fertilizer use, care should be taken to evolve optimum application procedures for particular cropping systems. Deep placement seems mandatory where the topsoil is prone to drying and in situations where phosphate fixation is a problem, but may be unnecessary in well-watered systems. There is scope for further evaluation of partially soluble fertilizer P sources for these crops, especially in view of the activity of their root exudates in solubilizing P and their mycorrhizal associations. The various mechanisms proposed by which chickpea and pigeonpea can enhance the available P status of the total cropping system need to be quantified, so that their significance and scope for exploitation can be determined. The extent of genotypic difference in P-use efficiency needs to be adequately studied in these crops so that the genetic improvement option can be appropriately assessed.

Introduction

Chickpea (*Cicer arietinum* L.) and pigeonpea [*Cajanus cajan* (L.) Millsp.] are usually grown as rainfed grain legume crops in semi-arid regions. The biotic and abiotic constraints that they usually face, with few inputs given by farmers to overcome the constraints, result in the low yield levels obtained in the major growing regions of the world: in 1987, the world average productivity of chickpea was 691 kg ha^{-1} and that of pigeonpea 707 kg ha^{-1} (FAO 1988). However, phosphorus (P) deficiency does not rank as a major

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constraint in traditional growing areas, as evidenced by the marginal responses to P fertilizer measured for these crops, as discussed later. This apparent lack of responsiveness has perhaps resulted in less than adequate study of the P requirements of these crops in the different cropping systems in which they are found.

The major cropping systems of chickpea and pigeonpea referred to in this chapter in relation to P requirements are summarized in Table 1. It is understandable that at least one of the reasons for the low P responsiveness of these crops in traditional systems would be less P demand due to limited biomass and yield realization, caused by other constraints. With the recent development of chickpea and pigeonpea cropping systems with high biomass and yield potential, as in short-duration pigeonpea sole crops, it is expected that P demand, and hence P fertilizer requirements, will increase. These newly evolving cropping systems have received little research attention to date as to their mineral nutrient limitations and fertilizer requirements.

The objective of this chapter is to summarize current knowledge on P fertilizer requirements of chickpea and pigeonpea in different cropping systems and suggest means of maximizing efficiency of use of P fertilizer in both traditional and evolving cropping systems.

Phosphorus Responses Recorded

Most knowledge concerning response of chickpea and pigeonpea to P fertilizer has been generated in India, where these crops are predominantly grown and most research on them done. Tandon (1987) has summarized the results of 2181 P fertilizer trials with chickpea and calculated a mean increase in yield of 310 kg ha^{-1} over a nonfertilized control mean yield of

Table 1. Major chickpea and pigeonpea cropping systems considered in this chapter.

	Cropping system	Major region	Major constraints
A. Chickpea			
1.	Long- and medium-duration rainfed in South Asia	Subtropical South Asia	Foliar diseases, pod borer, terminal heat and drought stress, cold stress (pod-filling stage)
2.	Short-duration rainfed in South Asia	Peninsular India	Drought stress, soilborne diseases, pod borer
3.	Irrigated short- and medium-duration in South Asia[1]	Central and peninsular India	Initial and terminal heat stress, pod borer
4.	Spring-sown in West Asia	Mediterranean and West Asia	Terminal drought and heat stress, leaf miner
5.	Winter-sown in West Asia[1]	Mediterranean and West Asia	Ascochyta blight, cold stress (vegetative stage)
6.	Rice fallow crop	Subtropics	Establishment, soilborne diseases, drought stress
B. Pigeonpea			
1.	Perennial (agroforestry)[1]	Potential for semi-arid regions	Drought, pod borer, soilborne diseases
2.	Medium- and long-duration types, as intercrops	South Asia and eastern Africa	Terminal drought, pod borer, pod fly, sterility mosaic disease, fusarium wilt
3.	Short-duration sole crops in rotation (e.g. wheat)[1]	Northern India	Pod borer, phytophthora blight, waterlogging, drought
4.	Short-duration multiple harvest[1]	Peninsular India	Pod borer, drought
5.	Extra-short-duration for contingency cropping[1]	Low and variable rainfall environments	Drought, pod borer
6.	Rice fallow crop[1]	Tropics	Establishment, low-temperature stress drought stress, pod borer

