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Phosphorus Requirements of Soybean and Cowpea as Affected by Mode of N Nutrition[1]

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ABSTRACT

A field experiment was conducted on a tropical soil (Humoxic Tropohumult) with a high P sorption capacity to compare the critical external and internal P requirements of soybean (*Glycine max (L)* Merr.) and cowpea *(Vigna unguiculata ()* Walp.) as affected by the predominant mode of N nutrition during crop growth. The experiment had a split-plot design with two N-level subplots established within each of six P-level mainplots. Phosphorus treatment ranged from 0.0015 (unamended soil) to 0.08 (1,880 kg P/ha) µg P/ml in 0.01M $CaCl_2$ solutions equilibrated with soil for 6 days. Nitrogen levels were either deficient (plants primarily dependent on N fixation) or sufficient (N fertilizer supplied at rates sufficient to satisfy the crop N requirement). Nitrogen-fixing soybeans required 750 kg P/ha to obtain a 900/. relative yield which was 320 kg P/ha more than that required by N-supplied plants to obtain a comparable relative yield. The P concentration of N-fixing soybean plants was significantly lower than that of N-supplied plants at all levels of applied P fertilizer. The external P requirement and tissue P concentration of cowpea were unaffected by soil N level. The data show that cowpea was more tolerant of P stress than soybean, especially when dependent on N fixation. The cowpea cultivar grown without P or N fertilizer yielded 72% of the maximum yield obtained at optimum P levels while the comparable relative yield for the soybean cultivar was 28%. We conclude that (i) some N-fixing grain legumes can make respectable yields with little or no P fertilizer while others might not and, (ii) screening N-fixing grain legumes for tolerance to nutrient stress should be conducted on N-deficient soil to insure that nutritional requirements are assessed for the N-fixing plant, especially on the highly weathered soils of the tropics.

Additional index words: **N fixation, P deficiency, Critical external P requirement, Critical internal P requirement.**

N soil, plant P uptake and fertilizer P requirements are dependent on root growth Khasawneh and Copeland, 1973; Edwards and Barber, 1976). The inherent differences in root morphologies of N-fixing and N-supplied legumes may affect their critical external P requirement. A negative correlation between lateral root number and nodule number has been reported for some legume species (Nutman, 1948; Dart and Pate, 1959). Cassman *et al*. (1980) showed that soybean *(Glycine max (L.)* Men.) plants supplied with adequate N had a larger and more extensive root system than comparable N-fixing plants and this difference was greatest at suboptimal P levels. The more extensive root system of an N-supplied legume should increase its capacity to absorb P and lower the requirement for added P fertilizer. A field experiment was conducted to compare the critical external and internal P requirements of soybean and cow pea *(Vigna unguiculata (L.)* Walp.) as affected by the predominant mode of N nutrition during crop growth.

MATERIALS AND METHODS

The experiment was conducted at the University of Hawaii Kuiaha Experiment Site on the island of Maui, Hawaii. Elevation at the site is 320 m and mean average rainfall is 1,800 mm. The soil is classified as a Haiku clay (clayey, ferritic, isohyperthermic Humoxic Tropohumult) weathered from basic igneous rock and volcanic ash. Surface and subsoil pH was 4.8 before liming. Nine months before planting 2,100 kg/ha finely ground agricultural lime and 1,600 kg/ha dolomitic lime were incorporated into the surface soil which raised the pH to 5.9. Six P treatments were also established to provide 0.0015, 0.011, 0.024, 0.070, 0.170, and 0.500 µg P/ml in the soil solution as estimated by the method of Fox and Kamprath (1970), requiring P applications of 0, 400, 620, 960, 1,360, and 1,880 kg/ha. Phosphorus was surface broadcast as treble super phosphate and rotary-tilled to 18 cm depth. Plots were 5-m X 10-m and were arranged in a completely randomized block design with three replications. One week before planting soil N availability was modified by incorporating sugarcane bagasse into the entire field at a rate of 16,000 kg/ha (equivalent to 0.8% of the surface soil on a dry weight basis). Two N-level subplots, each 5-m X 5-m, were established within each of the six P mainplots. One subplot received no N fertilizer (-N subplot) while 700 kg urea-N/ha was incorporated in the other subplot (+N subplot). Supplemental applications of 200 and 100 kg urea-N/ha were side dressed on +N subplots 4 and 6 weeks after emergence, respectively. Before planting blanket fertilizer applications of 200 kg/ha K as K_2SO_4 15 kg/ha Zn as $ZnSO_4$ and 2 kg/ha Mo as MoO_3 were applied. Seeds were coated with peat cultures containing highly effective strains of *Rhizobium* using gum arabic as a sticking agent. Soybean inoculum contained equal numbers of *Rhizobium* strains TAL 378 and TAL 379. Cowpea inoculum contained equal numbers of *Rhizobium* strains TAL 169 and TAL 309. Viable plate counts made from coated seeds indicated that there were 10^7 viable rhizobia on both soybean and cowpea seeds at planting. Three 5 m rows of both soybean and cowpea were planted in each subplot on 6 June 1978. Soybeans were

