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*Full Length Research Paper*

# Phosphate rock utilization by soybean genotypes on a low-P savanna soil and the status of soil P fractions after a subsequent maize crop

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**Information on the inter- and intra-specific variability in the acquisition and utilization of phosphorus (P) by promiscuous soybean genotypes under low-P conditions can be helpful in the short-term management of soil P availability. Thirteen promiscuous soybean genotypes were evaluated in a low-P soil at Fashola in the derived savanna of Nigeria to compare their ability to acquire and utilize P from phosphate rock (PR) and single superphosphate (SSP). Changes in soil P fractions after a subsequent maize crop were also assessed. The treatments were 90 kg P/ha added as PR (90-PR), 30 kg P/ha as SSP (30-SSP), and 0 kg P/ha as a control (0-P). Large differences occurred in growth, nodulation, and mycorrhizal infection rates among the soybean genotypes and were related to the P sources. Three genotypes (Tgm 1511, Tgm 1419, and Tgm 1360) increased their shoot dry matter yield significantly with PR application. The efficiency of the genotypes to acquire and utilize fertilizer or soil P differed significantly, and their ranking depended on how efficiency is defined. Shortly after application, 90-PR and 30-SSP resulted in similar increases in available P but the effects of 90-PR on the Ca-bound pool were significantly higher than those of 30-SSP. The difference in Ca-bound P between 90-PR and 0-P decreased from 44 to 26 mg/kg after the second cropping, leading to significantly higher levels of resin-P ($p = 0.006$) and $HCO_3$-Pi ($p = 0.038$) in the PR treatment than in the control. The results of this study indicate that exploiting genotypic differences in P use efficiency may lead to the selection of soybean genotypes that can potentially enhance productivity in the low-P savanna soils.**

**Key words:** Phosphate fertilizer, phosphorus availability, phosphorus use efficiency, West Africa.

## INTRODUCTION

Owing to the inherently low fertility status of most West African savanna soils, nearly all crops or varieties achieve low yields. As a result, inputs, particularly of nitrogen (N) and phosphorus (P) that have been identified as the most limiting nutrients in savanna soils (Jones and Wild, 1975) are essential for increased crop productivity. Besides the difficulty smallholder farmers encounter in obtaining inorganic fertilizers that limits their use in the region, there is the problem of low use efficiency of applied fertilizers. The recovery of applied P is generally lowered by the relatively high amounts of iron (Fe) and aluminum (Al) oxides in tropical soils that lead to P fixation. Phosphate rock (PR) may be a cheaper source of inorganic P for crop production than commercial P fertilizers but, despite being relatively abundant in the area, it is not commonly used. Reasons include its low solubility, particularly in non-acid soils (Vanlauwe and Giller, 2006). There-

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fore, management strategies are desirable to increase the availability of P from PR and thus, to improve its agronomic effectiveness. Residual effects may also improve the growth of subsequent crops.

Soybean (*Glycine max* L. Merr.), an important grain legume commonly incorporated in the cereal-based cropping systems in the region, can contribute to the N economy of the soil through biological N fixation (BNF). It is estimated that as much as 25–85% of its total shoot N content can come from BNF (Vasilas et al., 1995). However, an adequate supply of P to the crop is critical for optimal growth and BNF. Differential growth among soybean genotypes has been reported in low-P soils (Abdelgadir, 1998), and several mechanisms have also been proposed to explain the ability of plants to tolerate soils with low P levels (Gaume et al., 2001). Although the mechanisms exhibited by soybean genotypes in adapting to low availability of P are not well understood, the identification and use of P-efficient genotypes (i.e. with the ability to utilize sparingly soluble soil or fertilizer P) may alleviate P deficiency in the short term.

The sequential extraction of soil P with various chemicals can result in the separation of biologically significant pools (Tiessen and Moir, 1993). Information on the status of soil P fractions following PR application and the growth of grain legumes such as soybean can reveal the possible contribution of legumes to PR dissolution. This study assessed genotypic variability in the utilization of PR by soybean in a low-P soil, appraised the residual effects of PR application on a subsequent maize (*Zea mays*) crop, and examined changes in soil P pools during the growth periods.

## MATERIALS AND METHODS

### Site description

The experiment was conducted from 1997 to 1999 on a field at Fashola (7° 50'N, 3° 55'E) in the derived savanna zone of Nigeria. The average annual rainfall is about 1200 mm with a bimodal pattern. The soil is classified as Oxic Paleustalf (Soil Survey Staff, 2003) with the following characteristics in the topsoil (0–15 cm): pH ($H_2O$) 6.0; Bray-1 P 5.33 mg/kg; organic C 4.8 g/kg; total N 0.4 g/kg; exchangeable cations: Ca 4.2 cmol/kg, Mn 0.03 cmol/kg, Mg 0.42 cmol/kg, K 0.11 cmol/kg and total acidity 0.01 cmol/kg; sand 800 g/kg, silt 120 g/kg, and clay 80 g/kg.