1. Relatively recent system.

770 kg ha^{-1}, up to an application level of 17 kg P ha^{-1}. The same mean P response was calculated for 503 trials with pigeonpea, but from a nonfertilized control yield of 460 kg ha^{-1} (Tandon 1987). Tomar et al. (1987) also report many P fertilizer trials with chickpea in India giving P responses up to about 20 kg P ha^{-1} but not beyond. For trials done exclusively on farmer's fields, similar levels of response to P fertilizer are also found (e.g., Table 2; Joshi et al. 1988). Thus, biological optimum P application rates appear to be in the range 15-30 kg P ha^{-1} for both crops and the normally recommended P fertilizer rates for these crops in India are in the vicinity of 20 kg P ha^{-1}. However, there are also many reports of nonresponsiveness to P application in both chickpea (e.g., Saxena 1980; Saxena 1984) and pigeonpea (e.g., Sheldrake 1984). Further, we have noted that results of many P fertilizer trials where no P response is found are simply not reported.

Outside India, the P response of chickpea and pigeonpea has been less thoroughly documented. In West Asia, responses of chickpea to P fertilizer are varied (Murinda and Saxena 1985; Matar et al. 1988). Large P responses of pigeonpea have been recorded in Africa (Ogunwale and Olaniyi 1981; Rhodes 1987) and the Caribbean (Dalal and Quilt 1977; Hernandez and Focht 1985), mainly on acid soils.

In comparing P responsiveness between crop types, Matar et al. (1988) reported that in West Asia chickpea responds to P in a manner similar to lentil, faba bean, pea, and vetch. In Pakistan, chickpea is less responsive to P than other crops normally grown in the same season, such as lentil, wheat, and mustard (Rashid et al. 1988). Pigeonpea response to P application is comparatively less than that of other nonlegume crops normally grown in the same season (Johansen 1990), but is similar to that of other tropical grain legumes (Nandal et al. 1987).

Table 2. Pooled mean phosphorus response of chickpea grain yield in trials on farmers' fields in Chittorgarh and Alwar Districts of Rajasthan, India. (From Rawal and Bansal 1986, and Rawal and Yadava 1986.)

[illegible] (kg ha^{-1})[1]	Grain yield (kg ha^{-1}) Alwar	Chittorgarh
0	1808	1142
8.5	1864	1356
17.0	1976	1525
25.5	2186	-
SE	±36	±26
No. of trials	48	58
Period of trials	1975-77	1978-82
Chickpea variety	RS 10	C 235

1. In the presence of 20 kg N ha^{-1}.

Major Factors Determining Phosphorus Response

The magnitude of P responses of chickpea and pigeonpea in the field can be primarily attributed to the following major factors:

- Capacity of the particular soil type to supply P. Alkaline, calcareous soils, where these crops are mostly grown, generally show less response to P fertilizer application than acid soils with high P-fixation capacities.
- Plant or crop demand for P. The potential biomass production of these crops is usually limited by the various constraints mentioned in Table 1, and it would be expected that P demand and P responsiveness would increase as biomass potential increases. This is illustrated in data showing an increased responsiveness of pigeonpea to P application at higher plant densities (Ahlawat and Saraf 1981). Although average yields of chickpea and pigeonpea in India are low, and similar to world averages (FAO 1988), there are large yield variations between districts (Sharma and Jodha 1982). For example, in the state of Uttar Pradesh in 1978/79, district average yields for chickpea varied from 200 to 1153 kg ha^{-1} and those for pigeonpea from 489 to 2924 kg ha^{-1} (Sharma and Jodha 1982). Such variation needs to be taken into account in comparing P responses and developing P fertilizer recommendations on a regional basis.
- Soil moisture availability during crop growth. As these crops are traditionally grown under rainfed conditions, the topsoil (e.g., 0-15 cm) is subject to drying. Thus P response can be reduced under low soil moisture conditions due to both decreased availability of applied P and reduced plant demand for P because of limitation of biomass production by drought. This is illustrated by increasing responsiveness to P with

increasing soil moisture supply (irrigation) measured in chickpea (Singh and Sharma 1980; Borgohain and Agarwal 1986; Kulhare et al. 1988). However, Sharma and Yadav (1976) found a negative interaction between P application and irrigation in chickpea. Further, in a survey of many P fertilizer experiments in India, Rajendran et al. (1982) found that irrigated chickpea responded less to P than rainfed chickpea. This may have been a consequence of irrigated sites having a higher initial P status, perhaps from residual P from fertilizer applied to previous crops, than would rainfed areas, which generally receive little P fertilizer. Irrigation and P treatments need to be included in the same experiment to enable conclusions to be drawn about the interaction of these factors.