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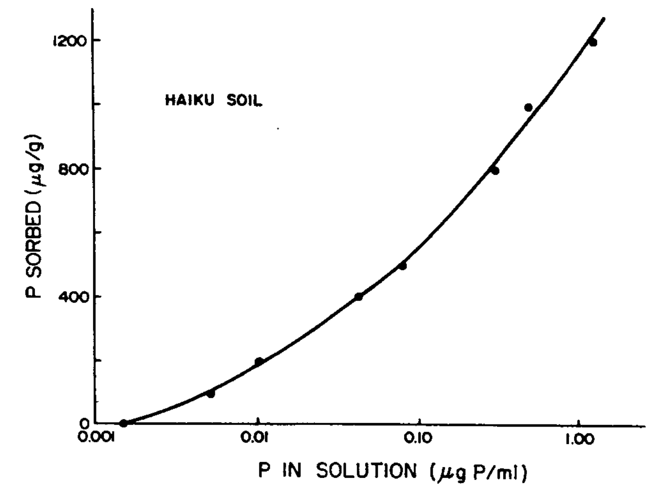

Fig. 1. Phosphorus sorption isotherm for the Haiku clay surface soil (Humoxic Tropohumult).

spaced 3 cm apart in rows 0.75 m apart (333,000 plants/ha). Cowpeas were spaced 7.5 cm apart in rows 1 m apart (133,000 plants/ha). The soybean variety used ('Clark 63') is a determinate cultivar of medium stature. The cowpea cultivar used (TVu 745-P3) is an indeterminate, viny entry from the 1976 Internation Cowpea Disease Nursery from the International Institute of Tropical Agriculture, Ibadan, Nigeria. Overhead irrigation supplemented rainfall whenever necessary.

The first fully-expanded leaf was sampled from 20 plants in the harvest row of each subplot 42 days after emergence, dried at 55 C, and ground. Nitrogen concentration in these index tissue samples was determined colorimetrically after Kjeldahl digestion (Mitchell, 1972) and P concentration was measured from the same digest using the ascorbic acid phosphomolybdateblue method developed by Murphy and Riley (1962) and shown to be effective for plant tissue P analysis by Throneberry (1974). Fine roots < 2 mm diameter were collected from three soybean and three cowpea plants randomly sampled from each subplot 50 days after emergence. After washing and staining as described by Phillips and Hayman (1970), mycorrhizal infection was rated on a scale of 0 to 10 by examination with a dissecting microscope.

Soybean plants were harvested at maturity, 81 days after emergence in -Nsub lots and 3 days later in the +N subplots. At harvest, soybean pants from 2 m of the middle row in each subplot were cut at the soil surface. Plants were dried at 55 C, seed and haulm yields determined, and subsamples ground for N and P analysis as previously described.

Cowpea was harvested 90 days after emergence. Plants from 2 m of the middle row in each subplot were cut at the soil surface, fresh weight recorded, and the plant material chopped. Two subsamples were taken; one to determine moisture content and another for N and P analysis. At harvest there were mature dry pods, green pods, and flowers present on plants in all treatments.

