EFFECTIVENESS OF PHOSPHATE ROCK
ON FERRALSOLS IN TANZANIA
AND THE INFLUENCE OF WITHIN-FIELD VARIABILITY
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EFFECTIVENESS OF PHOSPHATE ROCK ON FERRALSOLS IN TANZANIA AND THE INFLUENCE OF WITHIN-FIELD VARIABILITY

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op dinsdag 12 september 2000
des namiddags te vier uur in de Aula
Propositions (Stellingen)

1. The reactivity of phosphate rock depends mainly on the calcium carbonate content of the rock.
   This thesis.

2. Increasing the application rates of phosphate rock results in a decrease of the gronomic effectiveness of the rock, because the increasing amounts of dissolving calcium carbonate reduce the dissolution of calcium phosphate.
   This thesis.

3. On soils with pH(H_2O) above 6.0, phosphate rock will be effective only when applied at low rates. This rules out the use of phosphate rocks for the replenishment of the soil phosphorus capital in many sub-Saharan Africa soils.
   This thesis.

4. Overlooking spatial variability in soils negate the reality at the operations level. Soil pH is perhaps the major factor creating yield variability. As pH is much depending on the field’s history, e.g. on the accidental spots of former ashes, there is little hope that geostatistics can be of much help in taking into this within-field variability.
   This thesis.

5. Because of the low supply of protons in high pH soils, it is better to broadcast phosphate rock than to apply it in the planting hole.
   This thesis.

6. There is little scope for improving the effectiveness of phosphate rock by combined application with sulfate of ammonia, because the different application times (phosphorus at planting and nitrogen six weeks after planting) prohibit intimate contact between the two.
   This thesis.

7. Acid induced dissolution of phosphate rock incubated with farmyard manure is not possible given the high pH of both materials. However, through calcium chelation by organic molecules phosphate rock dissolution may be enhanced. The chelation process can be stimulated when phosphate rock is pre-treated with farmyard manure.
   This thesis.

8. Although there have been encouraging research results on the direct application of Minjingu phosphate rock, its use in Tanzania and neighboring countries is low. However, in Kenya farmers have expressed satisfaction with its performance. This is
because they apply it in the right conditions of low pH, low phosphorus and low calcium content in the soil.


9. Exploiting inter-African comparative advantages of each country should be the drive behind the many regional organizations being established in Africa. This need not be emphasized in the case of naturally occurring resource like Minjingu phosphate rock in Tanzania given the high cost of conventional fertilizers and the low incomes of the majority of the farmers in this part of the world.

10. To produce more per hectare and per person is the best way to reconcile the apparent conflict between output and welfare goals.

Fletcher et al. (1970).

11. Even though you have 10,000 fields, you can only eat one measure of rice a day.

Chinese wisdom.

12. Some people believe (with some uncertainty) that old Noah's animals re-assembled in the Serengeti. As for the birds, they must have settled at Minjingu.

13. Mans' mind once stretched by a new idea never regains its original dimensions.

Anonymous.

J.G. Mowo.
Effectiveness of phosphate rock on Ferralsols in Tanzania and the influence of within-field variability.
Wageningen, 12 September 2000.
Dedicated to the memory of my beloved sister,
The late Rev. Sr. Mathea (Clara Mathews) who
was recalled to the Lord in my absence.
Crop yields in Tanzania are often limited by P deficiency. Direct application of the locally mined Minjingu phosphate rock (MPR) is considered a possible option in addressing the problem. Being poorly soluble, it is more effective in low pH soils with sizeable P and Ca sinks. In soils rather high in pH, mechanisms are required to promote its dissolution. This research was initiated with the overall objective of increasing our understanding of the multiple interactions affecting the availability of P from MPR in the soil-plant system. This knowledge is required to enable optimal exploitation of the various factors influencing MPR effectiveness for increased crop production. The research program consisted of one laboratory experiment, six greenhouse experiments and four field trials.

The laboratory and greenhouse experiments dealt with single factors influencing the effectiveness of PR under controlled conditions. From the laboratory experiment it was established that the high content of CaCO₃ in Minjingu PR was the major factor that determined the amount of HCl extractable P. However, agronomically it did not differ from Khouribga and Mali PRs, which have relatively lower CaCO₃ content. High application rates lowered the effectiveness of PR pointing to a need to balance application rates with proton supply. In a study relating yield and soil pH, increasing dry-matter yield of maize, cowpea and pigeonpea could not noticeably affect the soil pH mainly due to the pH buffer capacity of the soils. However, when intercropped with maize, cowpea or pigeonpea took up more P from MPR and even improved the uptake of MPR-P by maize. This point to a possible proton induced dissolution of MPR by the legumes. Hence, when intercropping involves legume crops capable of fixing N lower rates of PR can be used which is an attractive option for resource poor farmers. A study on the response of maize, cowpea and pigeonpea to MPR and TSP on soils of low and high pH showed that response to MPR was stronger in the low than in the high pH soil. Both legumes gave a higher DM production with MPR than with TSP on the high pH soil and yields were higher on the high than on the low pH soil. This indicates that the legumes prefer a high soil pH to a low soil pH and are able to make use of MPR at a relatively high pH. The later is possible when the legumes can modify rhizosphere soil conditions with respect to pH.

Maize dry-matter yield response to P on soils with different pH and available P was observed where soil available P was low. There was no yield response to P when P-Bray-I was > 7 mg kg⁻¹ (P-Olsen > 10 mg kg⁻¹). Utilization of absorbed P was better from MPR than from TSP in low pH soils indicating a liming effect by the MPR.

Field experiments dealt with multiple factors influencing the effectiveness of PR. The influence of spatial soil variability on the effectiveness of PR and crop performance was studied using the Post-mortem Residual Analysis and Nearest Neighbor Means techniques. These techniques were effective in isolating environmental from treatment effects and they were more useful in the large than in the small trials. A study on the method and rate of P application showed that method of application was more important for MPR in high pH soils and that response to MPR will be obtained at modest rates. The residual effects of TSP and MPR were almost the same. Combined application of MPR and the acidifying fertilizer sulfate of ammonia showed that there is little scope for improving the effectiveness of MPR through the acidifying effect of sulfate of ammonia. Combined application of MPR and TSP gave best results in low pH soils when both of them were applied using the same method. Meanwhile, incubating MPR with farmyard manure could not stimulate MPR dissolution given the high pH of the two materials even after 40 days of incubation (pH (H₂O) = 8.35). It is concluded that the use of MPR could be extended to less acidic P deficient soils when mechanisms are employed that could stimulate its dissolution. They include use of low amounts of MPR (low input strategy), incorporating legumes in the cropping system and using the same method of application of mixtures of MPR and soluble P fertilizers.

Keywords: Minjingu phosphate rock, triple superphosphate, Rhodic Ferralsols, farmyard-manure, protons, dissolution, legumes, maize, management options, spatial soil variability, Tanzania.
Preface

Research on indigenous nutrient resources is high in the agenda of the National Agricultural Research master plan. Efficient direct use of the locally available Minjingu phosphate rock will offer farmers in Tanzania a cheap alternative source of phosphorus and reduce the country's dependence on imports of expensive soluble P fertilizers. The research reported in this thesis focuses on ways of improving the effectiveness of Minjingu PR and possibilities to extend its use in soils less favorable for PR dissolution. This research was jointly funded by the Tanzania Ministry of Agriculture through the Agricultural Research Fund and the Wageningen University and Research Center (WUR) of the Netherlands.

Too many people have helped me in one way or the other but it would be difficult to mention them all. Accomplishment of the greenhouse work was possible thanks to J. Nelemans, W. Menkveld, P. Pellen, A. Brader and W. van Tintelen at WUR and their counterparts E. Ngowi, J. Tenga, M. Mhina, J. Fwoma and G. Shija at ARI Mlingano. The assistance of Mr. van den Berg in the laboratory at WUR and his counterpart C.T. Shawa at ARI Mlingano is greatly acknowledged. Fieldwork was difficult but made simple through the faithful supervision of E. Ngowi, J. Tenga, T.S. Njau and M. Mhina, the constant guard against vermin by Mzee Y. Komba and field work by the many hard working women and men from the villages of Mzambaraoni, Azimio, Vanga and Mkanyageni. Mr. Van Rooijen and his wife Trudy assisted me at different times and notably by introducing me to Trudys' parents who at one time offered to carry some soil and plant samples from Tanga to Wageningen. Asanteni sana.