### Trial establishment

Thirteen promiscuous soybean genotypes (Tgm 0944, Tgm 1039, Tgm 1196, Tgm 1251, Tgm 1293, Tgm 1360, Tgm 1419, Tgm 1420, Tgm 1511, Tgm 1540, Tgm 1566, Tgm 1576, and Tgx 1456-2E) were planted in 1997 on experimental plots of 6 × 4 m each. Two seeds/hill were sown at a spacing of 0.75 m between and 0.05 m within rows but a week after emergence seedlings were thinned to one. Maize was also planted as a reference crop (plant spacing: 0.75 m between and 0.25 m within rows). Prior to planting, appropriate plots were fertilized with Togo PR at 90 kg P/ha (90-PR) or with SSP at 30 kg P/ha (30-SSP). A treatment without P addition (0-P) served as a control. To ensure optimal N fixation, no N fertilizer was supplied to the soybean. However, muriate of potash was applied to each plot to provide 30 kg K/ha. The field was laid out as a split plot in five randomized complete blocks. The P sources formed the main treatments; the genotypes constituted the subplots. To assess the residual effects of the PR application, maize was planted in all the plots in 1998 with urea as N fertilizer (30 kg N/ha) and allowed to grow to maturity. In 1999, the promiscuous soybean genotypes were replanted in the plots where they had been grown in 1997 but without N and P fertilization (data not presented). The plots were hand-weeded as appropriate throughout the growing seasons.

### Soil and plant sampling and analyses

In May 1997, soil samples (0–15 cm) were taken from each plot (10 cores, diagonally) at the onset of the growing season, i.e., before treatments were imposed, and referred to as pre-season samples. Another set of samples was taken in August 1997 when about 50% of the soybean plants had formed pods. In addition, pre-season samples were taken in the same way in 1998 and 1999. For each set, the samples from one plot were bulked, air-dried, and sieved (2 mm). Soil samples from the soybean plots were used to assess changes in P fractions following the addition of PR and SSP, and two seasons of crop growth (soybean/maize in rotation). The samples from replicate P treatments were bulked for each genotype to obtain 13 samples for each P treatment (0-P, 90-PR, and 30-SSP).

Soil P was fractionated sequentially using the modified Hedley procedure (Tiessen and Moir, 1993) and has been described fully by Nwoke et al. (2004). Briefly, the labile P fractions were extracted with anion exchange resin (BDH Prod 55164 2 S) strips in chloride form (Resin-P) and 0.5 M $NaHCO_3$, pH 8.5 (further separated into inorganic (Pi) and organic (Po) forms); 0.1 M NaOH extracted the moderately labile Pi and Po fractions and the Ca-bound pool was extracted with 1 M HCl. The stable Pi and Po were removed with hot concentrated HCl and the recalcitrant fraction was estimated after digestion with $H_2SO_4$ and $H_2O_2$. The molybdenum-blue method of Murphy and Riley (1962) was used to determine P concentrations in the extracts/digests. Total P was regarded as the sum of all the fractions. No significant effect from P addition was observed on some fractions, and only the pools of interest (labile and Ca-bound P) are presented.

Plant sampling was done at 50% podding stage by randomly selecting five plants from the mid-rows in each plot. The shoots of the selected plants were cut at soil level and the roots carefully dug out. These were used for the determination of dry matter yield (DMY), total N and P accumulation, nodulation, and arbuscular mycorrhizal fungi (AMF) infection. Grain yield was assessed at physiological maturity (plants on the border rows were excluded). The AMF infection rate was assessed on a 1 g sub-sample of fresh roots by the hot staining procedure of Kormanik and McGraw (1982) and counted with the modified grid line intersection technique as described by Giovanetti and Mosse (1980). The nodules were detached from the roots, counted, and weighed. The plant samples (taken at 50% pod filling stage) and the grains (taken at maturity) were dried (65°C, 24 h), weighed, and a sub-sample was ground (0.5 mm) and analyzed to quantify total N and P (IITA, 1982). The capacity of the legumes to fix atmospheric N was assessed by the ureide methodology using xylem sap, as described by Peoples et al. (1989).

### Statistical analyses and calculations

Treatment differences and interactions were assessed with a general linear model ANOVA using the procedure 'GLM" in SAS V9.1 (SAS, 1995). Mean separation was done by pair wise comparison, using the PDIFF option. Homogeneity of variances was