Surface soil (0 to 18 cm) samples were collected from each subplot 28 days after emergence. Soil samples were air dried and screened through a 2-mm sieve. Soil P was measured by three methods: modified Olsen's extraction (Banderis *et al.*, 1976), Bray P1 extraction (Council on Soil Testing and Plant Analysis, 1974), and equilibration for 6 days in .0.01M CaCl, (Fox and Kamprath, 1970). All yield data were correlated with the values obtained from these soil samples.

The critical soil P requirement was based upon the 900J$_o$ maximum yield level. Yield response curves for both soybean and cowpea best fit a Mitscherlich equation with three estimated parameters of the form:

$$Y = \grave{e}_1 - \grave{e}_2 \, {}^{\grave{e}}{}_3{}^{X}$$

where X is the soil P level, Y the predicted yield at any given X value, $\grave{e}_2$ the estimate of maximum yield at infinite soil P, *B*, the estimate of the difference between the maximum yield estimate and the estimated Y intercept and, $\grave{e}_3$ the estimate of the decreasing yield response to each added increment of soil P. The parameters were estimated by the Marquardt algorithm for nonlinear equations using the Statistical Analysis System (Barr et al., 1976). The critical internal P concentration was estimated by linear regression of yield at harvest on the index tissue P concentration. The critical internal P concentration was considered to be the index tissue P concentration which corresponds to the 90%maximum yield on the regression line.

Table 1. Phosphorus levels in the Haiku soil as affected by the rate of fertilizer P application†, extraction method, and N-deficient or N-luxuriant soil conditions.

P applied		Solution P‡	Bray P	Olsen P
kg/ha		ppm		
0	−N	0.0015	0.4	2.5
	+N	0.0015	0.5	2.6
400	−N	0.004	1.6	8.0
	+N	0.004	1.7	7.7
620	−N	0.007	3.8	14.1
	+N	0.007	3.5	14.7
960	−N	0.012	6.8	21.9
	+N	0.012	6.1	21.3
1,360	−N	0.018	11.4	33.3
	+N	0.016	9.6	31.6
1,880	−N	0.074	35.8	74.2
	+N	0.034	21.9	53.4

† Phosphorus fertilizer applied one year before soil samples collected for analysis. ‡ Solution P is the concentration of P in a 0.01 M $CaCl_2$ solution equilibrated for 6 days with soil (Fox and Kamprath, 1970).

RESULTS

The Haiku clay soil at the experimental site is a Humoxic Tropohumult and has a high P sorption capacity (Fig. 1). Incorporation of bagasse did not affect P sorption or available P; nor did added N fertilizer except at the highest P level (Table 1).

For soybean, there was a significant yield response to each added increment of P fertilizer up to 620 kg P/ha in -N subplots and 400 kg P/ha in +N subplots (Table 2). When no P fertilizer was applied, soybean seed yields from -N and +N subplots were equivalent. However, in all treatments in which P fertilizer was applied, soybean seed yield was significantly higher in +N treatments than -N treatments at comparable P levels. At P application rates of 400, 620, 960, and 1,360 kg/ha the relative yield of N-supplied soybean was also higher than that of N-fixing plants from comparable P treatments (Table 2). The maximum yield of N-fixing soybean was 75% that of the maximum yield of N-supplied plants.

For cowpea from both -N and +N subplots, there was a significant yield response to only the first increment (400 kg P/ha) of applied P fertilizer (Table 2). When no P fertilizer was applied, yield was higher in the -N treatment than in the +N treatment. As with soybean, in all treatments in which P fertilizer was applied, cowpea dry matter yields were significantly higher in +N subplots than in -N sub lots. The maximum yield of N-fixing cowpea was 89$_o$ that of the maximum yield of N-supplied cowpea.

Soybean index tissue P concentration and the seed P concentration were significantly higher in +N treatments than in -N treatments at any given level of applied P fertilizer (Table 2). Regression of soybean seed yield on index tissue P concentration indicated that the relationship between these two parameters differed depending on the N regime (Fig. 2). How-

Table 2. The yield, relative yield, index tissue† P content, and P content of harvested soybean seed and cowpea dry matter as affected by the mode of N nutrition and soil P level.