Local funding was made possible through the Agricultural Research Fund, Ministry of Agriculture, thanks to J. J. Mende, J. Kaaya and N. Lema. At WUR the sandwich program provided the external funding thanks to Mr. van Heijst and when extension was necessary the Sub-Department of Soil Science and Plant Nutrition came in handy thanks to the Dept. Chairman Dr. Van Beusichem. Logistics support at Mlingano was excellent thanks to the Director Dr. A. Nyaki, the Principal Mr. C.J. Liwa and the Soil Research co-ordinator, Dr. G. Ley. The assistance offered by E. Kaitaba and J. Meliyo (Soil survey and GIS), J. Wickama (Laboratory), K. Masuki (Soil Fertility and GIS) and C.V. Kassa (Electronics) at various stages in my research is very much acknowledged. While on logistics, the assistance of the WUR office of the Dean for International Students in all aspects (Housing, Insurance, residence permit, extension of stay etc.) is greatly appreciated. Here let me mention Ms Ankie Lamberts who not only made sure I was well accommodated but was also keen to see to it that I was in Schiphol in time for my flight back home.

The commendable assistance of Mr. G. Gort and his colleagues, Dr. M. van Montfort and Mr. A. Otten in statistical analysis is greatly acknowledged. The advice of Dr. J. Brouwer on Chapter 6 drawing on his experience on spatial variability in the Sahel is greatly acknowledged. Dr. R. Buresh of ICRAF and Dr. N. Chien of IFDC are thanked for their co-operation in soil analysis and information on phosphate rocks respectively. In the Sub-Department of Soil Science and Plant Nutrition I enjoyed the friendly atmosphere and the cordial working relations with my colleagues for which I am grateful.

From the early stages of formulating the proposal to implementation and write up of the thesis it was due to the constant encouragement, technical assistance and advice of my co-promoter Dr. Bert Janssen that made me sail through a smooth road. I simply have no words to express my appreciation for his patience and systematic approach to the whole work. Having supervised me also in my MSc it was a privilege to continue working with one of the notable soil scientists at WUR.

My promoter Prof. Dr. Oene Oenema drawing from his long experience in aspects of soil fertility and plant nutrition made critical comments which shaped the thesis. Thank you very much. Unlimited support was also offered to me by my local supervisor Dr. J.P. Mrema and his colleagues in the Department of Soil Science of the Sokome University of Agriculture.

My sisters, Callista Matthew and Regina Agustine, and my sister in law, Elizabeth Mowo (Mama Sia) were very important in communication between Tanzania and Wageningen at the various stages of the study for which I am grateful. To this end I would like to mention my brother Ignace Mowo who always came in handy on important issues that I should have addressed myself.
To keep my spirits high at Wageningen the community of Tanzanians played an important role. Special thanks should go to B. Libeta, E. Senkondo, E. Wella (+), E. Mwamaja, E. Chaggu, G. Mkamilo, G. Kajiru, J. Shoo, K. Mtunda, L. Mboera, L. Ndege, S. Mgenzi, and Z. Semgalawe for their good company and words of encouragement. The good co-operation of fellow Dutch students at Dijkgraf and Asserpark made my stay as well as my work at Wageningen more enjoyable for which I am very grateful. While in the Netherlands some of the Dutch colleagues I had worked with at the National Soil Service and elsewhere in Tanzania made me feel at home. Particularly Mr. Arie van Kekem (Staring Center), who also provided the map of Tanzania, Dr. Jan Douwe Meinderstsma (Netherlands Economic Institute) and Dr. Piet Oosterom. Only time limited my visits to their homes.

The unlimited study leave granted to me by my employer, the Ministry of Agriculture gave me ample time to concentrate on my research for which I am very grateful. Finally, the stability offered by my beloved wife Fausta and the children, Joackim and Callista merit special mention for without this the completion of the work would have been extremely difficult.
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<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>ARF</td>
<td>Agriculture Research Fund</td>
</tr>
<tr>
<td>ARI</td>
<td>Agricultural Research Institute</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variability</td>
</tr>
<tr>
<td>LSD</td>
<td>Least Significant Difference</td>
</tr>
<tr>
<td>m.a.s.l.</td>
<td>Meters above sea level</td>
</tr>
<tr>
<td>MATI</td>
<td>Ministry of Agriculture Training Institute</td>
</tr>
<tr>
<td>MPR</td>
<td>Minjingu Phosphate Rock</td>
</tr>
<tr>
<td>NNM</td>
<td>Nearest Neighbor Mean</td>
</tr>
<tr>
<td>NSS</td>
<td>National Soil Service</td>
</tr>
<tr>
<td>PR</td>
<td>Phosphate rock</td>
</tr>
<tr>
<td>Rs</td>
<td>Relative increase in plant size</td>
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<tr>
<td>SE</td>
<td>Standard Error</td>
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<tr>
<td>SQ</td>
<td>Sufficiency Quotient</td>
</tr>
<tr>
<td>TSP</td>
<td>Triple superphosphate</td>
</tr>
<tr>
<td>WUR</td>
<td>Wageningen University and Research Center</td>
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</table>
1 Introduction

1.1 General

1.1.1 Nutrient depletion in Tanzania

Agriculture is the major economic activity in Tanzania accounting for 40% of the Gross Domestic Product. The National Agriculture Production policy is to attain self-sufficiency in food and even to generate surplus for export, as well as to increase the production of the traditional export crops. This is expected to be achieved through the use of modern farming techniques with emphasis on nutrient management. However, the use of fertilizers (especially industrial fertilizers) is hampered by their high costs. Sumaye (1993) noted that Tanzania uses about 170,000 tons of mostly nitrogen (N) and phosphorus (P) fertilizers which is about 2 kg per hectare or only 20% of what is considered the required amount. Consequently crop production relies to a great extent, on the natural soil fertility resulting in serious depletion of soil nutrients (nutrient mining). For example, Stoorvogel et al. (1993) reported negative nutrient balances in several countries of Sub-Saharan Africa (including Tanzania) with an increasing trend towards the year 2000. With the least consumption of fertilizer compared to other regions of the world (Woomer and Muchena, 1996; FAO, 1996) this trend is bound to continue because of the low economic position of these countries and the small uneconomically viable farm sizes common with the majority of farmers. Coupled with this is the increasing population pressure and declining opportunities for shifting cultivation. Given these conditions the search for alternative but affordable nutrient resources is necessary. Indigenous nutrient resources could provide part of the answer.

1.1.2 Use of phosphate rock

Phosphorus is one of the nutrients often limiting agricultural production in Tanzania (Ikerra et al., 1994). The use of industrial fertilizer P is, however, restricted not only by the high costs but also because of the occasionally low crop responses to applied P which is attributed to P fixation by the soils (Ikerra and Kalumuna, 1991; Kamasho and Msaki, 1992; Assenga, 1993). Compared to soluble P fertilizers phosphate rock P is cheaper and it is supposed to be less prone to fixation. Due to this the Government is advocating the use of indigenous phosphate rock (PR) as an alternative source of P. Phosphate rocks (PRs) occur in various locations in Tanzania (Fig.1.1; Patel, 1975; Mchihiyo, 1991; Mwambete, 1991). Significant deposits occur at Panda hill in Mbeya region (igneous origin) and at Minjingu in Arusha region (sedimentary origin). At Panda hill deposits of up to 370 million tons of Panda hill carbonatite (Mchihiyo, 1991) with $P_2O_5$ content varying from 14 to 30 % are known to occur. At Minjingu, Mwambete (1991) reported PR deposits of about 10 million tons with $P_2O_5$ content varying from 6 to 32 Percent. Latest figures cite 3.3 million tons of soft ore and 4.8 million tons of hard ore (Van Straaten, 1997). The soft and hard ores differ in the amount of SiO$_2$ and other impurities. So far only the soft ore of Minjingu Phosphate rock which has the highest P content, is being mined commercially (Mwambete, 1991). It consists of about 60 % apatite, mainly the microcrystalline fluorhydroxy-apatite (NSS, 1989). Its direct use as a P source in P deficient soils is being encouraged and research efforts have been geared towards establishing appropriate recommendations for use by farmers. The major drawback of PR is its poor solubility.
Figure 1.1. Map of Tanzania showing deposits of phosphate rocks.
The agronomic effectiveness of PR could be improved through partial acidulation or compaction with soluble P fertilizers (Menon et al., 1991) but these improvements are still beyond the reach of the poor countries (Mapiki and Singh, 1990; Hellums et al., 1992). Direct utilization of PR could therefore be a more secure investment (World Bank, 1994). Studies conducted in several countries of Sub-Saharan Africa have shown that indigenous phosphate rocks can be used directly as a soil amendment. Kirk and Nye (1986) noted that they are the cheapest source of P available in the tropics where many soils are acidic, very low in P and high in P fixation. Hammond et al. (1986) noted that developing countries with reactive PR deposits might find it more profitable to use this source of P than the expensive water soluble P fertilizers which they have to import, even when the agronomic effectiveness of the later is higher. Because phosphate rocks are sparingly soluble, they have a long lasting residual effect ensuring P supply for several years. Phosphate rocks perform well when applied in soils which have a low pH (Kanabo and Gilkes, 1987), high amounts of reserve acidity and low available P (Bolland and Gilkes, 1990), and low exchangeable Ca (Mackay et al., 1986). In soils rather high in pH and low in available P, appropriate and affordable strategies are required to facilitate the dissolution of phosphate rocks.