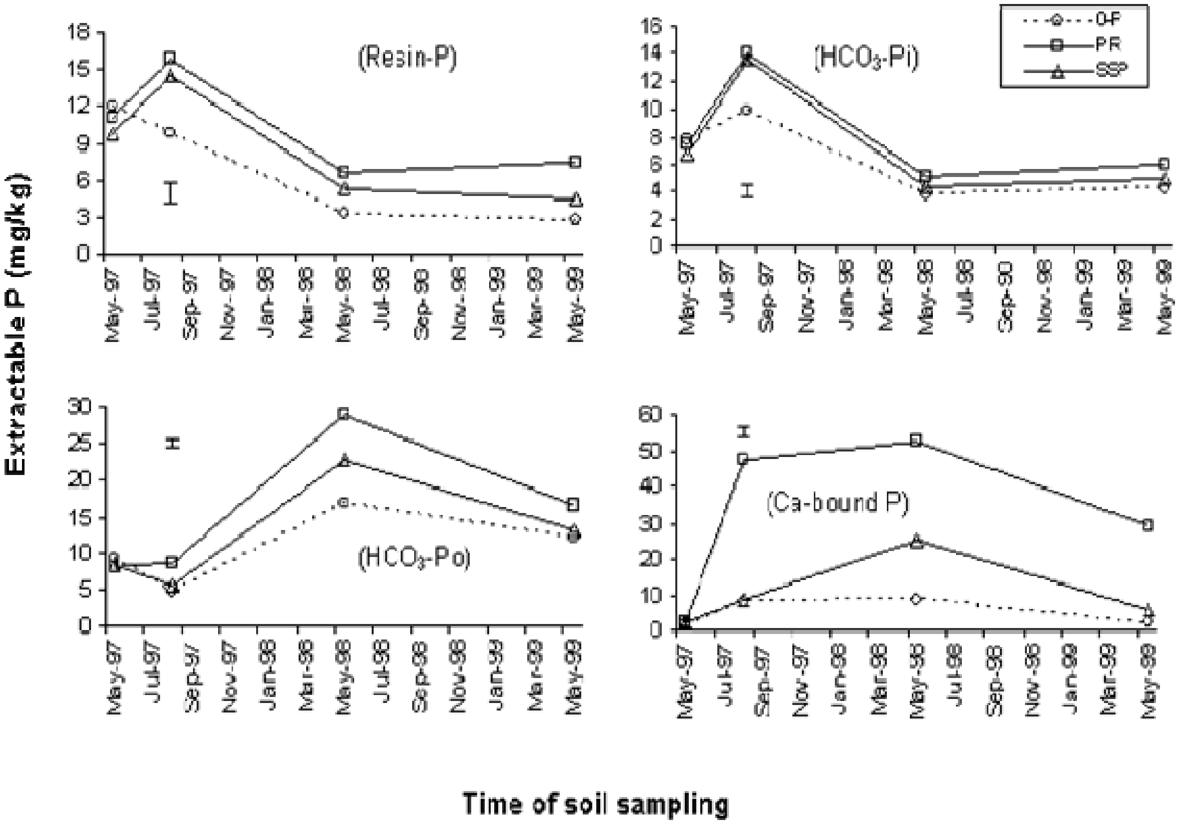

**Figure 1.** Changes in selected soil P fractions following the application of P fertilizer (PR or SSP) to a low-P savanna soil, and growth of soybean and maize crops in rotation. Bar indicates standard error of difference.

checked by plotting variance *y* against mean *y* and appropriate transformations (Gomez and Gomez, 1984) were made where necessary. Nonetheless, data are reported in their original values. Relationships among selected plant growth parameters were assessed with Pearson correlation coefficients. The efficiency of the genotypes in utilizing P was ranked with the additive main effects and multiplicative interaction (AMMI) model through the use of the microcomputer software MATMODEL Version 2.0 (Gauch, 1990). The terms used to describe P efficiency were PFUE (phosphate fertilizer use efficiency), IPUE (internal P use efficiency), and PUTE (P uptake efficiency). These were calculated with data generated during the season when P was applied as follows:

$$\mathrm{PFUE} = \frac{(\mathrm{GY}_{+\mathrm{P}} - \mathrm{GY}_{-\mathrm{P}})}{\mathrm{AP}} \qquad [1]$$

where $GY_{+P}$ is the grain yield (kg/ha) of the PR or SSP treatment, $GY_{-P}$ represents grain yield of the control treatment, and AP is the amount of P applied (kg/ha).

$$\mathrm{IPUE} = \frac{\mathrm{GY}}{\mathrm{PS}} \qquad [2]$$

where GY refers to grain yield (kg/ha) and PS refers to the amount of P in the shoot biomass (mg P).

$$\mathrm{PUTE} = \frac{\mathrm{PS}}{\mathrm{RDW}} \qquad [3]$$

where PS is mg P in the shoot biomass and RDW is the dry weight (g) of the roots.

## RESULTS

### Changes in soil P fractions as influenced by PR application and cropping

The resin-P and $NaHCO_3$-Pi fractions were lower at the end of the first cropping (year 1) than their initial values, despite the significant increase observed in plots that received P application during the growing period (Figure 1). However, a comparison of the PR treatment with the control showed significantly higher levels of resin-P ($p = 0.006$) and $HCO_3$-Pi ($p = 0.038$) in the PR treatment at the beginning of the third cropping (year 3) but the amounts in the SSP treatment were not significantly different from those in the control. The $NaHCO_3$-Po fraction was not significantly affected by P addition but significantly higher amounts were measured in year 2 than in year 1. The dilute HCl extractable fraction, commonly referred to as Ca-bound P, was larger in the PR treatment than in the other treatments for the entire study period. However, in year 3, the difference in Ca-bound P between the PR treatment and the control dropped from 44

