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# SOIL FERTILITY

## Soil and Plant Influences on Crop Response to Two African Phosphate Rocks

Ray R. Weil*

### ABSTRACT

**Affordable technologies are needed to allow smallholder farmers to effectively use the phosphate rocks (PRs) found in many African countries. A pot study was conducted in Tanzania using two PRs (Panda and Minjingu) and two soils (an Alfisol and an Andisol) to assess responses of several types of crops to these PRs and to determine whether changes in crop responses to PR with time are due to crop sequence or merely contact time with soil. The Panda PR had no effect on growth or tissue P content in maize (*Zea mays* L.), bean (*Phaseolus vulgaris* L.), and pigeon pea [*Cajanus cajan* (L.) Millsp.], but it nearly tripled these parameters for cabbage (*Brassica oleracea* L.) on the Alfisol. Freshly applied Minjingu PR only slightly stimulated maize and pigeon pea, but nearly tripled cabbage yield in both soils. Previous crop had a greater effect than previously applied PR on second crop maize. Yields and P content of maize were always lowest following cabbage and highest following pigeon pea. Minjingu PR, but not Panda PR, had residual benefits on maize. Severe Mn toxicity occurred in all crops on the unamended Andisol. The calcareous Minjingu PR, but not the Panda PR, increased yields dramatically on the Andisol, partly by raising the soil pH in water enough (from 4.6 to 5.6) to alleviate Mn toxicity. Future P fertility work in Africa should pay adequate attention to the effects of crop sequences and soil biological properties.**

The densely settled humid and subhumid regions in East Africa are suffering high rates of soil fertility depletion (Smaling et al., 1993). These areas are dominated by Alfisols, Oxisols, and Andisols—the productivity of which is commonly limited by deficiency of P (Weil et al., 1991; Jama et al., 1997). Because the majority of African farmers cannot afford to adequately fertilize their cropland with imported manufactured fertilizers, there is much interest in developing indigenous sources of nutrients, especially phosphate rock (PR) in sub-Sahara Africa (McClellan, 1989; Buresh et al., 1997).

Substantial deposits of PR in many sub-Sahara African countries are too low-grade to justify commercial production of refined fertilizer products, but could be mined and ground using labor intensive methods with a minimum of capital expenditure to produce inexpensive sources of potentially useful nutrients (Sheldon, 1982). However, since many of the PR deposits in sub-Sahara Africa are both low grade and low reactivity (Kurtanjek and Tandy, 1984), untreated PR often does not produce a plant growth response, even on acid soils (Lüken and Blümel, 1984; Ngatunga et al., 1989).

Tanzania has two principal deposits of PR that could potentially be used to boost agricultural production and enhance food security in Tanzania and neighboring countries (Harris, 1961). In northeast Tanzania, along the shores of Lake Manyara, a sedimentary PR occurs at Minjingu Hill. This material has been mined sporadically with and without various degrees of beneficiation since the early 1960s. After removing clay impurities, the Minjingu PR has a total P content of 115 to 160 g $kg^{-1}$ and a high content of carbonates. It is considered a reactive PR because of its high solubility in citric acid and moderate solubility in neutral ammonium citrate (Table 1). Minjingu's location relative to Tanzanias transport infrastructure makes it exportable to Kenya and Uganda as well as available for use in the northern part of Tanzania.

Panda Hill near Mbeya in southern Tanzania contains a residual PR derived from igneous rock, a carbonatite, with a total P content of about 46 g $kg^{-1}$ in the raw ore and up to 85 g $kg^{-1}$ in ore that has been concentrated by simple magnetic removal of magnetite. The Panda PR is well located for distribution throughout the well-

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**Abbreviations:** PR, phosphate rock; TSP, triple superphosphate; AM, arbuscular mycorrhizae.

**Table 1. Chemical composition of Minjingu and Panda phosphate rocks. The data are for various samples of PR from the batches of ground rock used in the pot study. Except for total P content, the data were determined by Kamasho et al. (1992), Floor and Kimambo (1989), and IFDC (personal communication, 1994).**

| Parameter | Concentration | |
|---|---|---|
| | Minjingu | Panda |
| | g kg$^{-1}$ | |
| Total P | 150 | 80 |
| Neutral ammonium citrate soluble P | 13 | 7 |
| Citric acid–soluble P | 60 | 22 |
| Ca | 330 | 19 |
| Mg | 20 | 8 |
| Na | 6 | 14 |
| K | 11 | 30 |
| Si | 48 | 224 |
| F | 28 | 17 |
| Al | 12 | 80 |
| Fe | 7 | 87 |
| Carbonate as $CO_2$ | 53 | 32 |

watered and densely settled Southern Highlands region of Tanzania, where soils are generally acid and deficient in P (Chesworth et al., 1988). The solubility of Panda PR (Table 1) is much lower than that of Minjingu PR, and the iron content is much higher (van Straaten et al., 1992). Yield responses to Panda PR, relative to triple superphosphate (TSP), have been even more erratic than to Minjingu PR (Kamasho et al., 1992; van Straaten et al., 1992). Panda PR generally failed to increase crop yields when used in direct application field trials on acid soils of the region (J.A. Kamasho, Uyole Agriculture Research Station, personal communication, 1994). Partial (50%) acidulation of the Panda PR significantly improved its effectiveness in field trials (van Straaten et al., 1992); however, the partial acidulation process may be nearly as costly as importing TSP (Sanchez and Salinas, 1981). Therefore, direct application of PR would be much preferred, if it can be done in a way that effectively alleviates crop P deficiencies.

