Agronomic Evaluation of Unacidulated and Partially Acidulated Chilembwe Rockphosphates for Clover Seed Production

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ABSTRACT

Phosphorus (P) is required to improve soil fertility for food and feed production in sub-Saharan Africa, but the high cost of conventional, water-soluble P fertilizers limits their use by resource-poor farmers. Rockphosphates are a low-cost alternative. The effectiveness, in terms of seed production, of unacidulated (RP), 25% partially acidulated (PARP25), and 50% partially acidulated (PARP50) Chilembwe rockphosphate relative to triple superphosphate (TSP) applied at 0 to 80 kg P ha^{-1} to *Trifolium quartinianum* L. on a Vertisol in the Ethiopian highlands was evaluated. The fertilizers were applied once and their effects were followed in four consecutive clover crops. Clover seed yields without applied P were below 260 kg ha^{-1} in the four years of the study. With P application, seed yields reached as high as 490 kg ha^{-1}. Over all the four crops, RP was 43%, PARP25 was 100% and PARP50 was 71% as effective as TSP in increasing clover seed yields. The corresponding relative responses in seed P contents were 56, 100 and 78% for RP, PARP25 and PARP50, respectively. The substitution rates in seed yields were 18% for RP, 100% for PARP25 and 50% for PARP50 while those for seed P were 31% for RP, 100% for PARP25 and 61% for PARP50. Significant ($P < 0.05$) effects of P on clover seed yields and P contents were observed only in the first crop, probably because of high data variability. It is concluded that unacidulated Chilembwe rockphosphate is not suitable for clover seed production in these soils. However, the partially acidulated products of this rockphosphate were more effective and could be used to elevate the P status of the P-deficient Vertisols and increase forage production for increased and sustainable crop and livestock productivity.

Additional index words: Ethiopia, forage legumes, phosphorus, soil fertility, sub-Saharan Africa, tropical soils.

INTRODUCTION

Low soil fertility is a serious constraint to food and feed production in sub-Saharan Africa. Most soils are so low in available P that, without added P fertilizer, the impacts of other agricultural technologies are limited (World Bank, 1994). However, the use of conventional water-soluble P fertilizers by resource-poor farmers is limited because of high cost. Where indigenous deposits of rockphosphates are available, their use for direct application to soils can be a low-cost alternative. Most studies on rockphosphates in sub-Saharan Africa (SSA) have been conducted with food crops (Sale and Mokwunye, 1993), and there is need to expand them into pasture and horticultural crops. Data on forage seed production in SSA are even more scarce.

Studies on the use of rockphosphates on pastures in Australia and New Zealand have produced contrasting results. Field studies in New Zealand have shown that rockphosphates can be as effective as soluble P fertilizers, but similar studies in Western Australia do not support the use of rockphosphates on pastures because of limited dissolution (Bolan, White and Hedley, 1990; Bolland and Gilkes, 1990a; 1990b). In the Ethiopian highlands, Egyptian and Togo rockphosphates were found to be 92% and 64%, respectively, as effective as triple superphosphate on *Medicago sativa* L. in a greenhouse experiment (Nnadi and Haque, 1988). In field experiments, Egyptian rockphosphate was 82-92%, and Togo rockphosphate 54% as effective as triple superphosphate in increasing herbage DM of seven consecutive crops of annual clovers (Haque and Lupwayi, 1998 a; b).

Since the effectiveness of raw rockphosphate is sometimes limited by low reactivity, partial acidulation is one way to increase its solubility. This is a process where rockphosphate is treated with only a portion of the sulphuric acid (and/or phosphoric acid) required to produce single superphosphate or triple superphosphate (Hammond, Chien and Mokwunye, 1986). In a four-year field study in the Ethiopian highlands, Haque, Lupwayi and Ssali (1999) found that unacidulated and acidulated Minjingu rockphosphates were all highly effective in increasing clover herbage yields. However, Chilembwe rockphosphate was found to be ineffective unless it was partially (50%) acidulated. In this work, we report the results of the effects of unacidulated and partially acidulated Chilembwe rockphosphate on clover seed yield and P contents in the same study.