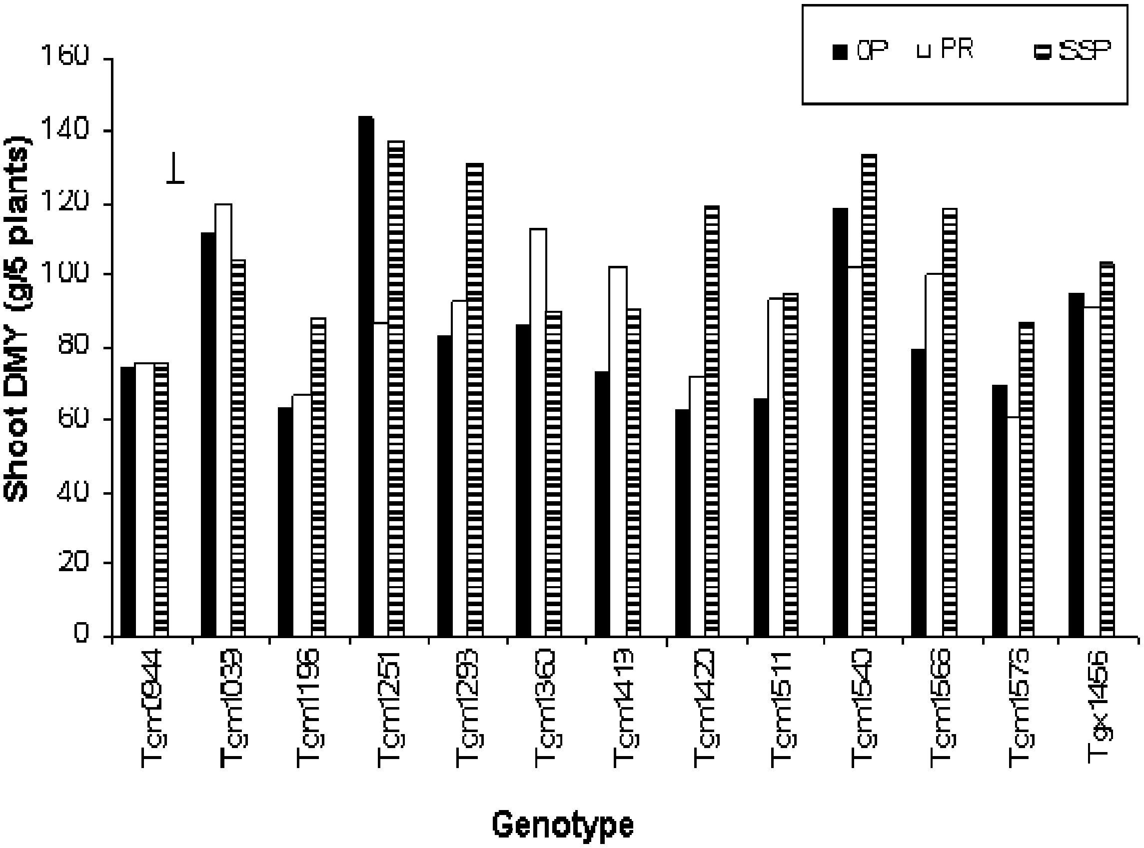

**Figure 2.** Shoot dry matter of soybean genotypes grown on a low-P savanna soil amended with P fertilizer (PR or SSP). Bar indicates standard error of difference.

to 26 mg/kg. At the same time, a higher amount of Ca-bound P was measured in the SSP treatment than in year 2.

## Shoot dry matter, N and P concentrations, and grain yield

Remarkable differences in growth occurred among the soybean genotypes and there was a significant genotype × P treatment interaction ($p < 0.05$) for shoot DMY (Figure 2). Compared with the control treatment, when PR was applied shoot DMY significantly ($p < 0.05$) increased in genotypes Tgm 1511 (by 41 %), Tgm 1419 (39%), and Tgm 1360 (31%). Some genotypes (e.g., Tgm 0944) produced relatively low shoot DMY with and without P application; Tgm 1420, Tgm 1293, and Tgm 1566 produced significantly higher yields in the SSP treatment than in the other treatments. The genotypes differed in the accumulation of N and P in their shoot biomass ($p < 0.001$) but no interaction was observed between genotype and P treatment ($p > 0.05$) (Table 1).

The grain yield varied considerably among the soybean genotypes, and no significant interaction between genotype and P treatment was observed at the 5% level of probability (Table 1). On average, it ranged from 647 kg/ha (Tgm 1540) to 2735 kg/ha (Tgm 1566). Differences in grain yield did not mirror those of shoot DMY. For example, there was no significant effect of P application on the grain yield of Tgm 1566, even though the shoot DMY was significantly increased. This genotype, however, produced more grain than the others.

## Nodule formation, N fixation, and AMF colonization of roots

There were significant differences in the number and fresh weight of nodules formed across genotypes and across P treatments (Table 1). Although no significant genotype × P treatment interaction was observed, some genotypes (Tgx 1456-2E, Tgm 0944, Tgm 1293, Tgm 1420 and Tgm 1540) nodulated relatively well in all treatments, while some others did not (e.g., Tgm 1511, Tgm 1196 and Tgm 1566). Across genotypes, the percentage of total shoot N fixed by the genotypes was not significantly different ($p = 0.864$) but across P treatments significant ($p < 0.001$) differences occurred (Table 2). AMF colonization of the soybean roots was significantly enhanced by P application; the increase was greater in the PR

**Table 1.** The grain yield, N and P contents of shoot dry matter (DM), number and fresh weight of nodules of soybean genotypes grown in a low-P soil. Values are means across P treatments and across genotypes.