- Other possible factors affecting P response, such as mycorrhizal infection, root distribution, and root exudates, have been discussed in earlier chapters and will also be referred to later in this chapter.

Methods of Determining Phosphorus Requirements

Multilocation fertilizer experiments conducted over many seasons in major chickpea- and pigeonpea-growing areas, primarily in India, have given some idea as to the extent of P limitation in specific regions and provided a basis for fertilizer recommendations. Nevertheless, for any given site, even on research stations, considerable uncertainty remains as to the P status of these crops and continued quantification is warranted, particularly where cropping systems are changing. The P status of these crops can be diagnosed by several possible methods, which offer differing degrees of precision. A stepwise use and combined interpretation of these methods is recommended. These are described as follows in approximate increasing order of precision of the information they can offer.

Soil and Geological Maps

Soil and geological maps are usually available for even the most remote of regions, to varying degrees of precision. Examination of these gives a first approximation as to possible problems of P deficiency as well as other nutrient imbalances for a given region; for example, they would indicate the likeliho or otherwise of P-fixation problems in acid soils.

Symptoms

In chickpea, P deficiency usually results in stunted plants of darker green color and anthocyanin pigmentation, with older leaflets then gradually losing their green color to become bronze (Smith and Pieters 1983). There are no distinct symptoms of P deficiency in pigeonpea, but in cases of severe deficiency plants remain stunted, with their foliage dark green, and the older leaves are eventually shed (Johansen 1990). However, symptoms are of little value in assessing P status, because of their similarity to and interactions with symptoms caused by other nutrient imbalances and biotic and abiotic stresses. The manifestation of symptoms would also differ between genotypes with different inherent levels of pigmentation; further, symptoms would only be apparent when plant growth has been severely impaired by P deficiency.

Soil Analysis

Although many soil P tests have been done in the chickpea- and pigeonpea-growing regions of India, there is a dearth of information on critical P levels applicable to these crops under field conditions in the various soil types and cropping systems. For calcareous soils of pH 8.1-8.4 in northern Syria, Cate-Nelson analysis (Cate and Nelson 1971) of P fertilizer trials indicates a critical level of available soil P for winter-sown chickpea of 5-7 mg P kg^{-1}, as Olsen's bicarbonate-extractable P (Fig. 1). This critical range also applies to other legumes comparable to chickpea in this region, namely, faba bean, pea, vetch, and lentil (Matar et al. 1988). For field-grown pigeonpea in an acid (pH 4.8) soil in Sierra Leone, Rhodes (1987) determined a critical level to be an equilibrium soil solution concentration of 0.26 μM P. As a broad generalization based on experience on Alfisols and Vertisols at ICRISAT, for the 0-15 cm soil horizon, Olsen-P values above 5 mg kg^{-1} would indicate a P response of chickpea and pigeonpea to be highly unlikely; 2-5 mg kg^{-1} would be a zone of uncertainty; and below 2 mg kg^{-1}, responses to P would be probable. The inadequacies of using standard soil P tests for chickpea and pigeonpea are explained by Ae et al. (1991a, 1991b). Nevertheless, in view of the large data base on P responses of these crops in India at least, it would seem worthwhile to subject these data to a

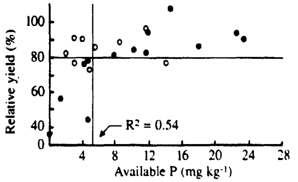

Figure 1. Cate-Nelson plot of relative grain yield of chickpea (yield without P relative to maximum yield with P) against bicarbonate-extractable P for field sites in Syria in 1985/86 (○) and 1986/87 (•) seasons. (From Matar et al. 1988.)

Cate-Nelson analysis on a soil type and regional basis in order to determine critical soil levels and the variability associated with them. The minimum data required for each experiment would be soil-test value without P fertilizer added, grain yield without P, and maximum grain yield with P. However, critical values obtained would need to be interpreted in the light of other environmental factors and stresses affecting yield.

Plant Analysis

Various estimates have been made of critical P concentrations in tissues of chickpea (Reuter 1986) and pigeonpea (Johansen 1990), but considerable care is required in interpreting these values, as they are strongly influenced by plant part sampled, plant growth stage, interactions with other nutrients, growth environment, and genotype (Bates 1971; Smith 1986). Further complications are the indeterminate growth habit of chickpea and pigeonpea and variability of phenology, which would make it difficult to standardize sampling time and plant part sampled. However, plant analysis may be more feasible for monitoring P status of short-duration, determinate sole crops of pigeonpea grown under assured soil moisture regimes, but the necessary calibrations are yet to be done.