MATERIALS AND METHODS

The experiment was conducted on a P-deficient highland Vertisol at the International Livestock Research Institute (ILRI) headquarters research farm in Addis Ababa (2370 metres above sea level, 1250 mm annual rainfall and 15.5° C mean annual temperature). Some physical and chemical characteristics of the top (0-23 cm) soil horizon are: 60% clay, 19% sand, 1.22 g cm^{-3} bulk density, pH 5.52 (1:1 water), 5.25% organic matter, 0.21% total N, 0.32 mg P (Bray II) g^{-1} soil, 65.36 cmol Ca kg^{-1} soil, 24.22 cmol Mg kg^{-1} soil, 1.76 cmol K kg^{-1} soil and 0.34 cmol Na kg^{-1} soil. (Kamara and Haque, 1987). Chilembwe rockphosphate is an igneous deposit in Zambia, with 14.9-19.6% P_2O_5 and 26.1-30.5% CaO (Sliwa, 1991; Van Kauwenbergh, 1991).

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Unacidulated Chilembwe rockphosphate (RP), 25% partially acidulated (with sulphuric acid) rockphosphate (PARP25), 50% partially acidulated rockphosphate (PARP50), and triple superphosphate (TSP) (46% P_2O_5) fertilizers were applied to 3 m x 3 m plots once at 0, 20, 40, 60, and 80 kg P ha^{-1}. The treatments were replicated three times in a split-plot randomized complete block design in which P sources were main plots and P rates were sub plots. Extra plots without P fertilizer were included in each replicate to permit fresh application of TSP in the second crop. The fertilizers were broadcast on the plots and incorporated into the soil on 6 June, 1988. *Trifolium quartinianum* L. (accession ILCA6301) was sown and harvested as outlined in Table 1. At harvest, seed yields were determined. The seeds were analysed for N and P (Tekalign Tadesse, Haque and Aduayi, 1991) to estimate N and P contents (yields) by multiplying the concentrations of these nutrients in the seed by seed DM yield. In subsequent years up to 1991, clovers were grown in the same plots without further fertilizer applications. In 1989, TSP was applied at the same rates as in 1988 to unfertilized extra plots in each replicate so that residual effects of P could be compared with the freshly applied P.

MSTAT-C statistical software (Michigan State University, 1988) was used for analysis of variance on the seed yield, P uptake and N uptake data each year. Means were separated by least significant difference (LSD) tests. The cumulative responses of seed yield and P uptake to P rate were best described by the following equation (Chien, Sale and Friesen, 1990):

$$Y_i = Y_0 + b_i\,(\text{P rate})^{1/2} \quad \text{.......(1)}$$

where Y_i = seed (or P) yield obtained with source (i), Y_0 = seed (or P) yield obtained without added P, b_i = regression coefficient of source (i), and P rate = rate of P applied.

The relative effectiveness of each rockphosphate compared with TSP was evaluated in three ways: (a) relative yield response (RYR) index, (b) substitution rate (SR) and (c) linear response comparison (Chien *et al.*, 1990). RYR and SR were calculated from the regression coefficients of the fitted response curves (Equation 1) as follows:

$$\text{RYR (\%)} = b_i / b_{TSP} \quad \text{.......(2)}$$

$$\text{SR (\%)} = (\text{RYR})^2 \quad \text{.......(3)}$$

Equation 3 applies only for the response curve described by Equation 1. The linear responses of seed yield and P uptake were determined for the P application rates of 0 to 40 kg P ha^{-1}. The regression coefficients of the fitted lines were then used to calculate RYR using Equation 2. In linear response comparison, RYR and SR are the same.

The residual effects of the fertilizers applied to the first crop were evaluated in the second crop by comparing the response of clover to each fertilizer applied previously with the response to a fresh application of TSP as follows:-

$$\text{Residual value}_{\text{Fertilizer applied previously}} = b_{\text{Fertilizer applied previously}} / b_{\text{Fresh TSP}} \quad \text{.......(4)}$$

where b is the regression coefficient according to the response equation (1).