Fertilizer P applied		Soybean Seed yield	Soybean Relative yield	Soybean Index tissue P content	Soybean Seed P content	Cowpea Dry matter yield	Cowpea Relative yield	Cowpea Index tissue P content	Cowpea Dry matter P content
kg/ha		kg/ha	% maximum yield	%	%	kg/ha	% maximum yield	%	%
0	−N	1,030	28‡	0.22	0.39	4,348	72‡	0.21	0.23
	+N	934	19	0.21	0.35	3,727	54	0.19	0.22
400	−N	2,699	74	0.37	0.54	5,727	94	0.47	0.34
	+N	4,207	87	0.49	0.61	6,592	96	0.50	0.32
620	−N	3,129	86	0.43	0.55	5,907	97	0.49	0.35
	+N	4,468	92	0.49	0.64	6,812	99	0.52	0.34
960	−N	3,303	90	0.44	0.55	6,025	99	0.49	0.33
	+N	4,586	95	0.53	0.65	6,797	99	0.52	0.34
1,360	−N	3,490	96	0.48	0.57	5,853	96	0.50	0.34
	+N	4,836	100	0.52	0.63	6,848	100	0.50	0.32
1,880	−N	3,638	100	0.50	0.60	6,075	100	0.50	0.35
	+N	4,695	97	0.54	0.65	6,830	100	0.52	0.33
L.S.D.$_{0.05}$ (N)*		210		0.03	0.04	450		n.s.	n.s.
L.S.D.$_{0.05}$ (N × P)**		305		0.04	0.04	750		0.04	0.05

† Index tissue for both legumes was the first fully-expanded leaf sampled 6 weeks after emergence. ‡ Relative yields were determined separately for +N and −N phosphorus treatments. * Used for comparisons between different N levels at the same P level.
** Used for comparisons between different N levels at different P levels or to compare the same N levels at different P levels.

ever, the critical index tissue P concentrations corresponding to 900], of their respective maximum yields were nearly identical, both approximately 0.45% P. For cowpea, soil N level had no significant effect on index tissue P concentration or the P concentration in the harvested dry matter (Table 2). There was no significant correlation between cowpea dry matter yield and index tissue P concentration in -N or +N treatments and consequently the critical internal P requirement could not determined for cowpea.

Figures 3 and 4 show the relationship between yield and soil P as quantified by (i) P fertilizer applied and (ii) soil equilibration in 0.01M $CaCl_2$. Similar patterns were found when yields were regressed on Bray P1 extraction and Olsen's extractable soil P values. Mitscherlich equations which best fit the data were used to estimate the critical external P requirements (Table 3). The critical external P requirement of soybean was greatly affected by soil N availability. Under N-deficient soil conditions, the critical external P requirement of N-fixing soybean was 47 to 75% higher than that of N-supplied soybean plants as estimated by four methods of soil P evaluation. Soil N availability and the subsequent mode of N nutrition had no effect on the critical external P requirement of cowpea. The cowpea cultivar appeared to be more tolerant of low soil P levels than the soybean cultivar regardless of soil N status or method of soil P evaluation.

The fine roots of both legumes were heavily mycorrhizal 50 days after emergence in all P and N treatments. There were no significant differences in the intensity of mycorrhizal root infection among any of the N or P treatments for either soybean or cowpea and the infection ratings were similar for both legumes.

DISCUSSION

Valid comparison of the mineral nutrient requirements of an N-fixing and N-supplied legume under field conditions requires that three conditions be met.