1.1.3 Phosphate rock research in Tanzania

Research work on PR for direct application in Tanzania dates back to the 1960's with efforts directed towards establishing appropriate packages for farmers. Conclusions from work by Anderson (1971) on groundnuts, Scaife (1968) and Gama and Mowo (1990) on cotton, Patel (1975) on maize and Ngatunga and Deckers (1984) on sorghum showed that responses to Minjingu phosphate rock (MPR) were erratic. However, it performed better in light textured soils derived from acidic parent materials like granites than in heavy textured, high pH soils derived from quartzite gneiss (NSS, 1989). A higher residual effect was also evident with MPR in the second and third year after application compared to soluble P sources. Minjingu PR and triple superphosphate (TSP) were compared in a six year trial on Rhodic Ferralsols and Chromic Luvisols of pH (H2O) = 5.8 and low available P (P-Bray-I) = 4 mg kg\(^{-1}\) at Mlingano, Tanga region. Both P sources increased maize yield but there was no significant difference between them. The performance of the P sources was greatly influenced by rainfall amounts and distribution. Working with Panda and Minjingu PRs on Inceptisols (pH (H2O) = 5.5 - 6.2) and Ultisols (pH (H2O) = 5.8) in the Southern Highlands of Tanzania, Kamasho et al. (1992) reported relatively higher maize yields when the PRs were applied either in a row or in the planting hole 5 cm below the seed than when it was broadcast. This can be expected on soils high in P fixation where dissolved P from PR is rapidly fixed into unavailable forms. De Geus (1976) recommended band placement when relatively small quantities of PR are required. However, this would be more valid in the more acidic soils. Research has also been directed towards enhancing the effectiveness of PR through promoting its solubility. This has been in the form of applying PR with organic manure (Kamasho et al., 1992; Ikerra, et al., 1994) and acidulation with sulfuric acid (NSS, 1989). The role of organic manure in PR dissolution is sometimes conflicting as will be discussed later, while acidulation using sulfuric acid make the product expensive and out of reach for the small holder farmer.

1.1.4 Dissolution of phosphate rock

The main constituent of PR is apatite. The dissolution reaction of a fluoro-apatite, the basic form of apatite, can be expressed by the equation:

\[ \text{Ca}_{10} \text{(PO}_4\text{)}_6 \text{F}_2 + 12 \text{H}_2\text{O} \rightleftharpoons 10 \text{Ca}^{2+} + 6 \text{H}_2\text{PO}_4^- + 2 \text{F}^- + 12 \text{OH}^- \]
(Rajan et al., 1996.). Congruent dissolution of phosphate rock proceeds with high demand for protons bringing phosphate, calcium and hydroxyl ions into the soil solution. Any process taking away these ions stimulates PR dissolution.

For hydroxyl ions this is achieved through reaction with protons. Accessory compounds in the PR neutralize some of the protons. Most PRs have high pH. Mishra and Bangar (1986) reported pH range of 7.7 to 8.7 for Indian PRs while Kpomblekou-A and Tabatabai (1994a) reported high pH for most of the PRs from Sub-Sahara Africa. This is including Minjingu PR, which they reported to have a pH of 9.0 (Table 1.1). In soils with pH 4.5 and lower, the availability of protons seems assured (Oenema, 1980). In other soils advantage must be taken of acidifying processes occurring in the soil-plant system. Microbial decomposition of soil organic matter and added organic manure results in production of protons mainly by oxidation of nitrogen, carbon and sulfur.

Various plants are capable of acidifying their rhizosphere, which could be due to reaction to P stress (Gardner et al., 1983; Lipton et al., 1987; Moorby et al., 1988; Ac et al., 1991; Hoffland, 1991; Gerke and Meyer, 1995; Li et al., 1997), exudation of protons (H⁺) due to imbalance in uptake of cationic over anionic nutrients (Riley and Barber, 1971; Smiley, 1974; Soon and Miller, 1977; Aguilar and van Diest, 1981; Bekele et al., 1983; Weinberger and Yee, 1984; Wen-Chen Liu et al., 1989) and by high calcium uptake (Bako Boan and van Diest, 1989; Bekele and Höfler, 1993; NSS, 1989; Hartemink, 1995). Imbalance in uptake of cationic over anionic nutrients is common with some legumes utilizing atmospheric N and plants relying on NFLt⁺ for their N source. Protons are exuded into the rhizosphere to maintain electro-neutrality. The application of ammonium fertilizers also stimulates acidification either through NH₄⁺ uptake by the crop or upon nitrification by bacteria.

Table 1.1. Selected properties of some phosphate rocks from Africa*.

<table>
<thead>
<tr>
<th>Phosphate rock</th>
<th>pH(H₂O)</th>
<th>Total P (%)</th>
<th>Water soluble P mg kg⁻¹</th>
<th>CaCO₃ equiv. %</th>
<th>Length of a axis (Å)²</th>
<th>Trace metals mg kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mali (Tlemsee) (Mali)</td>
<td>7.7</td>
<td>14.0</td>
<td>0.20</td>
<td>3.03</td>
<td>9.359</td>
<td>19</td>
</tr>
<tr>
<td>Khouribga (Morocco)</td>
<td>8.1</td>
<td>13.9</td>
<td>0.00</td>
<td>4.52</td>
<td>9.336</td>
<td>40</td>
</tr>
<tr>
<td>Minjingu (Tanzania)</td>
<td>9.0</td>
<td>15.0</td>
<td>9.10</td>
<td>7.10</td>
<td>9.353</td>
<td>16</td>
</tr>
<tr>
<td>Gafsa (Tunisia)</td>
<td>7.5</td>
<td>13.4</td>
<td>0.10</td>
<td>10.30</td>
<td>9.327</td>
<td>11</td>
</tr>
<tr>
<td>Tahoua (Niger)</td>
<td>6.5</td>
<td>11.9</td>
<td>0.70</td>
<td>1.13</td>
<td>9.365</td>
<td>20</td>
</tr>
</tbody>
</table>

¹ From Kpomblekou-A and Tabatabai (1994a).
² From van Kauwenbergh (1995).
* Dimension of unit-cell of the apatite.

Calcium ions may be removed by chelating organic anions released by plants or by microbes. Alternatively, microbial and chemical transformations of organic matter releases various organic acids which can chelate calcium (Chien, 1979). Chelates may also be formed with Fe³⁺ and Al³⁺ commonly found as impurities in PRs, and this may prevent precipitation of Fe and Al phosphates. Kpomblekou-A and Tabatabai (1994b) suggested that chelation by organic acids of metals associated with PRs was responsible for increased dissolution of PR. On the other hand, organic acids excreted by plant roots can be used as substrates by microbes and in so doing the pH is raised and PR dissolution curtailed (Gardner et al., 1982). Further, the microbes need P for their metabolism and hence compete with plants for the same resource. In contrast, some
Introduction

Microbes, notably bacteria, produce organic acids (Moghimi et al., 1978), which enhance PR dissolution.

Phosphate ions may be taken up by plants thus furthering PR dissolution. Stimulation of crop growth, for example, by application of other nutrients than P or by improving soil physical conditions, may therefore indirectly promote PR dissolution. Phosphate ions may react with soil constituents such as Fe\(^{3+}\) and Al\(^{3+}\), which go into solution under acid conditions. Depending on the capability of plants to intercept P before it is fixed by Fe\(^{3+}\) and Al\(^{3+}\), the effect of acid on PR dissolution may or may not manifest itself in plant P uptake and dry-matter yield. So the fate of added PR is difficult to predict and depends on contrasting processes in the rhizosphere.