An intriguing phenomenon reported in many longer-term experiments is a delay in crop response to PR such that the first crop grown after PR application gives little or no response, but the second and third crops respond well (Anderson, 1965, 1970; Bromfield et al., 1981; Gichuru and Sanchez, 1988; Kimbi, 1991; Haque and Lupwayi, 1998). For example, Bromfield et al. (1981) used Minjingu PR at 50 kg P ha$^{-1}$ and found a nonsignificant 29% increase in maize (*Zea mays* L.) yield compared with the control in the first harvest after PR application, but there was a significant 73% increase in the third harvest.

Understanding such a delayed response to PR would be important because taking this delay into account might lead to more efficient use of PR in cropping systems by planting a high-P demanding, staple crop later in the rotation after applying the PR. Also, since poor farmers look for an immediate return on their investment, this delayed action of PR could discourage them from using even relatively reactive PRs. It has generally been assumed that the increased effectiveness of PR with time in acid soils is due to a slow reaction by which soil acids dissolve a certain fraction of the P from the PR over a period of several months to years (Sanchez and Salinas, 1981; Rajan et al., 1996). However, observations from some pot studies (Mughogho and Weil, unpublished data, 1993) have indicated that the PR benefits a second crop much more than the first crop, even if the first crop was grown for only about 1 mo. An alternative hypothesis is that improved effectiveness over time is related to the action of the particular plants growing in the soils, and not simply to the time of soil–PR contact.

Most studies of crop response to direct application of PR in Africa have used maize as the test crop (e.g., Bromfield et al., 1981; Mnkeni et al., 1991; Buresh et al., 1997). However, research has shown that some plants are better able than others to use PR as their source of P (Bekele et al., 1983; Flach et al., 1987; Floor and Kimambo, 1989; van Diest, 1991; Haynes, 1992). Further, arbuscular mycorrhizae (AM) infection is well known to greatly improve P uptake by many plants in low P soils (Islam et al., 1980; Flach et al., 1987). Crop strategies for P uptake may be grouped into four types.

First, many monocots have extensive fibrous root systems, generally with AM infection, that allow these plants' roots to have very intimate contact with PR particles in the soil, and may give them some advantage in PR use (Menon et al., 1995). Second, despite a less extensive root system, annual legumes have also been shown to use PR efficiently (Aguilars and van Diest, 1981; Bekele et al., 1983). Because of their $N_2$ fixation ability, legumes generally use such low amounts of nitrate that the plants take up an excess of cations over anions. This imbalance leads to an excretion of $H^+$ ions, which acidify the rhizosphere and release soluble P from Ca phosphates such as found in PR. Third, pigeon pea [*Cajanus cajan* (L.) Millsp.] has been shown to excrete piscidic acid, which specifically complexes with Fe to greatly increase the availability of Fe-bound P (Ae et al., 1990). Fourth, it is well known that crops in the *Cruciferae* family, such as rape (*Brassica napus* L.) and

**Table 2. Selected properties of the two soils used in the pot experiment. Both soils were sampled from the Ap horizon (0–15 cm).**

| Soil name | Suborder | Clay | Sand | Bulk density | Water holding capacity | Total C† | Total N† | $pH_w$ | $pH_{KCl}$ | CEC‡ | Bray 1 P | Total Mn§ | DTPA Mn¶ | Langmuir# 1/*b* | Langmuir# *k* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | g kg$^{-1}$ | | Mg m$^{-3}$ | L L$^{-1}$ | g kg$^{-1}$ | | | | cmol$_c$ kg$^{-1}$ | mg kg$^{-1}$ | | | | |
| Ihanda | Kandiustalf | 300 | 630 | 0.97 | 0.35 | 22.1 | 1.4 | 6.3 | 5.60 | 18.4 | 3.0 | 2200 | 120 | 1667 | 0.11 |
| Sasanda | Melanustand | 200 | 400 | 0.72 | 0.40 | 46.1 | 3.7 | 5.3 | 4.66 | 27.9 | 0.7 | 3234 | 480 | 3058 | 0.75 |

† By LECO high temperature combustion analyzer.
‡ By ammonium acetate at pH 7.0 (National Soil Survey Center, 1996).
§ By pressurized microwave digestion with $HNO_3$.
¶ DTPA buffered at pH 5.3 by method of Norvel (1984).
# Langmuir parameters from Chesworth et al. (1988).

**Table 3. Effect of initial P amendment and the first crop on shoot dry matter and shoot P content of a second crop of maize grown for 40 d.**

| | Treatment factor | | Shoot dry matter | | |
|---|---|---|---|---|---|
| Treatment no. | Initial P amendment | First crop | Ihanda soil | Sasanda soil | Shoot P content† |
| | | | g pot$^{-1}$ | | mg pot$^{-1}$ |
| 1 | No P | Bare | 3.96ab* | 0.90a | 3.56a |
| 2 | No P | Bean | 6.35c | 1.17a | 6.01b |
| 3 | No P | Maize | 5.93c | 0.90a | 4.66b |
| 4 | No P | Pigeon pea | 6.44c | 1.07a | 7.00b |
| 5 | No P | Cabbage | 3.38a | 0.89a | 3.15a |
| 6 | Panda PR | Bare | 4.22b | 0.98a | 3.14a |
| 7 | Panda PR | Bean | 6.54c | 1.46a | 5.22b |
| 8 | Panda PR | Maize | 5.00bc | 1.51a | 5.15ab |
| 9 | Panda PR | Pigeon pea | 6.45c | 1.71a | 4.05ab |
| 10 | Panda PR | Cabbage | 4.61b | 1.09a | 2.56a |
| 11 | Minjingu PR | Bare | 6.17c | 2.21ab | 6.41b |
| 12 | Minjingu PR | Bean | 6.53c | 6.23c | 13.12c |
| 13 | Minjingu PR | Maize | 6.40c | 6.23c | 13.00c |
| 14 | Minjingu PR | Pigeon pea | 8.16d | 6.62c | 13.01c |
| 15 | Minjingu PR | Cabbage | 4.67b | 2.32ab | 5.62b |
| 16 | TSP‡ | Bean | 6.84b | 4.50ab | 9.54bc |
| 17 | TSP | Maize | 2.41cd | 1.65ab | 3.16ab |
| 18 | TSP | Pigeon pea | 6.14bcd | 3.16ab | 9.11bc |
| 19 | TSP | Cabbage | 5.08bc | 1.71ab | 4.06ab |