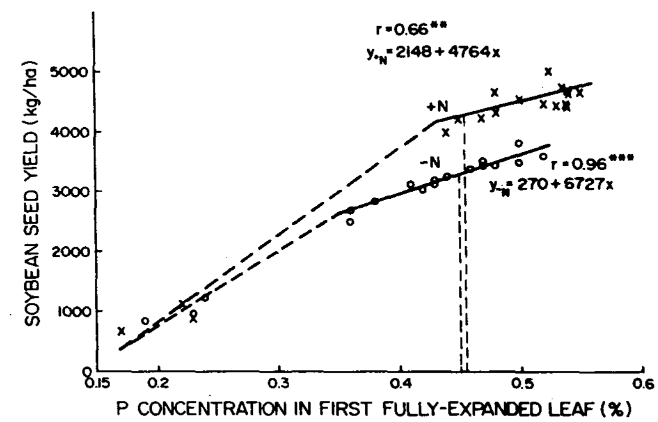

Fig. 2. Relationship between soybean seed yield and P concentration in the index tissue (first fully-expanded leaf sampled 42 days after emergence). Vertical lines represent the critical internal P concentration required for 90% maximum yield of N-fixing (−N) and N-supplied (+N) plants.

First, soil N availability must be controlled such that the N-fixing plant is primarily dependent on symbiotic N fixation to fulfill its N requirement for growth and the N-supplied plant must be provided with sufficient combined N to satisfy its N requirement. In -N subplots soil N availability was monitored throughout the cropping period and found to be extremely low while nodulation and acetylene reduction rates of both soybean and cowpea indicated that these plants were primarily dependent on symbiotic N (Cassman, 1979). In -I-N subplots soil N availability was high and nodulation and acetylene reduction rates were negligible throughout crop growth.

Second, highly effective *Rhizobium* strains must be provided at planting to insure that the infection process and nodule development proceed at optimum rates unless specifically inhibited by the nutrient deficiency. This condition was satisfied by inoculating all seeds with highly effective *Rhizobium* at rates approximately 40 times higher than that required for maximum nodulation in soil (Burton and Curley, 1965; Weaver and Frederick, 1972). Third, soil modifications employed to establish N-deficient and N-sufficient soil conditions must not adversely affect soil P availability to the plant. The data indicated that soil P availability was similar in the -N and +N subplots at each of the four lowest P treatments and appeared to be higher in the -N subplots at the two highest P levels (Table 1). Increased microbial activity stimulated by high P and N soil conditions may have caused some immobilization of labile soil P in these treatments. However, it is clear that the lower P availability in the +N subplots at the two highest P levels was more than adequate for optimal growth and yield for both soybean and cowpea, and thus should not have affected- the yield response to P.

The data indicate that the soybean cultivar was more sensitive to P stress when dependent on symbiotic N whereas the cowpea cultivar had similar P requirements irrespective of the mode of N nutrition. The tolerance of cowpea to low soil P could be characterized by: (i) tissue P concentrations which were unaffected by soil N availability, (ii) a critical external P requirement which was also unaffected by soil N availability, and (iii) a relatively small difference between the maximum yield obtained from N-fixing and N-supplied plants. The sensitivity of N-fixing soybean plants to P stress could be characterized by: (i) lower index tissue and seed P concentrations than for Nsupplied plants grown at comparable P levels, (ii) a higher external P requirement than N-supplied soybean plants, and (iii) a relatively larger difference between the maximum. yield obtained from N-fixing and N-supplied plants than for cowpea.

The fact that the cowpea cultivar used in this study was more tolerant of P stress than the soybean cultivar does not, mean that all cowpea and soybean cultivars would behave similarly. It has been well documented that among genotypes within a plant species there are large differences in P feeding capacities (Lyness, 1936; Whiteaker *et al.*, 1976; Nielsen and Barber, 1978). Nonetheless, a specific comparison of the two plants used in this study allows identification of the important features of tolerance or sensitivity to low soil P by N-fixing legumes. It is noteworthy that Nangju (1973) reported a yield response to applied P fertilizer with soybean and not with cowpea on a Nigerian soil.