1.1.5 Organic manure

A lot of work has been done on the use of organic manure in enhancing the effectiveness of PR with contrasting results. Some workers have reported enhanced dissolution when organic manure interacts with PR while others have observed just the opposite. For example, whereas Welte (1978) and Panda (1990) observed significant increases in P availability and dry-matter yield, Rastogi et al. (1976) and Khanna et al. (1979) observed no improvement in P availability when PR was mixed with farmyard manure. In a detailed review on "Combined application of organic manure and phosphate fertilizers", Oenema (1980) noted that organic substances had a small influence on the availability of PR. Since that time more work has been done along this line (Bangar et al., 1985; Muchovej et al., 1989; Mishra and Bangar, 1986; Singh and Amberger, 1991; Ikerra et al., 1994; Mahima and Bhagat, 1995) and like before, results have been mixed.

The contradictions in the various findings throw doubts on the general applicability of the results and the reliability of the advises to farmers inferred from those results. One of the contradictions is the beneficial effect ascribed to organic manure in enhancing the effectiveness of PR. Most organic manure has alkaline pH. Musa (1975) reported a pH of 8.5 for cattle manure while Mahima et al. (1995) observed a pH of 8.5 for poultry manure. Wickama and Mowo (1999) reported pH ranging from 7.3 to 9.8 for farmyard manure from various kraals in Lushoto, Tanzania. Wong et al. (1998) observed that farmyard manure like most other organic manure was a good soil acidity ameliorant, high in proton consumption capacity. Notwithstanding decomposing organic manure does produce protons, it is questionable, in view of the alkaline pH of most of them, whether the pH can be lowered to levels conducive to the dissolution of PR when the two are mixed. Given that most PRs are themselves high in pH, mixing them with such manure will lower instead of increasing the amount of protons available for PR dissolution. Therefore, the positive interactions found when farmyard manure is combined with PR must arise from mechanisms other than proton-induced dissolution of PR. It is likely the result of chelation by released organic molecules. Pre-treatment of PR with organic manure may stimulate the chelation process. Incubation of PR with organic manure before the mixture is used as a fertilizer is reported to enhance PR dissolution (Hue et al., 1991). This is valid especially for the less reactive PRs. Purnomo and Black (1994) compared incubation for 30 days of the reactive North Carolina PR before sowing with application at sowing, and observed a increased Colwell P concentration but no significant dry-matter yield increase. The length of incubation may be critical; short periods will not ensure enough production of protons or chelating organics while in long periods solved P may react with soil constituents, especially in high P fixing soils, making dissolved P unavailable for plant uptake (Mishra and Bangar, 1986; Singh and Amberger, 1991; Ikerra et al., 1994).
Another result of combining PR and organic manure may be the improvement of the quality of organic manure. Fodder crops and natural vegetation growing on P-depleted soils have low P concentrations, and manure from animals using such fodder is low in P too. Hence addition of PR may result in a more balanced supply of the various nutrients in such organic fertilizers. The effects of organic manure and plants on phosphate rock dissolution and availability are schematically presented in Figure 1.2.

![Figure 1.2. Schematic presentation of the effects of organic manure (OM) and plants on phosphate rock dissolution and availability. Decomposition of OM releases organic acids that may solubilize PR (solid P) or through exchange reactions desorb sorbed P. Some plants release organic acids due to various reasons with similar effects on solid and sorbed P. Through mineralization, OM contribute P to the soil solution. Supply of growth factors by OM promote plant growth, which increase P demand. P from the soil solution can be taken up by plants, reconverted to solid forms or sorbed. As P is withdrawn from the soil solution more is dissolved from solid P (law of mass action) or desorbed.]

1.1.6 Field conditions

**Broadcasting** is the method usually advocated for directly applied phosphate rock. Through this method of application many PR particles do not enter the rhizosphere. The rhizosphere acidification does not influence bulk soil pH under natural field conditions; even in pot experiments in the greenhouse PR dissolution due to rhizosphere acidification is difficult to achieve. Aguilar (1981) failed to observe acidification of the rhizosphere and PR dissolution by soybean exhibiting alkaline uptake in a sandy loam in the greenhouse although a substantial lowering of pH and PR dissolution were observed when pure sand was used. Difficulties in lowering the bulk soil pH substantially arise from the high pH buffering capacities of soils (Thomas and Hargrove, 1984; Bache, 1985).
Some workers are advocating a one-time large amount of PR application (Buresh et al., 1997) followed by periodic maintenance levels (high input strategy). Pieri (1987) and Sanchez et al. (1997) indicate that this could be attractive for medium to highly reactive PRs applied in acid soils near the source. To most farmers in the tropics such large amounts might be difficult to apply due to costs. Moreover given the high pH of most PRs large amounts will work to their disadvantage given the increased demand for protons. For example, Brenes and Bornemisza (1992) observed in an incubation experiment with the reactive North Carolina PR that amounts of the PR beyond 600 mg P kg$^{-1}$ did not result in appreciable increase in solubilized P. Similar results have also been reported by various other workers (Kanabo and Gilkes, 1988; Bolland and Barrow, 1988; Rajan et al., 1991). Amounts of PR applied should be such that optimum use of available soil protons is achieved.

Spatial variability within and between fields is common in the tropics. Various factors are responsible for this including difference in landscape, decaying roots of former trees and ash from burnt vegetation. Occurrence of specific trees capable of enriching the soil by adding nutrients from lower soil layers and even a minor micro-relief which could encourage rain water to stand longer and hence seep more are some of the situations associated with spatial variability within and between fields. Other factors include slaking and soil depth (Janssen, 1970), termite activity (Brouwer et al., 1992), small differences in soil available P (Wendt et al., 1993) and surface crusting (Geiger et al., 1992; Geiger and Manu, 1993; Buerkert et al., 1995). Van der Eijk (1997) observed within and between field differences in maize yield in Kenya which he attributed to the spatial variability in biological activity apart from differences in total P values. Spatial variability of soil characteristics and its effect on crop growth are often indicated by occurrence of closely spaced patches of good and bad plant growth. Janssen and Van der Weert (1977) could not find larger sites than 5 m$^2$ with uniform growth; differences in yield were related to various soil characteristics, but most obvious to organic matter content and volume of macropores (> 180 μ). Mostly considered a nuisance by many researchers (Moormann and Kang, 1978), the influence spatial soil variability on fertilizer response is not incorporated in most field studies. Wilding and Hossner (1987) noted that effective analysis of field experiments is hindered by spatial variability in the field. Working in the Sahel, Brouwer and Bouma (1997) observed that soil and crop growth variability play an important role in agriculture and artificial means should not be used to eliminate it from agronomic trials. Such variability could be exploited in increasing the use efficiency of the natural nutrient resources available in the tropics such as PR and organic manure.

Therefore, it can be said that the availability of P from PR to plants, after application to soil, depends on a complex of interacting factors. The effectiveness of PR can be related to (i) PR properties (ii) soil characteristics (iii) crop characteristics and, (iv) management factors. The dissolution of P from PR is a prerequisite, and the basic aim of this thesis is to find appropriate combination of soil, crop and management to generate a sufficient amount of protons for the dissolution of PR within reach of the plant roots.

1.2 Aims of the research

From research work done so far it can be established that:
- Direct application of PR under the right environment (low pH, low P and Ca) is a cheap source of P compared to commercial P fertilizers especially for resource poor farmers.
- Different crops have differing abilities to utilize P from less soluble sources like PR.
- Dissolution of PR requires substantial amounts of protons.
- Organic manure and acidifying fertilizers could promote the effectiveness of PR.
Knowledge is however, still lacking in the following areas:

- Quantification of the various factors responsible for PR dissolution.
- Possibilities to extend PRs use to soils less favorable in PR dissolution but deficient in P.
- The actual mechanism by which organic manure promote PR dissolution given the high pH of both materials.
- Influence of spatial soil variability (common in the tropics) on the effectiveness of PR and ways of exploiting these variabilities in improving PR management and crop performance.