RESULTS

Responses to P over time

The responses of seed yields and P and N contents varied considerably over time (Figs. 1-3). However, some trends could be detected. In the four crops following application of P, seed yields in control plots ranged from 257 kg ha^{-1} in crop 1 to 55 kg ha^{-1} in crop 3 (Figs. 1a-d). Yields with applied P were as high as 490 kg ha^{-1} in crop1 (Fig. 1d). Unacidulated rockphosphate had no significant effect on seed yields at any time. At the application rates of 20 or 40 kg P ha^{-1} (Figs. 1a and b), all the other P sources produced significantly ($P < 0.05$) higher seed yields than the control only in crop 1. Even

Table 1. Clover planting and harvesting details of the four consecutive crops.

	1988	1989	1990	1991
Planting date	6 June	14 June	11 June	24 June
Seed rate (kg ha^{-1})	10	10	10	10
Row spacing (cm)	20	20	20	20
Harvest date	12 Nov	22 Nov	21 Nov	20 Nov
Harvest area (m^2)	3.6	2.4	2.4	2.4

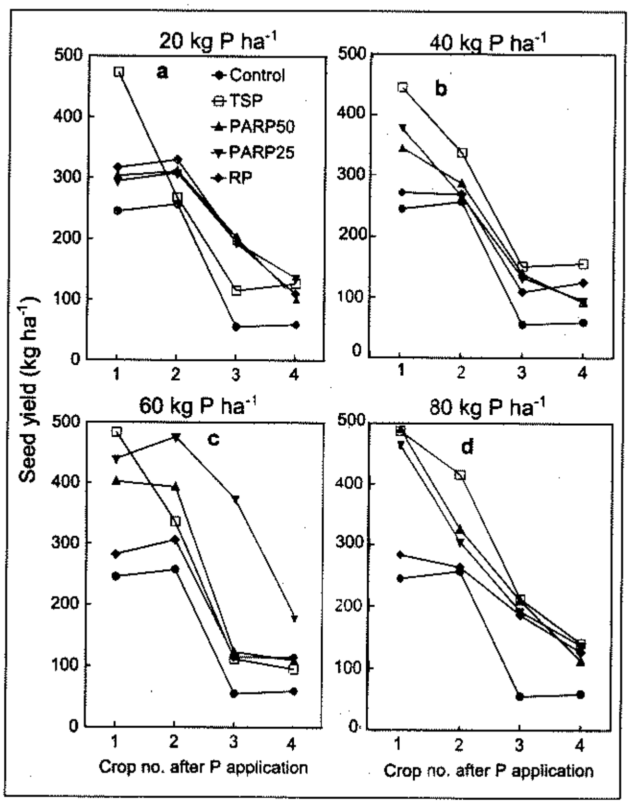

Figure 1. Seed yield trends of five crops at 20 (a), 40 (b), 60 (c) and 80 (d) kg P ha^{-1}.