* Means in a column followed by different letters differ significantly at the 0.05 level by *F*-protected Fishers LSD.
† Means shown are for two soils because there was no significant soil × P treatment interaction.
‡ For treatments involving TSP, which was applied to only one replication, least square means are given.

cabbage (*Brassica oleracea* L.) do not form mycorrizhae, but apparently can enhance P availability from calcium phosphates by the excretion of citric and malic acids, the formation of extensive fine root hairs, and the uptake of high amounts of Ca (van Diest, 1991; Hoffland, 1992).

This paper reports on a glasshouse pot study conducted in Tanzania mainly to investigate the delayed response phenomenon and to test the hypothesis that one crop may influence the effectiveness of PR for a following crop. Secondarily, this study was designed to provide information on the responses to Panda and Minjingu PRs by the four types of crops mentioned in the previous paragraph.

## MATERIAL AND METHODS

Maize was used as the test crop in a pot study because this is the main staple food crop in the region where the Panda and Minjingu PRs are found and because it is the crop that has usually shown a delayed response to PR. Maize was planted after PR had been in moist soil for 58 d, with either no crop (bare soil), or one of four crops that are important in the southern highlands of Tanzania and have differing mechanisms of P utilization in soil: (i) open-pollinated maize ('Kalimina-SR')—a crop with fine, fibrous, AM-dependent roots; (ii) bean ('Kabamina')—a legume that is AM-dependent and acidifies its rhizosphere; (iii) pigeon pea (unnamed, large seeded local land race)—a crop with special ability to solubilize iron phosphates; or (iv) cabbage ('Glory of Enkhuizen')—a crop that does not form AM.

### Soils and Crops Used

The study was conducted in a glasshouse at the Ministry of Agriculture Research and Training Institute at Uyole, Tanzania (1750 m above sea level) using two soils (Table 2). The Ihanda soil is representative of the Kandiustalfs formed from hillwash from mafic rocks, which are commonly used for smallholder food crops in areas with approximately 1200 mm annual rainfall. The Sasanda soil is representative of the soils formed in volcanic ash and pumice in the higher rainfall (1500 mm yr$^{-1}$) and elevation (>2000 m) areas of the southern highlands, which are commonly used for coffee (*Coffea arabica* L.) and smallholder food crops. Since both soils also had been used for several years in field trials of maize response to P, the optimum levels of P application were known for each (J. Kamasho, personal communication, 1994).

### Treatments and Statistics

The main study included 18 treatments applied to two soils and replicated four times plus four treatments replicated only once for each soil, giving a total of 152 pots (Tables 3 and 4). The experimental design was a split plot randomized complete block, with soils as main plots and crop × P amendment combinations (treatments) as subplots. Once a week, pot locations on the greenhouse bench were rerandomized within each main plot (soil).

The treatments to compare the effects of plants and soil contact time consisted of combinations of five initial crops (the four listed above plus bare soil) and four P sources (Panda PR, Minjingu PR, TSP, and no P) applied 1 d before planting the initial crop. Additional treatments were also included in which three P sources were applied just before planting the second crop (Treatments 20, 21, and 22, Table 4). Effects of

**Table 4. Effect of P amendments applied just before planting on shoot dry matter and shoot P content of a second crop of maize grown for 40 d following bare soil for 58 d without P applications.**

| Treatment no. | Experimental factor | Shoot dry matter | Shoot P content |
|---|---|---|---|
| | | g pot$^{-1}$ | mg pot$^{-1}$ |
| | Soil | | |
| | Ihanda | 4.84b | 7.81b |
| | Sasanda | 2.32a | 3.24a |
| | Second crop P amendment† | | |
| 1 | No P | 2.48a | 3.45a |
| 20 | Panda PR | 2.07a | 3.56a |
| 21 | Minjingu PR | 2.08a | 3.01a |
| 22 | TSP | 7.67b | 12.08b |

† All amendments were mixed into upper 7.5 cm of soil. Means across both soils are shown because there was no significant soil × P treatment interaction for the subset of treatments in this table.

soil, P source, initial crop, and the interactions of these factors were analyzed by general linear models procedures capable of handling unbalanced designs such as resulted from the incomplete replication of the initial TSP treatments. Differences between the two soils were tested by ANOVA *F* test for the soil main effect. Differences among soil × P source × initial crop treatment combinations were tested using the appropriate LSD value, but only if the corresponding *F* test was significant. The probability level for significance is 0.05, unless specified otherwise.