To fill the knowledge gap this study was initiated with the overall aim of increasing our understanding of the multiple interactions (Fig. 1.2) that affect the availability of P from PR in the soil-crop system. Such knowledge is required to enable optimal exploitation of the various factors that contribute to the improvement of the effectiveness of PR and hence contribute to improvement of agricultural production by reversing the current trend in P mining in the tropics in general and Tanzania in particular.

Specifically the objectives were:

- To determine the amount of extractable P from Minjingu PR in comparison to other PRs under conditions of limited and unlimited proton supply and different shaking times.
- To assess the effectiveness of Minjingu PR in comparison to other PRs and soluble P as source of P to maize under conditions of limited proton supply.
- To assess the influence of crops in promoting PR dissolution.
- To study the influence of soil pH and the interaction of pH and soil available P on the recovery of P from Minjingu PR compared to soluble P sources.
- To assess the effectiveness of low amounts of PR (low input strategy) and different placement methods in the utilization of the available protons under field conditions.
- To study the effect of mixing Minjingu PR with soluble P source on the effectiveness of Minjingu PR.
- To establish the probable role of organic manure and N fertilizers on Minjingu PR effectiveness.
- To establish whether PR use can be extended to soils less favorable for its dissolution.
- And finally to study the influence of within field spatial soil variability on Minjingu PR effectiveness.

1.3 General methodology and outline of this thesis

The study was conducted in three phases. Phase I was in Wageningen from September 1994 to February 1995, and it involved literature review, laboratory studies and greenhouse experiments. Literature review aimed at finding out current views on enhancement of PR effectiveness using farmyard manure and plant uptake characteristics. Laboratory studies concentrated on characterization of Minjingu PR, farmyard manure and a Ferralsol from Tanga, Tanzania. Greenhouse experiments centered on establishing the P supply potential of the soil from Tanga, response to MPR by maize, and the potential of farmyard manure and cowpea in enhancing MPR effectiveness.

From results of Phase I more greenhouse and laboratory work was necessary to enable definite designs of field trials. This period was Phase IIa and run in Tanga from March 1995 to April 1996. During this phase three experiments were conducted using four soils differing in pH to study the influence of soil properties and of cowpea or pigeonpea as intercrops on MPR effectiveness. Based on the results of Phase IIa, field trials were designed on two Ferralsols differing in pH. They were run during the long rains of March to May 1997 and the short rains
Introduction

of October to December 1997 in Phase IIb. The field trials aimed at studying the influence on Minjingu PR in relation to soil properties of:

- Application rate for broadcast as well as for localized MPR,
- Acidifying and non acidifying N fertilizers,
- Stimulating P uptake by the use of TSP or other fertilizers to trigger off crop growth and,
- Incubating MPR with farmyard manure.

The effect of spatial variability on MPR effectiveness was studied in each of the field trials by applying the 'Post-mortem Residual Analysis' (PRA) and the Nearest Neighbor Means (NNM) techniques. This was done by calculating the error term (residuals in statistical analysis) of individual experimental units in the field. The means of the residuals of the nearest neighbors for each experimental unit were calculated and entered as covariates in the ANOVA. The NNMs were also used to relate the different response to soil properties. Referred also as 'post stratification' (Buerkart et al., 1995), PRA enables the exploitation of natural variability for a better understanding of the crop responses to nutrient application. This phase was concluded by laboratory analysis and an additional greenhouse experiment on the liming effect and the effectiveness of MPR under different soil pH and available P conditions.

Phase III was spent on data interpretation and write up partly in Tanzania and in the Netherlands between October 1998 and September 1999.

The thesis is organized into 8 chapters. Description of the sites where the field experiments were done as well as an overview of the materials used in the greenhouse and laboratory experiments is covered in Chapter 2. Chapter 3 discusses one laboratory and two greenhouse experiments. In the laboratory experiment Minjingu and two other PRs: Mali (Tilemsi) PR from Mali and Khouribga PR from Morocco, are extracted with HCl at different concentration and shaking times. One of the greenhouse experiment compares the P supply potential of the Ferralsol from Tanga with three other soils from Netherlands, Ivory Coast and Kenya while the other studies the response of maize to the three PRs referred above using the Ferralsol from Tanga. In Chapter 4 two greenhouse experiments look into the influence of increasing dry-matter yield on soil pH and the effectiveness of Minjingu PR in a maize-legume intercropping system. Chapter 5 covers results of two greenhouse experiments studying the recovery of P from Minjingu PR by maize, cowpea and pigeonpea and the performance of Minjingu PR under different soil and available P conditions.

Chapters 6 and 7 deal with field experiments. In Chapter 6 the influence of spatial soil variability on the effectiveness of Minjingu PR is studied on the field experiments conducted. Chapter 7 covers four field trials studying the use of different management options in enhancing the effectiveness of Minjingu PR. Finally the implications of results from this research, recommendations and future research scenario are dealt with in Chapter 8.
2 Location and site characteristics

2.1 Introduction

The field trials described in this thesis were conducted at the research farm of Mlingano Agricultural Research Institute (ARI Mlingano) and in the bordering village of Mzambaraoni (Fig. 2.1). Soils used in most of the laboratory and greenhouse experiments come from the same sites where the field trials were conducted. Other soils come from Bagamoyo village close to the institute and from different sisal estates in Tanga region. The major soils of interest were the Rhodic Ferralsols. They were chosen because of their nutritional problems especially related to P and their importance as agricultural soils in Tanzania. In this chapter a brief description of Ferralsols is given as well as the location, climate, physiography, geology and soils of ARI Mlingano and the surroundings villages. A brief explanation of other soils used in this study as well as test crops and fertilizers used is also given. Also briefly covered are the various methods used in the laboratory determinations.

2.2 About Ferralsols and their distribution in Tanzania

Most Ferralsols have good physical properties (Driessen and Dudal, 1989) such as excellent porosity, high permeability and infiltration rates and stable microstructure. They have friable consistency, are easy to work, are well drained and have good rooting conditions. These properties make them potentially suitable for agricultural production. However, they are weak in macrostructure and have low available water storage capacity. They are also chemically poor with very low contents of available P and weatherable minerals. Their pH vary greatly and values ranging from 3.7 (pH CaCl₂), (Assenga and Mrema, 1991) to 6.5 (pH H₂O), (Warren, 1994) have been reported.

Ferralsols occupy about 20 % of the land surface in the tropics. In Africa their estimated coverage would be about 22 % (Aubert and Tavernier, 1972). In Tanzania they cover about 20 % of the country (De Pauw, 1984). They are mainly found in areas between 750 and 2300 m.a.s.l. They are distributed over a wide range of landscapes, ranging from strongly dissected uplands to flat or gently undulating plains in medium and high altitudes. The parent materials of most Ferralsols consist of pre-weathered, mostly transported materials of old age, derived from a wide variety of rocks. The common parent materials for most Ferralsols in Tanzania include granite, gneisses, schists, phyllites and acid volcanics. The extent of P deficiency in Ferralsols in Tanzania has not been established but they are generally considered to have low levels of available P (Ikerra and Kalumuna, 1991). However, there is great variation and P values ranging from less than 0.5 mg kg⁻¹ to 12 mg kg⁻¹ (P-Bray-I) have been reported for Ferralsols (Hartemink, 1995).

In Tanga region where the study was conducted, Ferralsols together with Luvisols and Arenosols are the most predominant. The exact extent of each soil type has not been established. However, according to the reconnaissance soil map of Agrar-Und Hydrotechnic (1976) they occupy about 1300 km² to the north and west of Tanga town while in the uplands north of Usambara mountains Ferralsols and Luvisols cover about 2,400 km². In the central uplands they cover about 4200 km². Within the Ferralsols, Rhodic Ferralsols are the most dominant occupying about 20 % of the land surface of Tanga region (Floor, pers. comm.). Xanthic Ferralsols occurs less in magnitude mainly along the coastal plains. Sisal, cashewnut, coconut and citrus, the most important cash crops in the region, are grown on both Rhodic and Xanthic Ferralsols. Other crops common on these soils include maize, cassava, sorghum and various grain legumes.
Chapter 2

Figure 2.1. Soil map of ARI Mlingano showing location of the field trials and sites where soils used in most of the greenhouse experiments were collected.
Location and Site characteristics

2.3 Location

Mlingano Agricultural Research Institute is in Muheza district, Tanga region, in north-eastern Tanzania. It is about 32 km from Tanga municipality along the Tanga to Dar es Salaam highway. The approximate geographical coordinates of the institute are 39° 52'E longitude and 5° 10'S latitude at an altitude of 183 m.a.s.l. The location of the field trials and sites where soils for most of the greenhouse and laboratory experiments were collected are shown in Fig. 2.1.