Analysis of the data from this experiment does not provide answers as to why soil N availability affected the internal tissue P concentration and the external P

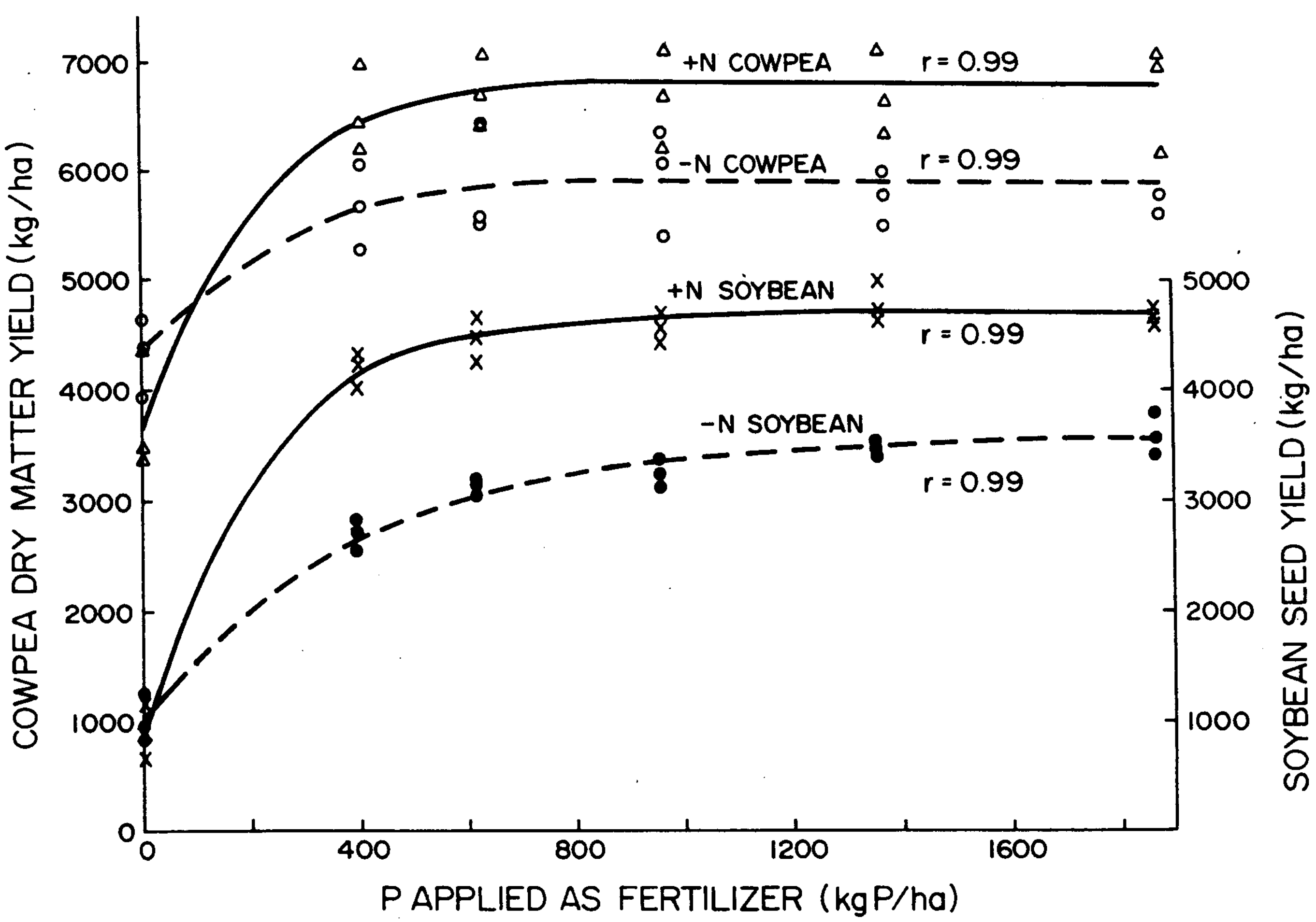

Fig. 3. Yield response of N-fixing (−N) and N-supplied (+N) soybean and cowpea to soil P as quantified by P applied as fertilizer.