### Soils and Phosphorus Amendments

For each soil, Ap horizon material was collected from an unfertilized maize field during the dry season. The soil was sieved to pass either a 12-mm screen (Ihanda) or a 3-mm screen (Sasanda) to homogenize the soil while preserving the natural structural aggregates. Four L of screened, air-dry soil (3.9 kg for Ihanda and 2.9 kg for Sasanda) was placed in each pot and mixed with the P amendment appropriate for the particular treatment 1 d before planting seeds. For Treatments 20, 21, and 22 the amendments were mixed into the upper 7.5 cm of soil 58 d later, just after the first crop was harvested. From previous field and pot studies (J.A. Kamasho, personal communication, 1994) it was determined that the optimum level of P application as TSP was 100 mg P $kg^{-1}$ of Ihanda soil and 400 mg P $kg^{-1}$ of Sasanda soil. Therefore all P amendments were applied to supply these rates of total P (390 mg P $pot^{-1}$ of Ihanda and 1160 mg P $pot^{-1}$ of Sasanda).

### Initial Crops

On Day 0 the soils were moistened and pregerminated seeds (four per pot, later thinned to two plants per pot) were sown for pots with initial bean, maize, or pigeon pea crops. Two seedlings were transplanted (after rinsing the roots) into each pot meant to grow cabbage as the initial crop. Pots were hand weeded weekly and plants checked for insect pests three times per week. On Day 17 chlorfenvinphos [2-chloro-1-(2,4-dichlorophenyl) vinyl] was sprayed on all plants to control white fly.

A P-free nutrient solution was added to all pots to supply the following amounts of nutrients per pot: 65 mg N as ammonium sulfate, 100 mg K as KCl, 25 mg Mg as $Mg(NO_3)_2$, 25 mg Ca as $CaSO_4$, 5 mg Cu as $CuSO_4$, and 5 mg Zn as $ZnSO_4$. An additional 100 mg N was applied as $NH_4NO_3$ on Day 28 for pots with nonlegume crops and on Days 65 and 85 for the second crop maize in all pots. Just before planting the first crop all pots were brought to −10 kPa water potential (0.35 L $L^{-1}$ for Ihanda and 0.42 for Sasanda) with distilled water (8.5 $\mu S\ m^{-1}$). Thereafter, this water content was reestablished every second day by bringing each pot up to its original weight with distilled water. Air temperature in the shade ranged from 20 to 35°C. Soil temperature at 5 cm depth ranged from 17 to 30°C. No supplementation of natural sunlight was used. On Day 58, all aboveground plant parts were harvested by cutting off the shoot 0.5 cm above the soil line. Fresh and dry (48 h at 65°C) weights of the tissue were recorded.

### Second Crop

The day after harvesting the first crop, fresh P amendments were mixed into the upper 7.5 cm of soil for Treatments 20, 21, and 22. On Day 62, four pregerminated maize seeds were planted in each pot. This second crop maize served as the test crop for the effects of previous crop, initial soil amendments, and fresh soil amendments.

On Day 102 (40 d after sowing), all maize plants were harvested. Shoots were harvested by cutting of 0.5 cm above the soil line and analyzed for fresh weight, dry weight, total P, and total Mn. Soil was sampled from selected treatments. Roots from Treatments 11 to 15 and 4 were harvested by soaking the root–soil mass in water and then washing over a 2-mm screen. The clean roots were then blotted dry, weighed, dried, and reweighed.

### Soil and Plant Analyses

The dried plant tissue was ground in a Wiley mill (<1 mm) and digested in perchloric acid. The digest was analyzed for total P by the Murphy–Riley colorimetric method and for total Mn (in Treatments 2–5, 7–10, and 12–15 for initial crops and in Treatments 1, 8, 9, 12–15, and 22 for second crop maize) by atomic absorption spectrometry. Samples of soil were obtained from selected treatments immediately after harvest of the first and second crops by removing two 1 cm by 8 cm cores. The soil cores were air-dried, sieved to <2 mm, and analyzed for Bray 1 extractable P, electrical conductivity of a 2:1 water/soil slurry (EC), and pH in a 2:1 water/soil slurry ($pH_w$) and in a 2:1 slurry using 1 *M* KCl solution ($pH_{KCl}$).

As an exploratory measure, roots of the first crop for Treatments 2, 3, and 17 for both soils in one block were collected from the soil cores before drying and cleared and stained for detection of AM fungal infection by the method of Koske and Gemma (1989). Mycorrhizal infection of the prepared roots was quantified by determining the total and infected root lengths in each sample by the grid intersection method under 50 to 100× magnification. The results were then expressed as percentage of total root length that was infected. For the second maize crop, roots in Treatments 11 to 15 and 4 were washed and blotted, and then a small subsample of fine roots (<2% of the total root mass) was removed and prepared for mycorrhizal analysis as described above.

## RESULTS AND DISCUSSION

### Initial Cropping Period

Levels of Bray 1 P were reduced by cropping from their low initial levels (Table 2) in both Ihanda and Sasanda soils (Table 5), with those in the Sasanda soil as low as 0.05 mg $kg^{-1}$. Amendment with Minjingu PR maintained the Bray 1 P levels near the original levels, but soil amended with Panda PR was not significantly higher in Bray 1 P than the unamended soils.

The dry matter response of four initial crops to the

**Table 5. Influence of P amendments on Bray 1 extractable P and soil pH for two Tanzania Southern Highlands soils after a 58-d initial crop growing period.†**

| Parameter | Bray 1 extractable P | $pH_{KCl}$‡ | $pH_w$‡ |
|---|---|---|---|
| | mg $kg^{-1}$ | | |
| Soil | | | |
| Ihanda | 1.53b* | 5.03b | 6.1‡ |
| Sasanda | 0.34a | 4.39a | 5.0 |
| Initial P amendment | | | |
| No P | 0.58a | 4.56a | 5.2 |
| Panda PR | 0.75a | 4.58a | 5.4 |
| Minjingu PR | 1.48b | 5.00b | 6.0 |

* Means for soil and P amendment followed by different letters differed significantly by the *F*-protected LSD test ($P < 0.01$).