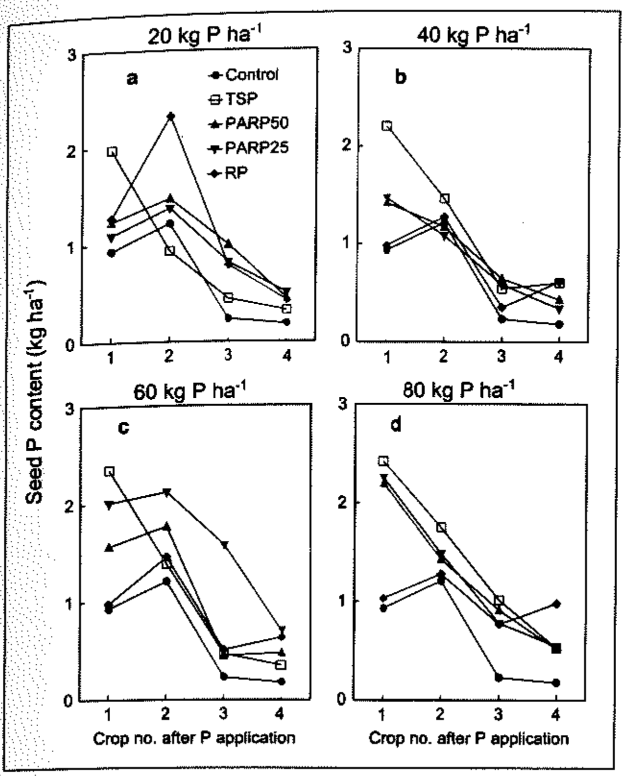

Figure 2. Seed P content trends of five crops at 20 (a), 40 (b), 60 (c) and 80 (d) kg P ha^{-1}.

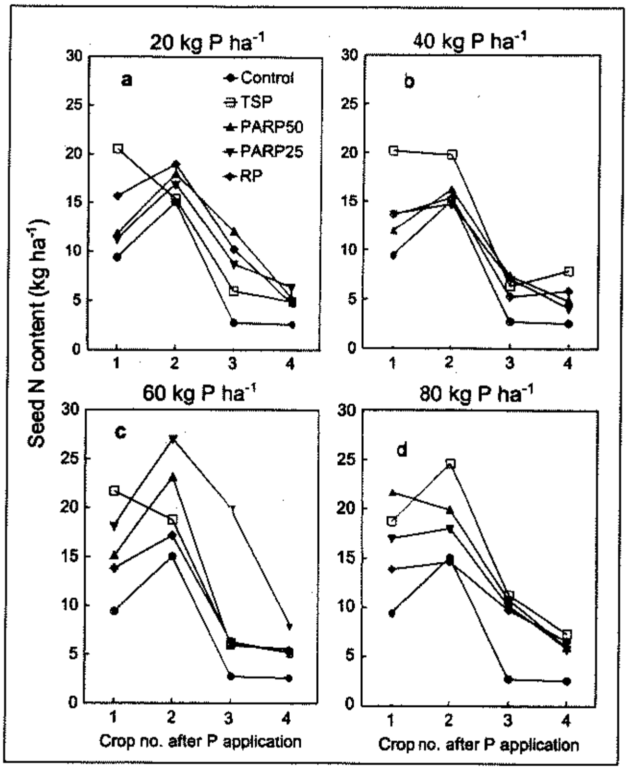

Figure 3. Seed N content trends of five crops at 20 (a), 40 (b), 60 (c) and 80 (d) kg P ha^{-1}.

at the high P rates of 60 or 80 kg P ha^{-1} (Figs. 1c and d), significant effects of TSP and the partially acidulated rockphosphates were not detected beyond the first crop, despite the high yields in crops 2 and 3. Trends similar to those for seed yield were observed for seed P (Figs. 2a-d) and seed N (Figs. 3a-d) contents. Thus, compared with the control, unacidulated rockphosphate generally had no significant effect and the other P sources had significant effects only in crop 1.

Overall response to P and relative effectiveness of the rockphosphates

The cumulative response curves for seed yield (Fig. 4a) and seed P content (Fig. 4b) show that yields were still increasing at 80 kg P ha^{-1}. The curves also show that the order of response was TSP = PARP25 > PARP50 > RP. The relative seed yield responses were 71% for PARP50, 100% for PARP25 and 43% for RP (Table 2). The corresponding substitution rates

Table 2. Relative yield responses (RYR) and substitution rates (SR) in cumulative seed and P yields for 50% acidulated rockphosphate (PARP50), 25% acidulated rockphophate (PARP25) and unacidulated rockphosphate (RP) relative to triple superphosphate (TSP). Phosphorus application rates and P uptake are in kg ha^{-1} and seed yields are in t ha^{-1}. Corrected coefficients of determination (r^2) are quoted for each response equation.