Plant Growth Tests

The above suggests that symptoms or soil and plant analysis cannot be relied upon for diagnosing P status of chickpea and pigeonpea, let alone for suggesting P fertilizer requirements. Plant growth tests are required both for reliable diagnosis and for arriving at fertilizer recommendations. Pot trials, conducted in an environment as nonlimiting as possible, so as to maximize chances of expression of any nutrient imbalance (e.g., in a greenhouse), can provide information as to the potential of a particular soil to supply P, or any other nutrient, for plant growth (Andrew and Fergus 1976). However, for chickpea and pigeonpea, only response of the vegetative growth stage can be adequately measured in such pot tests because of atypical growth during the reproductive phase, resulting in inferior pod formation, in the greenhouse as compared with field conditions. The magnitude of P response found in pots can indicate the extent of P deficiency likely to be observed in the field and thus assist in efficient design of field experiments, with P application rates covering an appropriate range.

It is necessary to establish plant growth and yield response functions under field conditions if biological and economic optimum rates of fertilizer or amendment application are to be precisely known. Fertilizer rate trials need to be conducted over several seasons and at different sites within a region before an accurate picture of fertilizer requirement can be established. This is because of the various growth and yield limitations interacting with P response in the field, particularly interactions between soil moisture and P application when the crops are grown under dryland conditions.

Where some knowledge exists of P status and fertilizer requirements in particular fields, small-plot field trials can be used to monitor P status; for example, to confirm whether fertilizer recommendations are indeed correct. At ICRISAT Center, such trials have been effectively used to demonstrate that chickpea and pigeonpea do not need P fertilizer in fields where P is regularly applied to other crops in a rotation. Indeed, in view of uncertainties in the applicability of currently used soil tests to predict P response of chickpea and pigeonpea, it is suggested that such small-plot trials (e.g., plot size of 8 rows, 4 m long, for chickpea and short-duration pigeonpea sole crops) are necessary for monitoring P status of these crops.

Modeling of Phosphorus Cycles

Chickpea and pigeonpea are usually grown as minor components of complex cropping systems. Thus an integrated approach is required to determine P fertilizer requirements of the entire system rather than of individual crops in it. It is therefore useful to consider the P cycles operative in given cropping systems, preferably formalized into a mathematical model. To our knowledge, no detailed P modeling exercises have been attempted so far for particular chickpea or pigeonpea cropping systems. However, a simplified P budgeting approach for cropping systems involving these crops has been developed by the All India Coordinated Research Project on Soil Test-Crop Response Correlation, using the concept of fertilizer application for targeted yields (Velayutham et al. 1985). Although calculations by this methodology rely on gross assumptions about nutrient availability from fertilizer and soil, it is reported to be a useful framework for arriving at fertilizer recommendations and in promoting understanding of, and stimulating research in, P cycling in particular cropping systems. In the recent literature, there are several examples of cropping system P models that could be adapted for chickpea and pigeonpea cropping systems, such as those of Bennett and Bowden (1976), Blair et al. (1976), Jones et al. (1984), Probert (1985), and Wolf et al. (1987).

For chickpea and pigeonpea cropping systems, information that is particularly required for modeling purposes, but is lacking, includes estimates of labile P available to these crops and residual value of fertilizer P applied to previous crops. As discussed earlier, there are difficulties in using standard soil analyses to measure labile P; it could perhaps be better estimated from extrapolated intercepts on the "x" axis of P-response curves, determined in pots or in the field (Russell 1978). However, response curves of good fit would be required to do this with any accuracy.

It is the normal practice for cropping systems involving chickpea and pigeonpea, in South Asia at least, to apply P fertilizer, if indeed it is applied, to other apparently more remunerative components of the cropping system (Jha and Sarin 1984). Mathur et al. (1979) found that, for acid (pH 5.0-5.5) soils in Bihar state of India, chickpea responded to P applied in the previous three seasons to a maize-chickpea rotation. Residual effects were greater with rock phosphate (phosphorite) than with single superphosphate. In northern Syria, chickpea responded to P applied to barley in the previous season (Matar et al. 1988).