† Means of bean and cabbage initial crops. P rates: 100 mg P $kg^{-1}$ for Ihanda; 400 mg P $kg^{-1}$ for Sasanda; 4 L of soil per pot.

‡ $pH_{KCl}$ = pH measured in 1 *M* KCl, $pH_w$ = measured in distilled water, which was subject to soluble salt effects and therefore not compared statistically.

Panda and Minjingu PRs and to TSP are shown in Fig. 1. Phosphorus uptake per pot closely paralleled dry matter production (data not shown). Except for cabbage fertilized with Minjingu PR, yields of all crops were lower in Sasanda soil than in Ihanda soil. Bean in both soils was unaffected by any P source, suggesting that bean growth was limited by some unidentified factor besides P supply. Maize, cabbage, and pigeon pea yields in both soils were increased when amended with Minjingu PR, which was at least as effective as TSP for these crops.

In contrast, Panda PR had no significant effect on any crop, except cabbage in Ihanda soil. Cabbage in the Panda PR–treated Sasanda soil was severely stunted by Mn toxicity, as discussed below. In fact, Panda PR more than doubled the dry matter yield of cabbage in Ihanda soil, producing plants in all four replications as large and vigorous appearing as those produced with TSP or Minjingu PR. This result is potentially of great importance since it suggests that even though Panda PR was not effective in raising maize yields, it may be a valuable P source for cabbage, an important cash crop widely grown at high elevations throughout East Africa. The reasons for this crop's good response to the unreactive and Fe-rich Panda PR are not clear. Earlier work (van Diest, 1991) with another member of the Brassica genus suggests that low P conditions induce roots of these plants to excrete several organic acids that complex with both Ca and Fe, increasing the solubility of P bound to these metals in the soil. Production of Brassica crops may provide an economically attractive use of low reactivity, Fe-rich, igneous PR deposits in East Africa that are otherwise ineffective for direct application to soils.

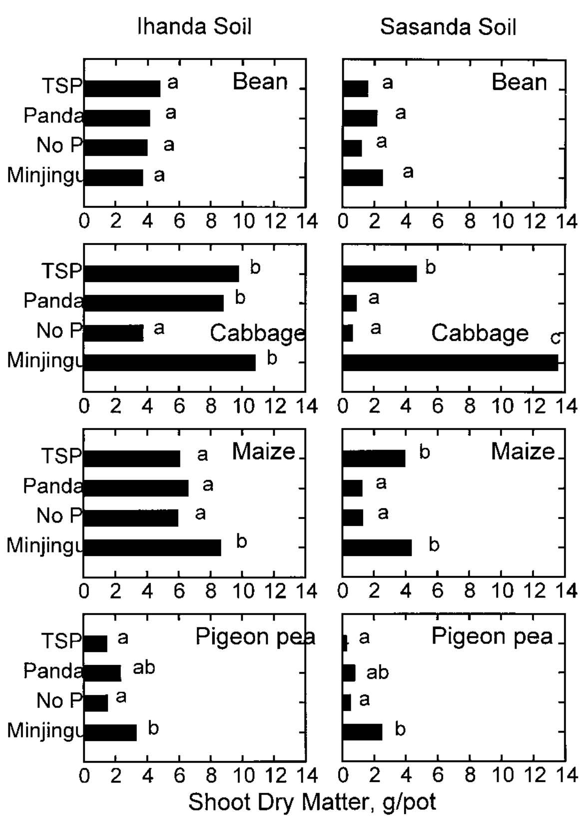


**Fig. 1. Effect of P source on shoot dry matter yield of four crops grown for 58 d in Ihanda and Sasanda soils immediately after P application. Different letters within a graph indicate statistically significant differences at $P = 0.05$ by Fishers LSD. For the unreplicated TSP treatment, least squares means are shown.**

## Manganese Toxicity

Toxicity of Mn was first suspected in a preliminary unreplicated pot trial using four soils. The pots were accidentally waterlogged for 5 d, after which bean plants growing in the Sasanda soil and another soil of volcanic origin became stunted and showed mottled interveinal and marginal chlorosis on the younger trifoliate leaves, and small (<0.5 mm) black to purple necrotic spots on the unifoliate leaves. Once the soil was allowed to dry down, the bean plants appeared to partially recover. This behavior is consistent with the occurrence of Mn toxicity (Weil et al., 1997; Flor and Thung, 1989), which has been reported for bean on volcanic soils (Andisols) in South America. The Sasanda soil is an Andisol very high in total Mn (Table 2).

Scientists and extension workers in Tanzania have reported difficulties growing bean crops on Sasanda and similar soils formed in volcanic materials (M. Madata, personal communication, 1994). In the area where the Sasanda soil was obtained for the present study, discussions with farmers revealed that sweet potato [*Ipomoea batatas* (L.) Lam.] when planted on 1-m high soil ridges was the only consistently successful crop. Since sweet potato has a very high tolerance for Mn and tall ridges would assure that the soil did not become waterlogged during wet periods, these field observations are consistent with the existence of a Mn toxicity problem on the Sasanda soil. Furthermore, the $pH_w$ of the Sasanda soil was 5.3 (Table 2), which is sufficiently low to promote excessive availability of Mn, but high enough that toxicity of Al is unlikely to be a problem (Weil et al., 1997). The high level of organic C in the Sasanda soil could also be expected to enhance toxicity of Mn, but not of Al, by promoting reduced conditions when the soil is wet.