2.4 Climate

Tanga region has two distinct rainfall seasons often referred to as long rains (masika) and short rains (vuli). The long rains fall between March and May while the short rains fall between October and December. The long rains are usually more reliable in distribution and onset dates. They provide about 60% of the total precipitation. Total annual average (24 years records from 1973 to 1993) is 1,115 mm ranging from 616 mm to 1736 mm. The wettest months are April and May when rainfall exceeds evapotranspiration. Total annual evapotranspiration is around 1695 mm (Penman). The main Dependable Growth Period (DGP) lasts for four to four and half months with onset in March while the secondary DGP with onset in October lasts between two and a half to three months. Crop failure is common in the secondary DGP due to its short duration and unreliability in onset dates. Diurnal and monthly variations in temperatures are low. Figure 2.2 shows average rainfall, evapotranspiration and temperature for ten years between 1988 and 1997.

![Figure 2.2. Rainfall, evapotranspiration, and temperature at ARI Mlingano. Mean of 10 years (1988 - 1997). Source: Meteorological Section, ARI Mlingano.](image)

During the decade, rainfall in the months of October and November also exceeded evapotranspiration mainly because of the exceptionally high rainfall during the short rains of 1997 (Fig. 2.3). The ten days running totals for 1997 during when the field trials were done are shown in Table 2.1. The long rains were normal and well distributed. The short rains coincided
with the El Niño phenomena which divided the country into two halves one very dry and the other very wet. Tanga fell in the later. Apart from the exceptionally heavy rains, it was poorly distributed with more than half of it falling in October. Within October the second decade was the wettest (Table 2.1) causing occasional water logging which affected maize growth at the early stages of the crop. Due to this, yields were just as low as in the normal short rains.

![Rainfall, evapotranspiration, and temperature at ARJ Mlingano during 1997. Source: Meteorological Section, ARJ Mlingano.]

**Figure 2.3.** Rainfall, evapotranspiration, and temperature at ARJ Mlingano during 1997. Source: Meteorological Section, ARJ Mlingano.

### 2.5 Physiography, geology and soils

Mlingano is located on the eastern edge of the low foreland plateau just south east of the Eastern Usambara mountains (Ojany, 1974). It is made up of dissected denudational plains consisting of ridges and valleys. According to De Pauw (1984) Mlingano is part of agro-ecological zone E6 comprising of the well drained, undulating to rolling plains at low altitudes (150 to 500 m.a.s.l.), and developed on intermediate metamorphic rocks, mainly acid and intermediate gneisses. About 2 km to the east of Mlingano starts the coastal plains in agro-ecological zone CI (De Pauw, 1984), comprising of nearly level to rolling plains with altitudes less than 200 m.a.s.l. The coastal plains consist of Paleozoic sedimentary rocks, marl, sand stones and shales.

The soils of Mlingano (Fig. 2.1) constitute a recurrent topographic sequence (catena), and differ from crest to the valley bottom due to factors of drainage, leaching and lateral movement of chemical constituents. On the crests are the red ferrallitic soils which are strongly weathered,
Location and Site characteristics

moderately deep to deep and generally well drained. The clay fraction is dominated by kaolinite and (hydro)oxides of iron and aluminum (Nandra, 1977). The sand fraction consists mainly of quartz. They have very low natural fertility, chemical fertility being restricted to the upper 30 cm. Their water holding capacity is low (AWC vary from 80 to 128 mm m$^{-1}$). Rhodic, Xanthic and Orthic Ferralsols are the dominant soils. In the incised valleys, the soils are mixed alluvia and colluvia, with strong variations in texture, profile development and mineralogical composition. Dominant soils are Orthic, Chromic and Ferric Luvisols. They are generally low in available P and values ranging from 1.7 to 4.5 mg P kg$^{-1}$ (P-Bray-I) for Rhodic Ferralsols at ARI Mlingano and the surrounding villages have been reported (Assenga and Mrema, 1991).

Table 2.1. Rainfall (mm). Ten days running totals during 1997.

<table>
<thead>
<tr>
<th>Month</th>
<th>Decade 1 - 10</th>
<th>Decade 11 - 20</th>
<th>Decade 21 - 30</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>February</td>
<td>2.9</td>
<td>0.0</td>
<td>0.0</td>
<td>2.9</td>
</tr>
<tr>
<td>March</td>
<td>0.0</td>
<td>21.5</td>
<td>51.9</td>
<td>73.4</td>
</tr>
<tr>
<td>April</td>
<td>56.5</td>
<td>30.2</td>
<td>71.2</td>
<td>157.9</td>
</tr>
<tr>
<td>May</td>
<td>33.8</td>
<td>7.0</td>
<td>82.3</td>
<td>123.1</td>
</tr>
<tr>
<td>June</td>
<td>42.2</td>
<td>11.8</td>
<td>18.0</td>
<td>72.0</td>
</tr>
<tr>
<td>July</td>
<td>6.8</td>
<td>6.4</td>
<td>0.4</td>
<td>13.6</td>
</tr>
<tr>
<td>August</td>
<td>0.0</td>
<td>24.1</td>
<td>0.2</td>
<td>24.3</td>
</tr>
<tr>
<td>September</td>
<td>4.8</td>
<td>2.5</td>
<td>3.4</td>
<td>10.7</td>
</tr>
<tr>
<td>October</td>
<td>154.1</td>
<td>424.2</td>
<td>124.1</td>
<td>702.4</td>
</tr>
<tr>
<td>November</td>
<td>60.5</td>
<td>93.5</td>
<td>55.4</td>
<td>209.4</td>
</tr>
<tr>
<td>December</td>
<td>70.1</td>
<td>40.4</td>
<td>21.9</td>
<td>132.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>431.7</strong></td>
<td><strong>661.6</strong></td>
<td><strong>428.8</strong></td>
<td><strong>1522.1</strong></td>
</tr>
</tbody>
</table>

2.6 Soils used in the experiments

The field experiments were located on Rhodic Ferralsols (Fig. 2.1). The Ferralsols at Mlingano could be considered representative of the Ferralsols found in the central uplands of Tanga region. One site was in the experimental farm of ARI Mlingano whose pH is relatively high (pH (H$_2$O) = 5.8) and the other site with relatively low pH (pH H$_2$O = 5.0) was near the village of Mzambaraoni which borders the Institute to the North about 2.5 km from the first site. The sites are coded S2 and S3 respectively (Fig. 2.1). For the greenhouse experiments at Wageningen, soils from Tanzania (Rhodic Ferralsol), Kenya (Luvic Phaeozem), Netherlands (Cumulic Anthrosol) and Ivory Coast (Plinthic Ferralsol) were used. The Tanzania soil (Soil S1) (Fig. 2.1) was obtained from an abandoned cashew field at ARI Mlingano that has been uncultivated for more than fifteen years. It has a pH (H$_2$O) of 6.8. Greenhouse experiments conducted at ARI Mlingano used apart from Soils S1 to S3 one sandy soil (Cambic Arenosol) coded S4 (pH (H$_2$O) = 5.7), from Bagamoyo village some 2 km East of the institute and nine other different soils collected from various sisal estates in Tanga region. The various experiments and soils used in each of them are summarized in Table 2.2. Unless indicated otherwise, properties of soils used in more than one experiment (S1 to S4) are summarized in Table 2.3. Profile descriptions for Soils S1 to S3 are shown in Appendix 1.

2.7 Crops and fertilizers used in the various experiments

Three crops were used in the various experiments reported in this thesis, namely maize, cowpea and pigeonpea (Table 2.4). Maize is the most important cereal crop and the staple food for most Tanzanians. The national average yield is 1.1 t ha$^{-1}$ while potential yield is 4.5 t ha$^{-1}$. Small
farmers account for more than 80% of the total maize production. Cowpea is mainly grown during the short rains and average yields range from 0.2 to 0.5 t ha\(^{-1}\) against a potential of 1.5 to 2.0 t ha\(^{-1}\). Small farmers produce almost all of it. It is either sole cropped or intercropped with cereals mainly maize. Pigeonpea is increasing in importance as both a cash crop and source of protein. It is mostly intercropped with cereals (maize and sorghum) and root crops. Average farmers yield is about 1 t ha\(^{-1}\) (Nkonya et al., 1992) while potential yield is about 4 t ha\(^{-1}\). There are various reasons for the low yields obtained but the most important is the low or non-use of agro-inputs mainly fertilizers.