In pigeonpea, Rao and Bhardwaj (1981) found that P applied to a preceding wheat crop enhanced subsequent pigeonpea yields (System B3 in Table 1). It has also been found that P applied to pigeonpea has residual benefits for following crops. For example, application of P to pigeonpea has been reported to increase growth, yield, and P uptake of a following wheat crop (Pannu and Sawhney 1975; Singh et al. 1983; Ahuja 1984; Dahama and Sinha 1985; Singh and Faroda 1985). This can primarily be attributed to P fertilizer stimulating pigeonpea growth and N_2-fixation such that more residual fixed N is made available to the subsequent wheat crop. However, data on P uptake by wheat indicate that P applied to the preceding pigeonpea crop can be taken up by wheat (Singh et al. 1983; Dahama and Sinha 1985; Singh and Faroda 1985). Unlike the stimulatory residual effect mentioned above, P application to a previous pigeonpea crop had little effect in stimulating wheat yields, although the pigeonpea itself responded to P; Rao and Bhardwaj (1981) therefore concluded that, for their particular pigeonpea-wheat rotation, the best strategy was to fertilize each crop with 18 kg P ha^{-1}.

Residual effects of P have also been measured in a rotation of a sorghum/pigeonpea intercrop with castor under rainfed conditions on an Alfisol (System B2 of Table 1; Venkateswarlu et al. 1986). Castor could benefit from P applied to the prior sorghum/pigeonpea intercrop to the extent that the P fertilizer recommendation for this system was 22 kg ha^{-1} applied to the intercrop only. There was also an indication (differences not significant) that pigeonpea could benefit from P applied to a prior castor crop.

For chickpea and pigeonpea cropping systems, more detailed studies are needed to allow calculation of rates of decay (e.g., half life) in availability of applied P over time. The methodologies for doing this are well documented (e.g., Russell 1978; Barrow 1980; Widjaja-Adhi et al. 1985; Janssen and Wolf 1988). Generally, decay rates are exponential, and half lives are in the order of 1 year, but parameters vary, primarily due to initial P status, crop removal, and the buffering capacity of the soil for P (Tisdale et al. 1985). It would be dangerous to extrapolate from other studies to chickpea and pigeonpea cropping systems. Calculation of appropriate decay rates would be fundamental to developing appropriate P balance models.

Phosphorus Requirements of New and Evolving Cropping Systems

The pattern of chickpea and pigeonpea cultivation i changing in traditional production areas, and thes crops are being introduced into new areas. The l fertilizer requirements of new systems cannot simpl be extrapolated from those of the traditional ones, particularly when there seems to be a high degree of uncertainty concerning P requirements of traditional cropping systems in the first place. For example, the particular P requirements of pigeonpea in a traditional intercrop system (B2) are very difficult to estimate. As can be generalized from trials conducted by the All India Coordinated Agronomic Research Project (Ahlawat et al. 1985), it seems that the P requirement of an intercrop would be the sum of the requirements of the individual components when grown as sole crops at similar spacings as in the intercrop.

Although it is recognized that more research is needed to establish P requirements in traditional cropping systems, especially in relation to interactions of P availability with soil moisture, following are some considerations for establishing P requirements of some newly evolving cropping systems with chickpea and pigeonpea.

Table 3. Total biomass, grain yield, and calculated phosphorus content of above-ground parts (assuming 0.30% P in grain and 0.10% P in rest of shoots, based on P analyses at ICRISAT Center) of chickpea in different cropping systems.

Cropping system	Biomass ($t\ ha^{-1}$)	Grain yield ($t\ ha^{-1}$)	Above-ground P content ($kg\ ha^{-1}$)
Spring-sown West Asia[1]	1.56	0.80	3.2
Winter-sown West Asia[1]	3.55	2.09	7.7
Rainfed, peninsular India[2]	2.09	0.91	3.9
Irrigated, peninsular India[3]	6.20	3.18	12.6

1. From M.C. Saxena (1987).
2. Mean of 16 genotypes in Vertisol at ICRISAT Center in 1985/86 (N.P. Saxena, ICRISAT, unpublished data).
3. Cultivar Annigeri in Vertisol at ICRISAT Center in 1980/81 (Saxena and Johansen 1990).

Winter-sown Chickpea in West Asia (A5)

Winter-sown chickpea in Mediterranean regions has greater biomass accumulation and grain yield potential than the normal spring-sown crop and would thus have a higher P requirement, as illustrated in Table 3. Phosphorus responses of winter- and spring-sown chickpea have not been directly compared to determine whether the increased demand results in a greater response to P fertilizer. However, if root volume of the winter-sown crop stays in proportion to its above-ground biomass, then extra native soil P could be accessed, thus minimizing a P response. Another consideration is that P applied to the winter-sown crop at sowing is likely to have a greater relative availability, because it would remain in moist surface soil throughout the winter and be available for uptake during much of the vegetative growth period. By contrast, P applied to spring-sown chickpea in a receding soil moisture situation is likely to become increasingly unavailable as the surface soil dries out.