requirement of soybean and not cowpea. We propose three hypotheses. One hypothesis is that symbiotic N fixation by soybean is more sensitive to P stress than in cowpea. Another hypothesis is that root development of soybean plants which are dependent upon symbiotically fixed N is slower than that of N-supplied plants. Greenhouse pot experiments have shown that effectively nodulated soybean plants, grown without combined N in the nutrient solution, had less total root length than plants provided combined N, and the difference in root development was greatest at suboptimal P levels (Cassman et al., 1980). No data are available on the root development of cowpea as affected by the mode of N nutrition. A third hypothesis is that the mycorrhizal-cowpea symbiosis is efficient in the uptake of P under deficient soil P conditions irrespective of soil N availability while the efficiency of the mycorrhizal-soybean symbiosis is adversely affected by deficient soil N levels. In this experiment the data collected on mycorrhizal root infection at 50 days after emergence did not support this hypothesis since infection ratings did not differ among treatments or between the two legume species. It is possible that differences in mycorrhizal infection of roots existed during an earlier growth stage. Yost and Fox (1979) found that soybean green pod weight and P uptake by cowpea were well correlated with an early mycorrhizal infection rating but not with a later rating. It is also possible that comparison of the intensity of internal root infection between plant species is not valid. These three hypotheses are not proposed independent of one another. A comprehensive understanding of the observed experimental results may involve all three.

There are large, potentially arable land areas in the humid and semi-arid tropics where light and water would not limit crop production (Sanchez, 1976; Uehara, 1977). Kellogg and Orvedal (1969) suggested that a major factor limiting utilization of tropical areas suited for crop production is inadequate knowledge of how to manage the highly weathered Oxisols and Ultisols in these regions. Nitrogen, lime, and P are the three major fertilizer inputs required to bring these soils into profitable agronomic production (Uehara, 1977). Nitrogen-fixing grain legume crops can provide high protein food without the use of petroleum-derived N fertilizers. The data in this report indicate that some N-fixing legumes can make respectable yields with little or no P fertilization while others might not. The cowpea cultivar grown without P or