Symptoms of Mn toxicity occurred in some treatments in the pot study, although never as severely as in the waterlogged preliminary pots. Symptoms suggestive of Mn toxicity included leaf cupping and stunting of cabbage and mottled chlorosis on younger leaves of bean and pigeon pea. The close relationship between the Mn concentration of initial crop tissue and the pH of the soil is illustrated in Fig. 2a for bean and cabbage. The relationship is shown for $pH_{KCl}$, but not for the $pH_w$, because the latter is subject to fluctuation with soluble salts such as accumulated from unused fertilizer in some of the pots. For soils with $pH_{KCl}$ below 4.5, Mn concentrations in bean and cabbage tissue were >500 mg $kg^{-1}$, a level reported to be toxic (Flor and Thung, 1989). None of the pots with Ihanda soil had $pH_{KCl}$ values this low, but pots with unamended or Panda PR amended Sasanda soil consistently had $pH_{KCl}$ values below 4.5 and tissue Mn concentrations as high as 1100 mg $kg^{-1}$. Sasanda soil without Minjingu PR also produced up to 400 mg $kg^{-1}$ Mn in maize tissue and up to 510 mg $kg^{-1}$ in pigeon pea tissue (data not shown).

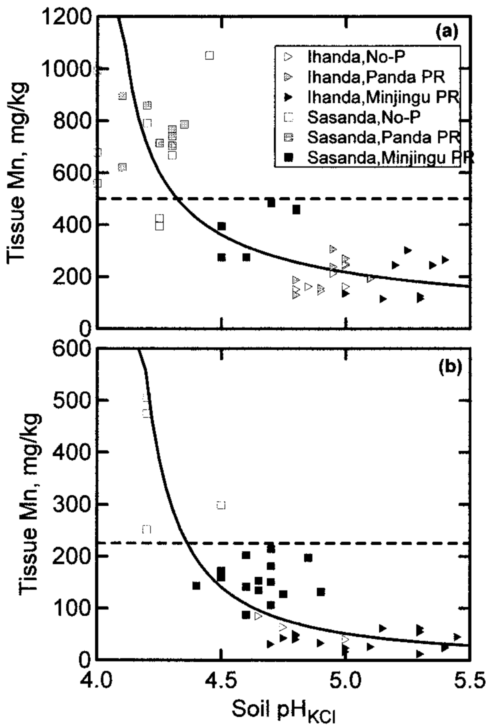


**Fig. 2. The relationship between soil $pH_{KCl}$ at harvest and tissue Mn concentration for (*a*) initial crop bean and cabbage and (*b*) second crop maize in two soils receiving one of two phosphate rocks (PR) or no added P.**

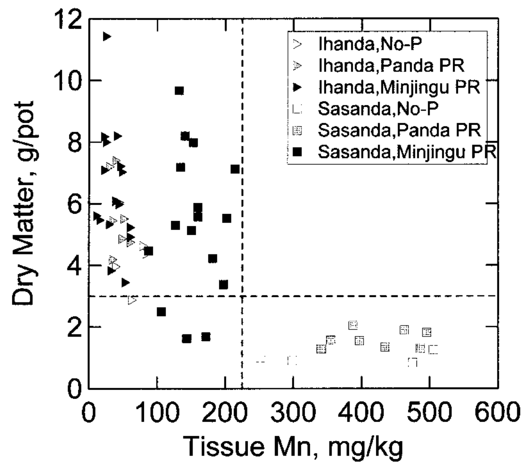


**Fig. 3. The relationship between shoot dry matter yield and tissue Mn concentration for second crop maize in two soils previously treated with no added P, or with one of two phosphate rocks (PR).**

Minjingu PR, a rock relatively rich in carbonates (Table 1), had a significant liming effect, raising the $pH_{KCl}$ of Sasanda soil by nearly 0.5 units (Table 5). Panda PR had no such effect. Crop grown also affected the soil pH, but to a lesser degree. Averaged for both soils, bean gave a mean $pH_{KCl}$ of 4.81 and cabbage gave a mean $pH_{KCl}$ of 4.62 compared with 5.14 in the absence of crops. Crop × soil and crop × P source interactions were not significant. Thus, the probable reason why cabbage responded well to both Panda and Minjingu PRs in Ihanda soil but only to Minjingu PR in Sasanda soil (Fig. 1) was that only Minjingu PR raised the pH of the latter soil above the critical pH for Mn toxicity ($pH_{KCl} > 4.5$ or $pH_w > 5.5$).

## Second Cropping Period

A very striking effect was the much lower mean yield for the second crop maize in the Sasanda (2.4 g $pot^{-1}$) than in the Ihanda soil (5.5 g $pot^{-1}$). In the Ihanda soil (where Mn toxicity was not a problem) a previous crop of bean, maize, or pigeon pea markedly increased the second maize shoot dry matter compared with that of the no P added, no previous crop control. This was true regardless of whether Panda PR, Minjingu PR, or no P amendment had been previously applied (Table 3). However, where cabbage was the previous crop (with or without a previous P amendment), maize shoot dry matter was not different from the no-P added bare soil control.