The fertilizer materials used in the various experiments are shown in Table 2.5. Minjingu PR was kindly provided by Minjingu Phosphate Company based in Arusha, Tanzania, while the Department of Soil Science and Plant Nutrition (WUR) provided Mali and Khouribga PRs as well as TSP. Triple superphosphate, sulfate of ammonia and Calcium ammonium nitrate used in the experiments at ARI Mlingano were obtained from stockists of agro-inputs in Tanga. Livestock keepers at ARI Mlingano kindly provided farmyard manure.

2.8 Laboratory analytical methods

Except where stated otherwise, laboratory methods for the various determinations in this thesis were: pH potentiometrically in an 1:2.5 soil to extract ratio with either H\(_2\)O or 1 mol. KCl, organic carbon by wet oxidation (K\(_2\)Cr\(_2\)O\(_7\) + H\(_2\)SO\(_4\)), total N and P by continuous flow analyzer after digestion with H\(_2\)SO\(_4\)/salicylic acid/H\(_2\)O\(_2\)/selenium, P-Bray and P-Olsen spectrophotometrically at 880 nm, CEC and exchangeable bases by percolation (BaCl\(_2\) unbuffered), Ca and K by flame photometer, and Mg by atomic absorption spectrophotometer as detailed in Houba et al. (1995).
Table 2.2. The various experiments and soils used in each of them.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Title</th>
<th>Where done</th>
<th>Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Extraction of phosphate rocks with hydrochloric acid</td>
<td>WUR laboratory</td>
<td>Na</td>
</tr>
<tr>
<td>3.2</td>
<td>Response of maize to various PRs on a Rhodic Ferralsol from Tanzania</td>
<td>WUR greenhouse</td>
<td>X</td>
</tr>
<tr>
<td>3.3</td>
<td>P supply of the soil from Tanzania</td>
<td>do</td>
<td>X</td>
</tr>
<tr>
<td>4.1</td>
<td>Effects of crop type and dry-matter yield on soil pH</td>
<td>ARI Mlingano greenhouse</td>
<td>X X X X</td>
</tr>
<tr>
<td>4.2</td>
<td>Effect of intercropping maize with legumes on MPR availability in Rhodic Ferralsols</td>
<td>do</td>
<td>X X</td>
</tr>
<tr>
<td>5.1</td>
<td>Response of maize, cowpea and pigeonpea to MPR and TSP</td>
<td>do</td>
<td>X X</td>
</tr>
<tr>
<td>5.2</td>
<td>Response of maize to application of MPR to soils varying in pH and available P</td>
<td>do</td>
<td>X X</td>
</tr>
<tr>
<td>7.1</td>
<td>Influence of rates and method of application on MPR effectiveness</td>
<td>ARI Mlingano farm and Mzambaraoni village</td>
<td>X X</td>
</tr>
<tr>
<td>7.2</td>
<td>Influence of different sources and amounts of N fertilizers on MPR effectiveness</td>
<td>do</td>
<td>X X</td>
</tr>
<tr>
<td>7.3</td>
<td>Influence of different application methods of combinations of MPR and soluble phosphates on MPR effectiveness</td>
<td>do</td>
<td>X X</td>
</tr>
<tr>
<td>7.4</td>
<td>Incubation of MPR with organic manure. Possible role of FYM</td>
<td>do</td>
<td>X X</td>
</tr>
</tbody>
</table>

Na = not applicable

S1 to S3 Rhodic Ferralsol Ne Netherlands (Cumulic Anthrosol)
S4 Cambic Arenosol IC Ivory Coast (Plinthic Ferralsol)
Ke Kenya (Luvic Phaeozem) SE Sisal estates
Chapter 2

Table 2.3. Some physico-chemical Properties of Soils S1 to S4 (0 - 20 cm).

<table>
<thead>
<tr>
<th>Property</th>
<th>Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay %</td>
<td>S1</td>
</tr>
<tr>
<td>Silt %</td>
<td>66</td>
</tr>
<tr>
<td>Sand %</td>
<td>8</td>
</tr>
<tr>
<td>Texture class</td>
<td>Clay</td>
</tr>
<tr>
<td>pH H₂O</td>
<td>6.8</td>
</tr>
<tr>
<td>pH KCl</td>
<td>6.0</td>
</tr>
<tr>
<td>Organic C g kg⁻¹</td>
<td>20</td>
</tr>
<tr>
<td>Total N</td>
<td>1.7</td>
</tr>
<tr>
<td>C/N</td>
<td>12</td>
</tr>
<tr>
<td>P-Bray-I mg kg⁻¹</td>
<td>1</td>
</tr>
<tr>
<td>P-Olsen</td>
<td>6</td>
</tr>
<tr>
<td>Total P</td>
<td>344</td>
</tr>
<tr>
<td>CEC mmol(+)kg⁻¹</td>
<td>129</td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>44</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>35</td>
</tr>
<tr>
<td>Exch. K</td>
<td>9</td>
</tr>
<tr>
<td>Exch. Na</td>
<td>1.2</td>
</tr>
<tr>
<td>BS %</td>
<td>69</td>
</tr>
<tr>
<td>pH buffer⁺ capacity mmol(+)kg⁻¹</td>
<td>64</td>
</tr>
</tbody>
</table>

⁺ Based on amount of CaCO₃ required to raise the pH(H₂O) of one kg of soil by one pH unit.

Table 2.4. Crops used in the various experiments.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Variety</th>
<th>Experiments where used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>Zea mais (L.) var. LG 11</td>
<td>3.2, 3.3</td>
</tr>
<tr>
<td></td>
<td>Zea mais (L.) var. TMV1</td>
<td>4.1, 4.2, 5.1, 7.1, 7.2, 7.3, 7.4</td>
</tr>
<tr>
<td></td>
<td>Zea mais (L.) var. Staha</td>
<td>5.2</td>
</tr>
<tr>
<td>Cowpea</td>
<td>Vigna unguiculata (L. walp) var. Vuli</td>
<td>4.1, 4.2, 5.1</td>
</tr>
<tr>
<td>Pigeonpea</td>
<td>Cajanus cajan var. ICPL87075</td>
<td>4.1, 4.2, 5.1</td>
</tr>
</tbody>
</table>

Table 2.5. Fertilizers used in the various experiments.

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>Origin</th>
<th>Experiments where used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock phosphates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minjingu</td>
<td>Tanzania</td>
<td>All except 3.3 and 4.1</td>
</tr>
<tr>
<td>Mali(Tilemsi)</td>
<td>Mali</td>
<td>3.1, 3.2</td>
</tr>
<tr>
<td>Khouribga</td>
<td>Morocco</td>
<td>3.1, 3.2</td>
</tr>
<tr>
<td>TSP</td>
<td>Stockists</td>
<td>All except 3.3 and 4.1</td>
</tr>
<tr>
<td>Calcium ammonium nitrate (CAN)</td>
<td>Stockists</td>
<td>7.1, 7.2, 7.3, 7.4</td>
</tr>
<tr>
<td>Sulfate ammonia (SA)</td>
<td>Stockists</td>
<td>7.2</td>
</tr>
<tr>
<td>Farmyard manure (FYM)</td>
<td>ARI Mlingano</td>
<td>7.4</td>
</tr>
</tbody>
</table>
CHAPTER 3

3 Phosphate release by phosphate rocks and soils. Laboratory and pot experiments

Abstract

In a laboratory experiment the dissolution in HCl of Minjingu PR was compared to that of Mali and Khouribga PRs. In a greenhouse experiments the agronomic effectiveness of these PRs was compared using a Ferralsol from Tanzania and soils from Kenya, Ivory Coast and Netherlands as test soils. The objective of these experiments was to investigate the potential of Minjingu and the other PRs in supplying P under conditions of limited and unlimited supply of protons. An important factor determining differences between the PRs was the CaCO₃ content. The relatively higher CaCO₃ content of Minjingu and Khouribga PRs made them hard compared to Mali PR. Differences in dissolution manifested more at low than at high acid concentration. Although Mali PR showed a higher reactivity than Minjingu and Khouribga in the extraction experiment it did not perform better agronomically and all had a substitution value of 0.1. The P supplies of the Tanzania and Ivory Coast soils were lower than those of the Kenya and Netherlands. The implications of these results are that availability of enough protons is an important factor in PR dissolution, the CaCO₃ content of a PR is an important property influencing PR's effectiveness and hence low rates of PR should be more desirable than high rates, and that soil and plant factors have an important role in the effectiveness of a PR.