| Genotype | Grain yield (kg/ha) | Shoot P content (g/kg DM) | Shoot N content (g/kg DM) | Number of nodules (/5 plants) | Fresh weight of nodules (g/5 plants) |
|---|---|---|---|---|---|
| Tgm 0944 | 1194 | 3.0 | 32.6 | 166 | 4.0 |
| Tgm 1039 | 1234 | 2.8 | 29.3 | 35 | 2.9 |
| Tgm 1196 | 1426 | 3.1 | 35.0 | 28 | 2.1 |
| Tgm 1251 | 1839 | 3.2 | 34.5 | 48 | 3.0 |
| Tgm 1293 | 995 | 2.7 | 28.9 | 144 | 3.7 |
| Tgm 1360 | 1288 | 3.3 | 34.5 | 23 | 2.3 |
| Tgm 1419 | 1338 | 2.9 | 33.1 | 49 | 2.1 |
| Tgm 1420 | 1107 | 2.8 | 32.6 | 98 | 3.7 |
| Tgm 1511 | 1124 | 2.9 | 26.9 | 22 | 1.5 |
| Tgm 1540 | 647 | 3.0 | 38.6 | 203 | 5.3 |
| Tgm 1566 | 2735 | 3.6 | 41.4 | 22 | 2.3 |
| Tgm 1576 | 1183 | 2.7 | 28.3 | 64 | 2.2 |
| Tgx 1456-2E | 1353 | 3.5 | 39.4 | 146 | 4.1 |
| SEM | 77.07 | 0.13 | 1.31 | 13.45 | 0.41 |
| **P treatment** | | | | | |
| 0-P | 1279 | 3.0 | 32.2 | 71 | 2.4 |
| PR | 1359 | 3.0 | 32.8 | 73 | 2.8 |
| SSP | 1392 | 3.2 | 35.3 | 98 | 3.8 |
| SEM | 37.02 | 0.06 | 0.63 | 6.46 | 0.20 |
| **P > F** | | | | | |
| P treatment (P) | 0.0899 | <0.0001 | 0.0014 | 0.0346 | <0.0001 |
| Genotype (G) | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| G × P | 0.0941 | 0.1705 | 0.1245 | 0.982 | 0.46 |
| CV (%) | 22.22 | 15.97 | 15.17 | 15.96 | 30.12 |

**Table 2.** Abuscular mycorrhizal fungi (AMF) infection of the roots of the soybean genotypes, N fixed (%) at mid-podding, and ratio of shoot dry matter (DM) to root DM as influenced by P application.

| Genotype | AMF (%) | | | N fixed (%) | | | Shoot DM/root DM | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0-P | PR | SSP | 0-P | PR | SSP | 0-P | PR | SSP |
| Tgm 0944 | 7 | 23 | 16 | 72 | 55 | 66 | 11 | 11 | 12 |
| Tgm 1039 | 10 | 22 | 23 | 81 | 83 | 85 | 21 | 21 | 19 |
| Tgm 1196 | 16 | 25 | 20 | 71 | 76 | 68 | 13 | 10 | 11 |
| Tgm 1251 | 10 | 32 | 24 | 69 | 71 | 68 | 28 | 11 | 20 |
| Tgm 1293 | 15 | 26 | 19 | 67 | 72 | 66 | 14 | 17 | 17 |
| Tgm 1360 | 8 | 23 | 17 | 66 | 64 | 71 | 12 | 14 | 13 |
| Tgm 1419 | 16 | 25 | 14 | 50 | 45 | 70 | 13 | 20 | 18 |
| Tgm 1420 | 8 | 24 | 19 | 60 | 61 | 63 | 8 | 11 | 14 |
| Tgm 1511 | 15 | 19 | 19 | 62 | 65 | 57 | 11 | 16 | 17 |
| Tgm 1540 | 10 | 21 | 20 | 41 | 45 | 31 | 12 | 9 | 9 |
| Tgm 1566 | 8 | 23 | 21 | 78 | 73 | 78 | 10 | 9 | 13 |
| Tgm 1576 | 14 | 28 | 23 | 71 | 64 | 67 | 10 | 13 | 13 |
| Tgx 1456-2E | 8 | 20 | 16 | 63 | 66 | 58 | 16 | 10 | 12 |
| SEM | 1.6 | | | 8.3 | | | 2.1 | | |