Irrigated Chickpea (A3)

With increased understanding of the extent of drought limitation to rainfed chickpea in central and peninsular India (N.P. Saxena 1987) and with relatively high prices for chickpea in recent years, irrigated chickpea is becoming increasingly popular in these regions. Considerations similar to those described for winter-sown chickpea in West Asia apply to irrigated chickpea; i.e., the increased biomass potential would cause increased P demand and hence increased fertilizer needs (Table 3). Again, however, available soil moisture would enhance the relative availability of fertilizer P. Also, the possible increasing importance of residual P in irrigated systems, (previously referred to with respect to the data of Rajendran et al. 1982), needs to be considered.

Chickpea in Rice Fallows (A6)

Although this has been a traditional and popular cropping system in subtropical South Asia, yields have remained low, as the seed is hand-broadcast at about the time of the rice harvest and no further inputs are generally given. Responses to P fertilizer are generally not found in such systems, because of both low P demand and, possibly, availability of residual P applied to the rice crop (Meelu and Rekhi 1981). With attempts to improve chickpea agronomy, and hence yield potential, in rice fallow systems (Johansen et al., in press), the P requirements of chickpea in rice fallows will need to be reevaluated, in terms of both increased P demand and residual value of P applied to rice. Indeed, it may be necessary to rely on P applied to the previous rice crop, because of the difficulty of fertilizer application and tillage to mix it into the soil surface in rice fallows. It will also be necessary to determine root configuration in relation to available P, due to the usually poor soil structure of rice fallows. The P model of Probert (1985) has been effectively applied to mung bean grown in a rice-based cropping system (Sreekantan and Palaniappan 1988); such a model could be adapted for chickpea in rice fallows.

Pigeonpea in Agroforestry (B1)

Perennial long-duration pigeonpea, with resistance to sterility mosaic disease and fusarium wilt, is showing promise as a tree component in agroforestry systems in peninsular India (Daniel and Ong 1990). For this use, the P requirements of pigeonpea as a tree crop need to be considered. In the first place, it is difficult to measure P response of such pigeonpea, as optimum methods of fertilizer placement are yet to be established. Along with P placement, other important considerations are: the extent of mycorrhizal activity and whether this can be enhanced, the ability to extract P from deep soil (e.g., below 1 m), and the extent to which P fertilizer is required for regrowth after the first year.

Short-duration Sole Pigeonpea in Rotation (B3)

There is already considerable knowledge on P response of short-duration pigeonpea, mainly indeterminate types grown in rotation with a cool-season crop such as wheat in northern India (Kulkarni and Panwar 1981). Generally, responses seem larger than reported for long-duration pigeonpea in intercrops, the traditional method of pigeonpea cultivation in the region. There has been a recent trend towards developing pigeonpea genotypes for this system that are determinate and shorter in stature (<1.5 m tall) and duration (<120 days). The P nutrition of this recently bred material has not yet been examined in any detail and, again, extrapolation from types where P response has been examined is unwise. For example, earlier types would have a shorter period in which to absorb P from the soil, and determinate types may have P translocation and retranslocation patterns different from indeterminate ones. Evidence suggests that the more recently developed short-duration determinate types have a lower rooting ability than traditional pigeonpea (Chauhan, in press) and this may limit access to native soil P. Changes in biomass production of the new types need to be considered in terms of possible P demand. It has been observed that P deficiency can delay maturity of short-duration pigeonpea (Chauhan et al., in press; and A. Kubota, ICRISAT, 1989, personal communication), and this needs to be borne in mind when fitting pigeonpea into particular rotations.

Short-duration Multiple-harvest Pigeonpea (B4)

In tropical environments with warm winters, it is possible to exploit the perennial nature of short-duration pigeonpea to take multiple harvests from the same crop (Chauhan et al. 1987). Thus a total of 5 t ha^{-1} grain and 10 t ha^{-1} remaining above-ground biomass may be produced from the same plot of land over a 9-month period, exerting a large P demand (estimated at 35 kg ha^{-1} P for above-ground production). There is evidence that second-flush yield may respond to an initial P application where the first-flush yield and above-ground dry-matter production did not. For instance, on an Alfisol with 5 mg kg^{-1} Olsen P at ICRISAT Center, first-flush yields with and without applied P were similar; however, second-flush yield was 46% higher with 200 kg ha^{-1} single superphosphate applied at sowing than with no P (Y.S. Chauhan and C. Johansen, ICRISAT, 1987, unpublished data). Further work is urgently needed to understand the P requirements of such multiple-harvest systems with high biomass potential.