P source	Cumulative seed yield b	RYR (%)	SR (%)	Cumulative seed P b	RYR (%)	SR (%)
Curvilinear response[1]				*Curvilinear response*[2]		
TSP	0.07 (r^2=0.91)	100	100	0.32 (r^2=0.92)	100	100
PARP50	0.05 (r^2=0.90)	71	50	0.25 (r^2=0.84)	78	61
PARP25	0.07 (r^2=0.61)	100	100	0.32 (r^2=0.64)	100	100
RP	0.03 (r^2=0.30)	43	18	0.18 (r^2=0.16)	56	31
Linear response[3]				*Linear response*[4]		
TSP	0.013 (r^2=0.90)	100	100	0.056 (r^2=1.00)	100	100
PARP50	0.008 (r^2=0.49)	62	62	0.038 (r^2=0.36)	68	68
PARP25	0.008 (r^2=0.49)	62	62	0.031 (r^2=0.43)	55	55
RP	0.006 (r^2=0.05)	46	46	0.036 (r^2=0.00)	64	64

[1] $Y = 0.62 + b\,(P\ rate)^{1/2}$ $(n=5)$
[2] $Y = 2.55 + b\,(P\ rate)^{1/2}$ $(n=5)$
[3] $Y = 0.62 + b\,(P\ rate)$, for 0-40 kg P ha^{-1} $(n=3)$
[4] $Y = 2.55 + b\,(P\ rate)$, for 0-40 kg P ha^{-1} $(n=3)$

were 50, 100 and 18%. With regard to seed P, the order of the rockphosphates in relative responses and substitution rates was the same as for seed yields, and the values were either the same or slightly higher (Table 2). In linear response, the order of seed yield response was TSP > PARP50 = PARP25 > RP and that of seed P was TSP > PARP50 > PARP25 > RP (Table 2). The data for TSP and acidulated rockphosphates fitted the curvilinear response curves better than the linear response, but unacidulated RP data did not fit either response pattern (see r^2 values in Table 2).

The relationship between seed P content and seed yield was linear (Fig. 4c), indicating that the internal efficiency of utilization of P from all the four sources was the same.

Residual effects

Seed and nutrient content trends in Figs. 1-3 give an indication of the duration of significant P effects over the years, but residual effects were evaluated more critically in the second crop by comparing the response of each P source

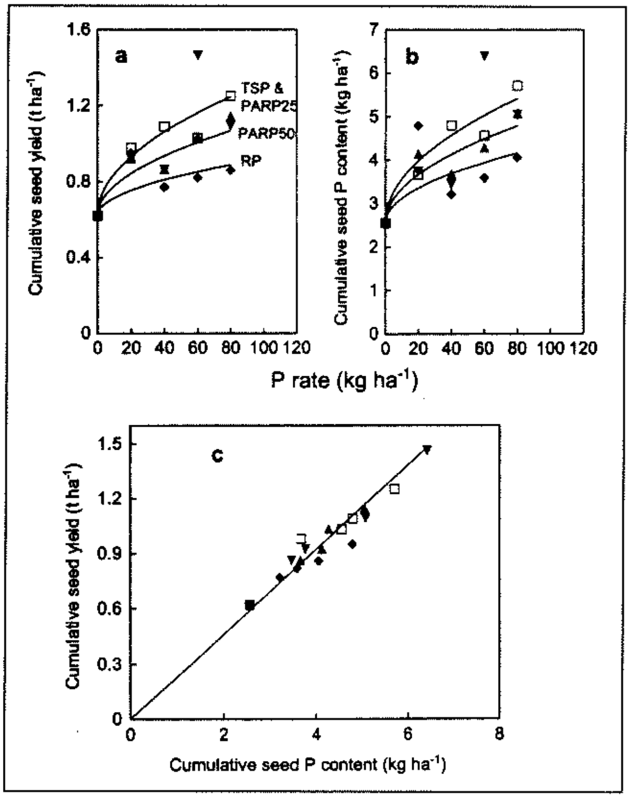

Figure 4. Cumulative response of clover seed yield (a) and seed P content (b) to different P sources, and the internal utilization of P (c). The legends are the same as those in Figs. 1-3. The response equations and their coefficients of determination (corrected r^2) are given in Table 2. The equation for internal P utilization is: Seed yield (t ha^{-1}) = 0.23 (P uptake, kg ha^{-1}), r^2 = 0.94.