In the Sasanda soil, none of the previous crops when combined with either Panda PR or no-P amendment produced a significant increase in maize dry matter compared with the no P added, bare soil control. This lack of response to a previous bean, maize, or pigeon pea crop was likely due to the inability of the Panda PR to alleviate Mn toxicity, as discussed above. Partially because of its ability to ameliorate Mn toxicity, Minjingu PR was dramatically more effective than Panda PR in the Sasanda soil (Table 3). Minjingu PR applied to Sasanda soil in combination with a non-cabbage crop in the initial cropping period gave second crop maize dry matter yields as high as those obtained in the Ihanda soil. When the Minjingu PR was applied in combination with either cabbage or no crop during the initial cropping period, the second crop maize yield was comparable with the no-P control. The combination of Minjingu PR with a previous crop of pigeon pea produced as much dry matter as did freshly applied TSP, and significantly more dry matter than any other PR treatment on the Ihanda soil.

As with the initial crop, the uptake of Mn by the second maize crop was related to the soil $pH_{KCl}$ measured at harvest (Fig. 2b). Tissue Mn levels >225 mg $kg^{-1}$ were associated with very low maize dry matter production (Fig. 3), a result that agrees well with the 200 mg $kg^{-1}$ level reported as toxic for young maize plants by Reuter and Robinson (1986). All treatments on the Ihanda soil had $pH_{KCl}$ values above 4.6 and maize Mn tissue levels below 100 mg $kg^{-1}$, however, on Sasanda soil without Minjingu PR the $pH_{KCl}$ was consistently below 4.5 and the Mn in the maize tissue was in the toxic range (Fig. 2b).

Treatments 20 and 21 in comparison with Treatments 6 and 11 were designed to test the hypothesis of an increase in PR effectiveness over time without crop effects. Because there were no responses by maize to Panda PR, the hypothesis could be tested only for Minjingu PR. Freshly applied Minjingu PR had no significant effect on maize dry matter or P content as compared with the bare soil, no P added control (Table 6). In contrast, the residual effects of Minjingu PR applied 58 d earlier with no previous crop were significant in both soils (Table 6). Because appropriate second crop

**Table 6. Increases in second crop maize dry matter and P content in response to freshly applied and residual Minjingu PR with no previous crop.**

| PR application† | Increase above the no P control | | |
|---|---|---|---|
| | Shoot dry matter | | |
| | Ihanda soil | Sasanda soil | P content |
| | % | | |
| Freshly applied just before planting | −21NS | +4NS | −13NS |
| Residual—applied to moist soil 58 d before planting | +56** | +121** | 86** |

** and NS indicate significance at the $P < 0.01$ level and nonsignificant, respectively.
† P rates: 100 mg P $kg^{-1}$ for Ihanda and 400 P $kg^{-1}$ for Sasanda; 4 L of soil per pot.

treatments (PR applied freshly after each previous crop) were not available, the effect of previous crop on any enhancement of PR effectiveness over time could not be determined from the present study. Although not strictly comparable to second crop maize responses, Minjingu PR freshly applied for the initial crop maize gave a 41% increase above the no-P control (Fig. 1). There was no treatment to test for comparable residual PR effects on the initial crops.

Since there was no significant soil × treatment interaction on P content values for second crop maize, the results were averaged across both soils (Table 3). Residual Minjingu PR approximately doubled P content in second crop maize compared with the no P treatments with the same cropping history. When combined with a non-cabbage previous crop, Minjingu PR increased maize P content almost fourfold compared with the control (no-P, no previous crop), equaling the P content observed with freshly applied TSP (Table 4). Among treatments with no P applied, P content in second crop maize was significantly higher where the maize followed a previous crop of bean, maize, or pigeon pea (but not cabbage). This result and the fact that Minjingu PR combined with a previous crop of pigeon pea gave higher maize yields than any treatment other than TSP on the Ihanda soil, may be related to the reported (Ae et al., 1990) ability of pigeon pea to solubilize and utilize Fe-bound P. Phosphorus released from Minjingu PR may be rapidly bound to Fe on colloid surfaces in both soils.

The large difference in maize growth between the two soils was also apparent when P amendments were applied to the second maize crop (Table 4). Neither Panda nor Minjingu PR, when freshly applied to the second crop maize following a 58-d bare fallow, had any effect on maize dry matter or P content (Table 4) compared with no P amendment. Freshly applied TSP produced about three times the dry matter and nearly four times the P content as did either of the freshly applied PRs.

Maize responses to a previous crop in conjunction with application of Minjingu PR are further elucidated by data on root dry matter and shoot/root ratio for second crop maize in the selected treatments for which roots were collected (Fig. 4). The shoot/root ratio for maize was low where no P was applied to pigeon pea first crop—the only no P treatment for which root

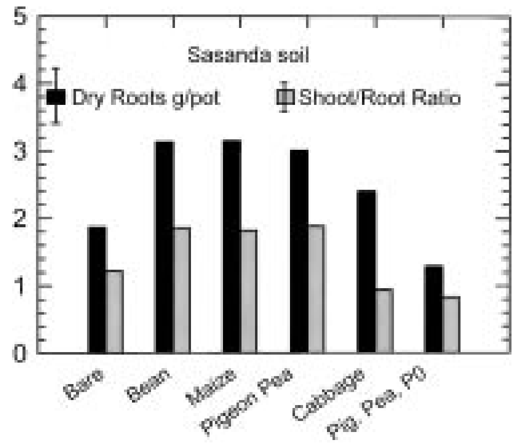


**Fig. 4. Influence of previous cropping history (bean, maize, pigeon pea, or bare soil) on second crop maize root dry matter (g $pot^{-1}$) and shoot/root ratio. All treatments, except pigeon pea with no P added (Pig. Pea, P0) had Minjingu phosphate rock applied at the beginning of the initial cropping period. Error bars indicate Fisher's LSD ($P < 0.05$) for the respective variable.**

weights were measured. Root growth where Minjingu PR was incubated in bare soil for 58 d was not significantly different from the no P treatment. But a previous bean, pigeon pea, or maize crop in combination with Minjingu PR significantly increased both root dry matter and shoot/root ratio of the second crop maize compared with pigeon pea with no P added. Thus, the residual effect of Minjingu PR on maize following pigeon pea, bean, or maize was to enhance shoot growth more than root growth. The shoot/root ratio and root dry weight for maize with residual Minjingu PR following cabbage did not differ from corresponding values obtained with bare soil during the initial period.