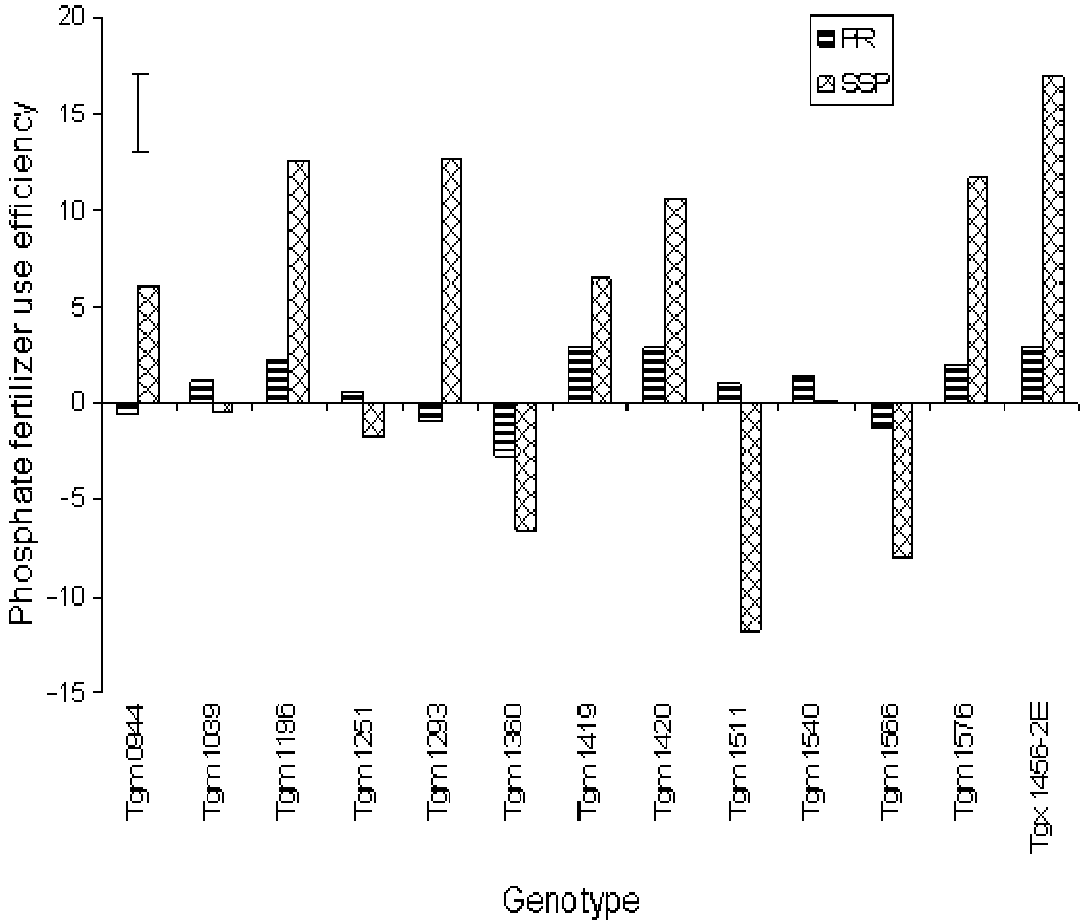

**Figure 3.** Differences in phosphate fertilizer use efficiency among soybean genotypes grown on a low-P savanna soil. Bar indicates standard error of difference.

treatment (Table 2).

### Use efficiency of soil and fertilizer P

The performance of the soybean genotypes under the different P efficiency parameters, including the shoot to root ratio, was dependent on the P treatment (Tables 2 and 3). A comparison showed that PFUE was lower in the PR treatment than with SSP, and on absolute terms, about eight genotypes had a positive PFUE with PR (Figure 3); IPUE was slightly lowered when in the SSP treatment but not with PR, whereas PUTE was not significantly different among the P treatments (data not shown). Ranking of the genotypes with the AMMI model revealed that when grain yield/unit of P applied as PR was considered, Tgm 1419, Tgx 1456-2E, and Tgm 1420 appeared more efficient than the others as they were the top three under PFUE (Table 3). But when the efficiency of P utilization within the plant (depicted by IPUE) was considered, Tgm 1566 appeared among the top three in all the treatments. In terms of the amount of P in shoot biomass/unit of dry root (PUTE), Tgm 1419, Tgm 1360, and Tgm 1039 were the highest under the PR treatment.

### Relationships between selected plant traits and some crop performance indicators

The IPUE of the soybean genotypes correlated with the selected crop performance indicators (shoot DMY, grain yield, and shoot N and P concentrations) in all the P treatments (Table 4). PUTE correlated with the crop performance indicators more in the 0-P treatment than in the RP and SSP treatments whereas no relationship was found between PFUE and the plant growth indicators. The percentage of N fixed correlated with grain yield in the 0-P and SSP treatments.

### Effect of PR application and soybean genotype on the growth of subsequent maize

The grain yield and shoot P concentration of maize were

**Table 3.** Differences in the ranking of the soybean genotypes within and among the P sources under various P efficiency traits. Ranking was performed with the additive main effects and multiplicative interaction model described by Gauch (1990).

| Genotype | Internal P use efficiency | | | P uptake efficiency | | | P fertilizer use efficiency | |
|---|---|---|---|---|---|---|---|---|
| | 0-P | PR | SSP | 0-P | PR | SSP | PR | SSP |
| Tgm 0944 | 6 | 7 | 3 | 10 | 10 | 9 | 10 | 7 |
| Tgm 1039 | 10 | 9 | 9 | 2 | 2 | 2 | 7 | 9 |
| Tgm 1196 | 2 | 4 | 2 | 4 | 9 | 12 | 4 | 3 |
| Tgm 1251 | 12 | 3 | 8 | 1 | 8 | 1 | 9 | 10 |
| Tgm 1293 | 9 | 11 | 10 | 8 | 4 | 4 | 11 | 2 |
| Tgm 1360 | 8 | 12 | 7 | 5 | 3 | 8 | 13 | 11 |
| Tgm 1419 | 3 | 8 | 5 | 9 | 1 | 3 | 1 | 6 |
| Tgm 1420 | 7 | 5 | 11 | 13 | 12 | 7 | 3 | 5 |
| Tgm 1511 | 5 | 6 | 12 | 7 | 5 | 6 | 8 | 13 |
| Tgm 1540 | 13 | 13 | 13 | 11 | 13 | 13 | 6 | 8 |
| Tgm 1566 | 1 | 2 | 1 | 6 | 11 | 5 | 12 | 12 |
| Tgm 1576 | 4 | 1 | 4 | 12 | 7 | 11 | 5 | 4 |
| Tgx 1456-2E | 11 | 10 | 6 | 3 | 6 | 10 | 2 | 1 |

significantly influenced by the preceding crop ($p < 0.05$) but not by P applied to the preceding crop (Table 5). Averaged across previous P treatments, maize grain yield varied from 1.9 to 2.6 Mg/ha while shoot P concentration ranged between 1.7 and 2.3 g/kg dry matter. No significant variation in shoot N concentration was observed. The yields of maize preceded by soybean genotypes Tgm 1540, Tgm 1251, and Tgm 0944 were significantly higher than when preceded by maize.