to that of fresh TSP application. In the year of application (crop 1), the relative effectiveness of the phosphate sources in seed production was 100% for TSP, 64% for PARP50, 67% for PARP25 and 15% for RP (Fig. 5a). In crop 2, the residual effects in seed yields were 30% for TSP, 23% for PARP50, 28% for PARP25 and 9% for unacidulated RP (Fig. 5a). Corresponding residual effects in P uptake were 15, 17, 22 and 12% (Fig. 5b). Figs. 5a and b also show that the relative seed yield and seed P responses to TSP decreased more between crops 1 and 2 than responses to PARP50 and PARP25, which in turn decreased more than response to RP.

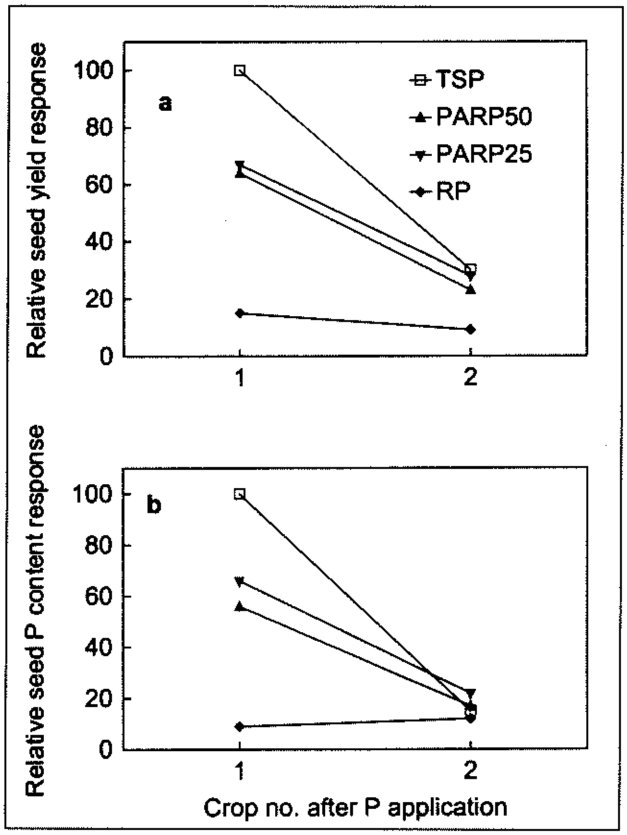

Figure 5. Residual values of the different P sources in (a) seed yields and (b) seed P uptake in the second crop compared with fresh applications of triple superphosphate.

DISCUSSION

Clover seed yields without applied P were below 260 kg ha^{-1} in the four years of the study. With P application, seed yields reached as high as 490 kg ha^{-1}. Soils in the Ethiopian highlands are known to be so deficient in P that responses of forage and browse legumes to applied P are high (Kahurananga and Tsehay, 1984; Haque, Lupwayi and Luyindula, 1996; Mugwira, Haque, Lupwayi and Luyindula, 1997). Nitrogen fixation by these legumes is severely limited by P deficiency because nodules fail to form without applied P (Haque *et al.*, 1996; Mugwira *et al.*, 1997). Nodulation or nitrogen fixation was not assessed in this work, but some of the response of seed N (and seed yield) to applied P is likely to be due to increased nitrogen fixation by the clover plants, especially since N fertilizer was not applied.