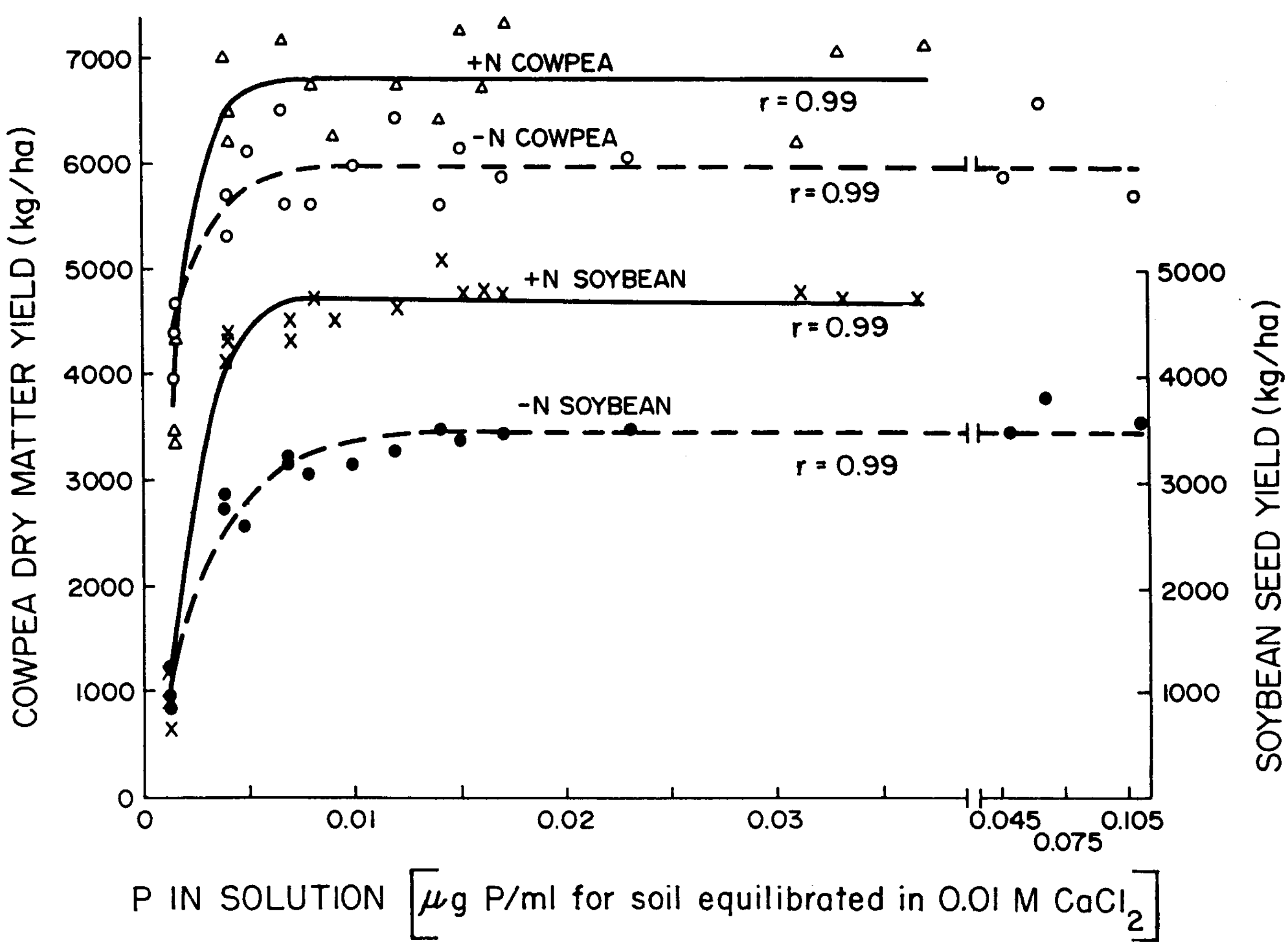

Fig. 4. Yield response of N-fixing (−N) and N-supplied (+N) soybean and cowpea to soil P as quantified by the concentration of P in a 0.01 M $CaCl_2$ solution equilibrated with soil for 6 days.

Table 3. The effect of soil N availability upon the external P requirement of soybean and cowpea as estimated by four methods.

Soil N status		P applied		Solution P†		"Bray" P		"Olsen" P	
		Extimated maximum yield	P required for 90% max. yield	Estimated maximum yield	P required for 90% max. yield	Estimated maximum yield	P required for 90% max. yield	Estimated maximum yield	P required for 90% max. yield
		kg/ha		kg/ha	ppm	kg/ha	ppm	kg/ha	ppm
Soybean	−N	3,590	750	3,480	0.007	3,440	2.8	3,500	13.5
	+N	4,710	430	4,660	0.004	4,680	1.9	4,680	8.3
Cowpea	−N	6,000	220	5,990	0.003	5,980	1.1	5,990	5.7
	+N	6,830	230	6,830	0.003	6,860	1.5	6,860	6.7

† Solution P is the concentration of P in a 0.01M $CaCl_2$ solution equilibrated for 6 days with soil (Fox and Kamprath, 1970).

N fertilizer yielded 72% of the maximum yield obtained at optimum P levels when primarily dependent upon symbiotic N fixation (Table 2). The comparable relative yield for the soybean cultivar was 287. The data also show that the critical external P requirement for the soybean cultivar differs depending upon the soil N status. For the Ultisol on which this field experiment was conducted, an application of 750 kg P/ha was required to obtain a: 90% maximum yield when soybeans were dependent upon symbiotic N fixation to meet their N requirement (Table 3). This was 320 kg P/ha more than that required by N-supplied soybean plants to obtain an equivalent relative yield. Moreover, the maximum yield of N-supplied soybean was 30% greater than the maximum yield of N-fixing soybean plants. Therefore to achieve a yield from N-supplied soybean plants equivalent in absolute terms to the 90% maximum yield of N-fixing plants required only 235 kg P/ha which is 515 kg P/ha less than that required by the N-fixing plants. It was estimated that an application of approximately. 225 kg P/ha would be required for 90% maximum yield of cowpea and this was not influenced by soil N availability.

In this experiment soil N availability was established at extremely efficient or luxuriant levels. In most arable soils the N availability would be intermediate between these two extremes. However, we conclude that screening N-fixing grain legumes for tolerance to nutrient stress should be conducted under N-deficient soil conditions to assure that nutritional requirements are assessed for the N-fixing plant, especially on the highly weathered soils of the tropics.

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