## DISCUSSION

The amounts of resin-P and $NaHCO_3$-Pi fractions measured in the soil before the second cropping commenced were lower than their initial values despite significant increases recorded during the season when P was applied (Figure 1). Since resin-P is generally taken as readily exchangeable soil P and $NaHCO_3$-Pi is also considered a labile fraction (Tiessen and Moir, 1993), they are biologically important and constitute a large proportion of the plant-available pool. It is evident that 90-PR and 30-SSP resulted in similar increases in plant-available P shortly after application. The significantly higher amounts of Na $HCO_3$-Po fraction measured in year 2 than in year 1 probably originated from decomposing crop residues, and can contribute to the available P pool only after mineralization. The relatively large amount of Ca-bound P detected in the PR treatment at the commencement of the second cropping (Figure 1) signifies that a large percentage of the PR still remained undissolved. However, the contribution of this pool to the P nutrition of the subsequent maize crop may have been negligible, as the maize grain yield was not significantly influenced by P application to the preceding crop. This may be due to the low levels of available P measured in the soil when maize was planted and the apparently slow release of P from the Ca-bound pool. Thus, the residual value of P applied to soybean as PR was not visible during the cropping season following application. Nevertheless, the drop in net Ca-bound P concentration (i.e., the difference between the PR treatment and the control) from 44 to 26 mg/kg observed just before the third cropping suggests that PR had further dissolved, leading to significantly higher resin-P ($p = 0.006$) and $HCO_3$-Pi ($p = 0.038$) levels in the PR treatment than in the control. In general, although 90-PR and 30-SSP gave similar increases in available P, the effects of PR on the Ca-bound pool and, of course, on the total P (data not shown) were significantly higher than those of SSP. Considering the amount of P introduced into the soil through each source, the results of this study corroborate the recommendation of Mokwunye and Bationo (2002) that PR be used for soil amendment to raise the total P stock, rather than for immediate improvement of P fertility with the expectation of instant returns to the investment on soil management. However, this may require repeated application of 90-PR as a one-time application is insufficient to raise total soil P stock appreciably.

The observed differences in the growth of the soybean genotypes could be attributed to their ability to acquire and utilize P to attain maximum growth at various levels of P availability. Similar differential growth characteristics have been reported for genotypes of soybean (Abdelgadir, 1998) and cowpea (Sanginga et al., 2000) grown in P deficient soils. The significant increase in shoot DMY achieved by Tgm 1419 following PR application coupled with the results of the ranking for PUTE and PFUE by the AMMI model indicate that this genotype has the potential to utilize sparingly soluble P. It was also evident that

**Table 4.** Pearson correlation coefficients showing relationships between crop performance variables (shoot DMY, grain yield, and shoot N and P accumulation) and arbuscular mycorrhizal fungi (AMF) infection, N fixed (%), shoot/root ratio, P uptake efficiency (PUTE), internal P use efficiency (IPUE), phosphate fertilizer use efficiency (PFUE), and number (nr) and fresh weight (FWT) of nodules formed by soybean genotypes under different P treatments in a low-P soil.

| | 0-P | | | | PR | | | | SSP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Shoot DMY | Grain yield | Shoot N | Shoot P | Shoot DMY | Grain yield | Shoot N | Shoot P | Shoot DMY | Grain yield | Shoot N | Shoot P |
| | ←----------------- kg/ha ------------------> | | | | ←----------------- kg/ha ------------------> | | | | ←-----------------kg/ha ----------------> | | | |
| AMF (%) | –0.23 | –0.21 | –0.33** | –0.27* | –0.15 | 0.17 | –0.05 | –0.12 | 0.20 | 0.09 | 0.04 | 0.16 |
| N Fixed (%) | –0.02 | 0.40** | –0.06 | 0.01 | 0.01 | 0.21 | –0.12 | 0.00 | –0.24 | 0.45*** | –0.26* | –0.29* |
| Shoot/root | 0.63*** | 0.05 | 0.59*** | 0.55*** | 0.22 | –0.20 | –0.09 | 0.01 | 0.13 | 0.05 | –0.07 | –0.03 |
| PUTE | 0.60*** | 0.21 | 0.62*** | 0.69*** | 0.27* | –0.04 | 0.10 | 0.32** | 0.26* | 0.25* | 0.20 | 0.27* |
| IPUE | –0.58*** | 0.54*** | –0.48*** | –0.45*** | –0.54*** | 0.54*** | –0.42*** | –0.49*** | –0.60*** | 0.61*** | –0.49*** | –0.53*** |
| PFUE | NA | NA | NA | NA | 0.01 | 0.16 | 0.00 | 0.10 | –0.04 | 0.14 | 0.10 | 0.00 |
| Nodule nr. | 0.10 | –0.33** | 0.10 | 0.01 | 0.02 | –0.39** | 0.15 | 0.06 | 0.11 | –0.21 | 0.30* | 0.23 |
| Nodule FWT | 0.16 | –0.18 | 0.11 | 0.09 | 0.16 | –0.09 | 0.26* | 0.31* | 0.13 | –0.18 | 0.32** | 0.28* |