Contingency Cropping with Extra-short-duration Pigeonpea (B5)

With the breeding of extra-short-duration pigeonpea genotypes that can mature in 90 days or less in tropical environments, studies are under way to evaluate these genotypes in contingency or catch-cropping systems where periods of available soil moisture supply are likely to be short. That is, such genotypes should be able to escape drought as can other short-season legumes, such as cowpea, mung bean, and urd bean. Again, the P requirements of this type of pigeonpea are yet to be evaluated. Limited periods of available soil moisture will undoubtedly limit biomass production and hence P demand. However, further improvements to this plant type will require increased capacity for initial growth rate for more rapid development of leaf area. This will also require increased rates of P uptake by seedlings, a process which may then become limiting in marginal P environments.

Pigeonpea in Rice Fallows (B6)

The development of short- and extra-short-duration pigeonpea has increased possibilities of using pigeonpea as a rice fallow crop in the tropics. The same considerations as discussed for chickpea would be applicable here.

Appropriate Fertilizer Type and Application Method

In India, in the rare instances that any fertilizer is used on chickpea and pigeonpea, diammonium phosphate (DAP) is the most commonly used form of P fertilizer (Tandon 1987). This is a convenient fertilizer for these legumes, as it supplies an often-required starter dose of N as well; responses to starter doses of N are common in both chickpea (Rajendran et al. 1982) and pigeonpea (Kulkarni and Panwar 1981). Other P sources used are superphosphate and various compound fertilizers. All of these fertilizers have high levels of water-soluble phosphate, immediately available to the crop if the soil is moist. However, in view of the likely increases in costs of manufacturing soluble P sources and the desirability of considering the longer-term P needs of whole cropping systems, sparingly soluble sources of P need to be considered for these crops.

The efficiency of rock phosphate in supplying the P needs of tropical legumes in acid soils is well documented (Kerridge 1978). Although many studies have been done on rock phosphate and other sparingly soluble P sources in Indian cropping systems (Tandon 1987), there are relatively few reports relating to chickpea and pigeonpea. On an acid (pH 5.0-5.5) soil, chickpea responded to rock phosphate and single superphosphate in a similar manner on a total P content basis (Mathur et al. 1979). The better residual value of rock phosphate in this study has already been referred to. In pot studies, rock phosphate stimulated growth of chickpea in alluvial sandy soils of Haryana, India, of pH 8 and low P status (Jalali and Thareja 1985). Further growth stimulation was obtained by mycorrhizal inoculation. In a presumably alkaline Vertisol from Pune, India, rock phosphate could also stimulate chickpea growth in pots, with a further stimulation when cellulolytic and phosphate-solubilizing fungi were added (Rasal et al. 1988). There are earlier reports of phosphate-solubilizing organisms enhancing yield and P uptake of chickpea (e.g., Subramanian and Purushothaman 1974; Ahmad and Jha 1977). Prabhakar and Saraf (1990) confirmed that growth response of chickpea on a sandy-loam soil of pH 7.6 was at least as good with rock phosphate inoculated with phosphate-solubilizing bacteria as with superphosphate. In field studies on granitic soils in Thailand, addition of 400 kg ha^{-1} rock phosphate in the presence of gypsum increased pigeonpea grain yield by 30-80%, at different spacings, in 1976 and 1977 (Andrews and Manajuti 1980). The ability of chickpea and pigeonpea to utilize P from rock phosphate over time, especially in view of their mycorrhizal and other microbial associations and their root exudates, warrants further study.

Although P fertilizer application for chickpea and pigeonpea is most feasible at or before sowing, there are situations where application during crop growth would be desirable, particularly for longer duration crops or in multiple-harvest systems. However, any topdressing of fertilizer, additional to an application at sowing, would require that the topsoil be moist for the applied fertilizer to be solubilized. Another alternative for nutrient addition to established crops is the use of foliar sprays or dusts. Some positive responses to foliar sprays of P have been demonstrated for chickpea (e.g., Sharma et al. 1975), but the results of such experiments often remain ambiguous. For example, where there are positive responses to the application of DAP, it is not possible to distinguish between the relative contributions of N and P (e.g., for chickpea, Pathak et al. 1985; for pigeonpea, Reddy et al. 1987).