Unacidulated Chilembwe rockphosphate was 43% as effective as TSP in increasing clover seed yields. This response is higher than the 27% relative effectiveness observed in herbage yields at flowering in the same plots (Haque *et al.*, 1999), but lower than the effectiveness of Egyptian rockphosphate (82-92%) and Togo rockphosphate (54%), which have been evaluated for clovers in the same soils (Haque and Lupwayi, 1999a; b). Therefore, use of raw Chilembwe rockphosphate cannot be recommended for clover seed production in these soils. Partial acidulation of this rockphosphate improved its effectiveness to 100% for PARP25 and 71% for PARP50. The substitution rate for PARP25 was 100% and that of PARP50 was 50%. It is not clear why the rockphosphate at lower acidulation (PARP25) should be more effective than that at higher acidulated with sulphuric acid, and formation of gypsum coating at high levels of acidulation may inhibit the release of P for plant uptake. However, this is unlikely to be the explanation in this case because the herbage DM present at flowering increased with increasing acidulation level (Haque *et al.*, 1999). The unusually high seed yield and seed P content of the plants that received PAPR25 at 60 kg P ha^{-1} seems to be the reason (Figs. 4 a and b), but it is not known why this occurred. The 100% relative yield effectiveness means that similar seed yields would be obtained when PARP25 is applied at the same rate as TSP. However, the 50% substitution rate of PARP50 means that it would have to be applied at twice the TSP rate to give comparable yields.

These rockphosphate fertilizers were not available commercially in Ethiopia at the time these studies were conducted, so an economic evaluation is not possible without knowing their prices. However, the 100% substitution rate for PARP25 also means that it will be more profitable to use it if its price is less than that of TSP. Similarly, the price of PARP50 has to be less than half of that of TSP for it to be more economical to use than TSP. This analysis assumes that all other costs are the same, which may not be true since the costs of transporting and applying the more bulky rockphosphate are likely to be higher than those for the more concentrated superphosphate.

The above analysis is based on the whole response curve up to 80 kg P ha^{-1}. However, resource-poor farmers are likely to apply fertilizers at low rates. At the low rates, farmers are operating in the region of the response curve which is most responsive and often linear. Therefore, the ratio of slopes of the linear responses in this region of the response curve gives a measure of substitution rate, which will be the same as the relative yield response (Chien *et al.*, 1990). The substitution rates calculated in this way in the 0 to 40 kg P ha^{-1} range for seed yields were 62% for both PARP50 and PARP25. Therefore, these figures could be used in the analysis given above if the farmer intends to apply the P fertilizer in the 0 to 40 kg P ha^{-1} range.

Use of other raw rockphosphates in Africa, mainly on cereal crops, has shown that some rockphosphates are almost as effective as superphosphates in increasing yields (Bationo, Chien, Henao, Christianson and Mokwunye, 1990), others are less effective (Bationo *et al.*, 1990; Owusu-Bennoah and Acquaye, 1996), and others are ineffective (Butegwa, Mullins and Chien, 1996). Several factors are known to affect the relative effectiveness of rockphosphates (Hammond *et al.*, 1986; Rajan, Watkinson and Sinclair, 1996). They include climate and soil pH, with high temperatures (and rainfall) and low pH favouring greater reactivity of rockphosphates than low temperatures (and rainfall) and high pH. The Vertisol used in this study was not very acidic (pH 5.5), and the study was conducted in the highland tropics which are characterized by cool temperatures. These may be some of the reasons for the low agronomic effectiveness of raw Chilembwe rockphosphate. However, rockphosphates like Egyptian and Minjingu have been found to be effective in the same conditions (Haque and Lupwayi, 1998a; b, Haque *et al.*, 1999).

Significant responses of seed yields to P were registered only in the first crop after application. Even for herbage yields of the same crops harvested at flowering each year, significant responses were detected only in the first two crops (Haque *et al.*, 1999). This apparent lack of residual effect was probably due more to high variability of the data than to low yields with applied P. In similar experiments with Egyptian and Togo rockphosphates on clover, significant effects were observed up to the seventh crop (Lupwayi and Haque, 1998a). The residual effects of TSP and the partially acidulated rockphosphates evaluated in the second crop of this work were similar to those that were observed in the other experiments. Experiments comparing a large single application and small annual applications to give the same total applied P are required to further understand the residual effects and to identify an optimum frequency of P application.

In conclusion, this work has shown that raw Chilembwe rockphosphate is not effective for clover seed production in the Ethiopian highlands. However, partial acidulation of this rockphosphate produced products that were more effective. Applying these partially acidulated rock-phosphates would elevate the P status of these highly P-deficient soils and increase forage production and live-stock productivity.

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