*Significant at 5% level, **Significant at 1% level, ***Significant at 0.1% level. NA = not applicable.

some of the genotypes could draw enough P from the inherent soil P for optimal growth. For example, Tgm 1251, Tgm 1039, and Tgm 1540 did not respond to P application but had a relatively high shoot DMY. There were significant differences among the soybean genotypes in the accumulation of N and P in their shoot biomass. Plants can improve their access to soil or applied nutrients by increasing their absorptive areas. It is not clear whether some of the genotypes adopted this mechanism, since differences in their shoot/root ratios were not large. Adjustment of the shoot/root ratio is a morphological response to limitation of nutrients, particularly P. In this regard, some cowpea genotypes have been found to respond to P stress by increasing their root biomass to explore more soil volume (Sanginga et al., 2000). In the present study, the significant correlation between PUTE and plant growth parameters at 0-P application (Table 4) underscores the importance of root characteristics in P acquisition under limiting conditions. Some genotypes can also rely on the symbiotic association between AMF and the plants' roots to overcome P stress. The AMF infection rate of the soybean roots was generally low (7–32%), even though the application of P resulted in a slight increase. Nwoko and Sanginga (1999) reported strong dependency on AMF for growth improvement under low P availability by some soybean genotypes, such as Tgm 1039 and Tgm 1420. In our study, such AMF-dependency was not measured but cannot be entirely ruled out. Although the genotypes differed in the number of nodules formed, the proportion of shoot N from BNF was relatively high (mean = 65%) and within the range reported for soybean in other studies (Vasilas et al., 1995). These results indicate that the genotypes retained their promiscuity in this soil, since there was no inoculation with *bradyrhizobia* strains.

The efficiency of the soybean genotypes in acquiring and utilizing P from PR was remarkably different and the ranking of the genotypes for the various parameters relating to P efficiency depended largely on how efficiency is defined. It has been noted that efficiency consists in the ability to obtain plant nutrients from the soil solution and/or to use them in the production of total above- and/or belowground biomass or other plant components such as grain (Blair, 1993). From the results of the present study, Tgm 1566 had a higher IPUE than genotypes such as Tgm 1540, irrespective of the P source. This signifies that translocation of P from the shoot to the grains was higher in Tgm 1566 and resulted in the higher grain yield than in Tgm 1540. However, the apparently low P harvest index of Tgm 1540 compared to that of Tgm 1566 could be advantageous where crop residues are incorporated into P fertility management strategies. Therefore, the desired output (biomass or grain) is of the utmost importance in assessing P efficiency traits in plants. The data presented indicate that a great potential exists for the selection

**Table 5.** The influence of previous crop and P application on grain yield and the concentration of N and P in the shoot dry matter (DM) of maize on a low-P soil in Fashola, Nigeria.

| Previous genotype or crop | Grain yield (kg/ha) | Shoot N content (g/kg DM) | Shoot P content (g/kg DM) |
|---|---|---|---|
| Tgm 0944 | 2561 | 11.9 | 1.9 |
| Tgm 1039 | 2372 | 13.2 | 1.9 |
| Tgm 1196 | 2403 | 12.9 | 2.0 |
| Tgm 1251 | 2639 | 12.2 | 1.9 |
| Tgm 1293 | 2390 | 13.2 | 2.1 |
| Tgm 1360 | 2045 | 12.8 | 2.3 |
| Tgm 1419 | 1924 | 11.9 | 2.0 |
| Tgm 1420 | 2047 | 12.7 | 1.7 |
| Tgm 1511 | 2190 | 13.2 | 2.3 |
| Tgm 1540 | 3080 | 13.1 | 1.6 |
| Tgm 1566 | 2228 | 12.2 | 2.2 |
| Tgm 1576 | 2021 | 13.9 | 2.0 |
| Tgx 1456-2E | 2380 | 12.6 | 2.0 |
| Maize | 2146 | 13.2 | 2.2 |
| SEM | 180.06 | 0.56 | 0.15 |
| **P treatment** | | | |
| 0-P | 2300 | 12.7 | 2.0 |
| PR | 2233 | 12.8 | 2.0 |
| SSP | 2415 | 12.9 | 2.0 |
| SEM | 84.152 | 0.26 | 0.07 |
| **P > F** | | | |
| P treatment (P) | 0.303 | 0.8151 | 0.7788 |
| Crop (C) | 0.001 | 0.3996 | 0.0487 |
| C × P | 0.0387 | 0.7718 | 0.4024 |
| CV (%) | 30.12 | 16.96 | 29.21 |

of soybean genotypes for enhanced biomass and grain production in the low-P savanna soils. Genotypes that have the potential to acquire soil P efficiently and fix high amounts of N (e.g., Tgm 1039) could be incorporated into legume-cereal cropping systems to augment soil N through their residues and enhance soil fertility in the short term.

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