For predominantly rainfed crops, lack of responsiveness to fertilizers can at least partly be attributed to drying of the surface soil to which the fertilizer is applied, and thus reduced P availability during dry periods. There are many reports demonstrating positive effects of deep placement of P fertilizer on chickpea yield under rainfed conditions in India (e.g., Sharma and Richharia 1962; Sinha 1972; Kumbhare et al. 1978). However, some studies attempting to further demonstrate this principle have obtained anomalous results, for example the pot study of Ghosh (1985), where no interaction was found between soil moisture regime and P placement; thus, additional interacting factors perhaps need to be considered. For short-duration pigeonpea cv T 21 grown in Punjab, India, placement of P fertilizer at a depth of 10 or 15 cm increased yield by 35% over broadcast application (Pannu and Sawhney 1975). The ICRISAT experience with P placement is presented by Arihara et al. (1991); generally deep placement was beneficial under rainfed conditions. While it can be concluded that the most appropriate mode of P fertilizer placement is largely determined by the likely moisture status of the soil profile during crop growth, other factors—such as P-fixation capacity of the soil, availability of appropriate equipment for deep placement, and the economics of P fertilizer application—would need to be considered in formulating any recommendations about P fertilizer placement method.

Exploiting the Ability of Chickpea and Pigeonpea to Mine Phosphorus

In summary, as discussed in detail in earlier chapters of this volume, it has been proposed that chickpea and pigeonpea can access more native soil P than other comparable crops through the following mechanisms:

- strong development of mycorrhizal associations;
- deep-rooting ability of both crops and, presumably, ability to retrieve P from deeper soil layers;
- acid exudates from chickpea, which allow it to access more P in alkaline soils; and
- exudates from pigeonpea which allow it to utilize iron-bound P in the soil.

The extent to which additional P is made available by these mechanisms needs to be quantified; only then can their significance in contributing to the P status of the total cropping system be estimated. If indeed chickpea and pigeonpea can access extra P for their own use, then this can also be considered as an addition to the total cropping system, in terms of conversion from otherwise unavailable P to organic P in chickpea and pigeonpea tissue, which could eventually release labile P from organic residues of these crops. If such effects are significant, then this should be considered in the overall economic evaluation of the crop, along with the direct products of food, fuel, and fodder, and established indirect values, such as contribution of N_2-fixation to the N economy of the cropping system.

If these mechanisms do prove quantitatively significant, then it would be worthwhile to examine the extent of genotypic variation, to assess whether genetic enhancement of the particular trait is feasible. However, it must be recognized that traits such as deeper rooting ability and increased root exudation would probably involve penalties of reduced potential for above-ground biomass formation. This aspect should tie in with an overall understanding of genotypic differences in P-use efficiency—including P-uptake capacity and P translocation and retranslocation. There have been several studies where P response of a range of chickpea genotypes has been measured but interaction effects—that is, comparative P response between genotypes—were not presented (Raju and Varma 1984; Singh et al. 1984; Ahlawat et al. 1985; Yadav et al. 1985). Manjhi et al. (1973) demonstrated genotypic differences in P response between pigeonpea genotypes: variety Sarada reached a yield plateau at lower P application rates than T 21 or AS 10. There is scope for much wider assessment of the extent of genotypic differences in P response, including further analysis of existing data, and determination of the basis of these differences.

Future Research Emphases

In view of the many unanswered and newly raised questions in this and earlier chapters, and thus the many possible research directions that can be taken, it seems appropriate to prioritize research areas where greater practical returns could be expected. We suggest that:

- in developing new cropping systems for chickpea and pigeonpea, determination of P and other nutrient requirements be considered an integral part of the research involved, rather than an afterthought;
- P models be developed for the main cropping systems of interest, to provide a basis for P management strategies and highlight gaps in knowledge;
- a coordinated attempt be made to decide on best methods of measuring labile P for these systems;
- residual values of fertilizer P be determined for the major chickpea and pigeonpea cropping systems;

- more realistic assessment be made of the usefulness or otherwise of plant tissue analysis in determining plant P requirements, especially for newer cropping systems where water supply is more assured, phenology more predictable, and plants have a more determinate habit;
- less soluble—i.e., less processed—sources of P be evaluated for chickpea and pigeonpea on a long-term cropping system basis;
- more research be done on the engineering aspects of deep placement of P fertilizer in rainfed, water-limited environments;
- the contributions of various mechanisms of increasing P accessibility proposed for chickpea and pigeonpea be quantified and their significance assessed; and
- genotypic differences in P-use efficiency be further assessed and their basis understood.

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