## Soil Microbial Effects

The pronounced negative effect (or lack of positive effect) of cabbage on P content of maize, in comparison to the effects of the other three crops, suggested that the previous crop effect might be related to differences in AM infection since it is well known that plants in the Cruciferae family do not form mycorrhizal relationships. At the end of the initial cropping period, Sasanda soil had about half the AM infection potential (25% root length infected) of Ihanda soil (53%), whether determined on roots of maize or bean plants. As expected, application of TSP reduced maize AM root infection in both soils (from 48 to 34%). These observations of root infection were made after 58 d of plant growth in the glass house under conditions that did not preclude some inoculation from airborne fungal spores. Therefore, the infection potential in the Sasanda soil may have been even lower under field conditions.

For the second crop maize, pots amended with Minjingu PR were analyzed for AM fungi infection on roots. Infection was still significantly lower in the Sasanda (27% of root length) than in the Ihanda soil (37% of root length). Because there was no significant soil × crop interaction, AM infection data were averaged across both soils to compare treatments (Fig. 5). A previ-

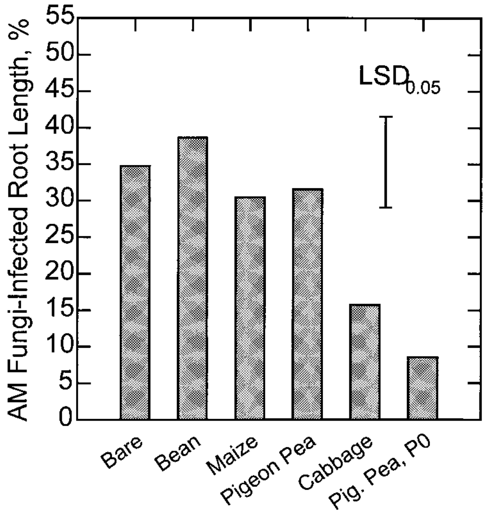


**Fig. 5. Arbuscular mycorrhizal infection (infected root length as a % of total root length examined) on second crop maize as influenced by previous crop in Sasanda soil. All treatments, except pigeon pea without P amendment (Pig. Pea, P0) had Minjingu phosphate rock applied at the beginning of the initial cropping period. Error bar indicates Fisher's LSD ($P < 0.05$).**

ous crop of cabbage depressed second crop maize AM infection. Residual Minjingu PR tended to enhance AM infection in the second crop maize (as compared with the no P treatment following pigeon pea). One could speculate that although AM fungi helped the maize take up P from the Minjingu PR, the P availability from this PR was low enough to not inhibit AM infection. Thus, the limited evidence available suggests the effects of previous crop and PR application may have been partially due to differences in AM infection, but that AM infection by itself cannot explain all the effects.

## CONCLUSIONS

Although the results of a pot study cannot be directly applied to the field, several discoveries were made that may have important implications for the development of indigenous PR deposits for direct soil application, and for the general management of low P soils in East African highlands. The study provided some evidence for a delayed effectiveness of the PRs on the second maize crop. However, the substantial response to fresh Minjingu PR by the initial maize crop makes this data less conclusive, suggesting that further study of this phenomenon is warranted both with pots and in the field.

This is the first work to show a dramatic response of cabbage to the otherwise ineffective Panda PR, indicating that cabbage (and probably other Brassica cash crops grown in the region) may be key to obtaining an economic benefit from certain local PR deposits. This result should be followed up by using Brassica crops to test Panda and other unreactive, Fe-rich, igneous PRs in both pots and the field.

The present study provides clear evidence that one crop treated with unacidulated PRs may substantially influence the residual effectiveness of the PR for following crops. Where Mn toxicity was not a problem, second crop maize had significantly greater dry matter and P content when bean, pigeon pea, or maize was previously grown in the soil, with or without application of PR. Although inadequate to fully explain the effect of the previous crop, a role for mycorrhizae is suggested by the limited data on AM root infection, and by the fact that cabbage, a nonhost plant for AM fungi, consistently failed to have a positive effect comparable to that of the other crops. Certainly, with the adequate fertility applied to all plots and with previous crop maize showing the same effect as the legumes, the previous crop effect is unlikely to be associated with enhanced availability of N or other nutrients (except P).

The discovery that Sasanda soil produces Mn toxicity in four crops is of great importance to the management of farming systems on this and similar soils. This study should therefore be followed up by field and pot studies investigating the occurrence of Mn toxicity in similar acid Andisols from high rainfall areas of East Africa. Use of carbonate-rich, reactive PRs such as Minjingu may have special value in combining P supply with Mn toxicity alleviation. Also, plant breeders could make Mn tolerance a goal in developing varieties of bean and other Mn sensitive crops. This work has already begun in western Tanzania.

Finally, the results reported here suggest that future P fertility work in Africa should take a whole cropping system approach. Adequate attention should be paid to the effects of crop sequences and soil chemical and biological properties.

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