3.1 Introduction

One of the nutrients often limiting crop production in Tanzania is phosphorus (P) (Ikerra et al., 1994). Continual cropping without use of P fertilizers will further deplete soil P stocks, making crop production unsustainable. The possibilities to use industrial P fertilizers are small because of the poor financial resources of the smallholder farmers, who form the majority of the farming community. However, PR deposits abounds in the country (Mchihiyo, 1991) and could be exploited as a source of P. The direct application of such locally available P resource is seen by many workers as a viable alternative (World Bank, 1994; Buresh et al., 1997). Their effectiveness upon application to soil relies on the presence of protons and sinks of phosphorus and calcium (Robinson and Syers, 1991; Robinson et al., 1992). Phosphate rocks differ greatly in their physico-chemical properties and hence in their effectiveness as sources of P when applied directly to soils. Coupled with this, different plants and soil conditions have varying influence on PRs. Interactions of these factors play an important role in determining the fertilizer value of a given PR.

Many PRs contain large amounts of CaCO₃ and have a high pH (Mishra and Bangar, 1986; Kpomblekou-A and Tabatabai, 1994a). When applied to soils, large amounts of protons are needed to make these PRs effective. This also means that the amounts of PR applied must be balanced in relation to the amounts of available protons, as high rates will work to the disadvantage of the effectiveness of the PR itself. Low soil solution P concentrations due to high rates of PR have been reported by Rajan et al. (1991). Minjingu PR which occurs in Tanzania has a pH of 9.0 and a CaCO₃ content of about 7% (Kpomblekou-A and Tabatabai, 1994a). Direct application of this material is reported to perform well in soils with the right conditions necessary for its dissolution. Studies at ARI Mlingano (NSS, 1989), comparing directly applied Minjingu PR and the soluble triple superphosphate, showed no significant difference between the two sources of P. Both P sources increased maize yield equally well.

In this chapter, Minjingu PR as source of P, and the P supply of a Rhodic Ferralsol from Tanga were studied in three experiments. The solubility of Minjingu PR was compared in the laboratory with that of two other PRs using varying concentrations of hydrochloric acid (HCl) and varying shaking times (Experiment 3.1). In Experiment 3.2 Minjingu and the other two PRs
Chapter 3

were evaluated with respect to their agronomic effectiveness. Finally, the P supply of the Rhodic Ferralsol was compared to that of soils from Ivory Coast, Kenya and the Netherlands in Experiment 3.3. These experiments were carried out in the greenhouse and the laboratory of the sub-department of Soil Science and Plant Nutrition, Wageningen University and Research Center (WUR).

The objectives of these experiments were:
(i) To assess the amounts of extractable P under conditions of unlimited and limited supply of protons and how this is affected by varying shaking times, and, (ii) to evaluate the response of maize to the PRs and to evaluate the P supply of the Ferralsol from Tanga. Increased concentration of the extracting acid is expected to increase the amount of P extracted. At low proton concentration, the reactivity of the PRs will play an important role in the amount of P extracted. Increased shaking time (Amarasiri and Abeyroon, 1977; Deeley et al., 1987) will increase the amount of P extracted, provided the removal of the dissolution products (Kirk and Nye, 1986) ensures continued dissolution according to the law of mass action. Increased rates of PR will increase the amount of extractable P up to the level where, due to increased proton consumption, the proportion of P extracted decreases (Bolland et al., 1988a; Kanabo and Gilkes, 1988; Brenes and Bornemisza, 1992). Eventually, dissolution will cease when the ionic product equals the solubility product of the PR (Rajan et al., 1991).

These experiments will provide insight into the role of protons in PR dissolution and how one can cope with situation of low proton supply in soils. Such information is required to enable extension of PR use to a wider range of soils beyond those considered ideal for PR use.

3.2 Materials and Methods

3.2.1 Experiment 3.1. Extraction of phosphate rocks with hydrochloric acid

The solubility of Minjingu PR in hydrochloric acid was compared with that of Khouribga PR from Morocco and Mali (Tilemsi) PR from Mali at the laboratory of the Department of Soil Science and Plant Nutrition of WUR. First the PRs were analyzed for total P, P-Bray-I and P-Olsen. On the basis of the proportion of P-Bray-I and P-Olsen (Table 3.1) the PRs were graded as soft (Mali PR) and hard (Khouribga and Minjingu PRs). The PRs were extracted with different concentrations of HCl for different shaking times. The HCl concentrations were 0.001 M, 0.01 M, 0.1 M, 1 M. Later, Minjingu PR was also extracted at HCl concentrations of 2 M, 3 M, 4 M and 5 M at the Soils laboratory of ARI Mlingano, in Tanga, Tanzania. Five grams of ground PR (100 mesh) was weighed in 50 ml shaking bottles and 35 ml of HCl of the required concentration was added (1:7 solid to acid ratio). Shaking was done for 1 min, 30 min, 6 h and 24 h in a reciprocating shaker at 150 oscillations per minute. The solution was filtered immediately after the required shaking time was over, diluted where necessary, and P was determined spectrophotometrically at 880 nm.

3.2.2 Experiment 3.2. Response of maize to various PRs on a Rhodic Ferralsol (Soil S1) from Tanzania

Minjingu PR as a P source for maize (Zea mais var. LG11) was compared to Mali and Khouribga PRs in a greenhouse experiment at WUR using the double pot technique (Janssen 1974, 1990). This technique is based on the fact that plants can simultaneously take up nutrients from soils and from a nutrient solution. When the nutrient under study is omitted in the nutrient solution the plant can only take it from the soils and the seed itself. Growth is measured by the relative increase in plant size (analogous to relative growth rate) per unit of time (t) denoted by R, (For details see Appendix 2).
Table 3.1. Some properties of the PRs used in the experiments.

<table>
<thead>
<tr>
<th>Phosphate rock</th>
<th>Type of apatite</th>
<th>Total P^f</th>
<th>P-Bray-1^g</th>
<th>P-Olsen^h</th>
<th>CaCO₃ equiv^i</th>
<th>pH(H₂O)^j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mali (Tilemsi)</td>
<td>Fluorapatite</td>
<td>11.40</td>
<td>0.681</td>
<td>0.122</td>
<td>3.03</td>
<td>7.7</td>
</tr>
<tr>
<td>Khouribga</td>
<td>Fluorapatite</td>
<td>12.76</td>
<td>0.004</td>
<td>0.018</td>
<td>4.52</td>
<td>8.1</td>
</tr>
<tr>
<td>Minjingu</td>
<td>Fluorapatite</td>
<td>10.85</td>
<td>0.007</td>
<td>0.006</td>
<td>7.10</td>
<td>9.0</td>
</tr>
</tbody>
</table>

^g Sub-department of Soil Science and Plant Nutrition, WUR.

The experiment was conducted for 26 days from 24th November to 19th December 1994. A short duration was considered in all the pot experiments because effects of P application are more pronounced in young plants. Triple superphosphate (TSP) was included as a reference P fertilizer. Two rates of P for each of the P sources and two controls (with no P applied in the soil); one on complete nutrient solution (Control (+P)) and another on minus P nutrient solution (minus (-P)) (Appendix 3) made a total of ten treatments. For the control on -P nutrient solution eight extra pots were included to make a total of twelve pots. In addition, for each of the levels of fertilizer P there was one pot on +P nutrient solution. A randomized complete block design with four blocks was used.

The levels of P were based on the P requirement for maize grown on a complete nutrient solution (+P) up to the eighth leaf stage (about 26 days old). At this stage the P mass fraction of maize is about 0.3% (Janssen, pers. comm.). Assuming an average dry-matter weight of about 4 g, the P content is 12 mg. The amount of the different P sources required was based on their recovery fraction and P content. In pot experiments, the recovery fraction of P from TSP may be as high as 30% (Janssen, pers. comm.). Given a P content of 20%, the amount of TSP required for an uptake of 12 mg P is 200 mg. This was considered the high rate and half that the low rate. Given the P content of the PRs (Table 3.1) and considering a recovery fraction relative to TSP (Wolf et al., 1987) of 20% for Mali and 10% for Khouribga and Minjingu PRs, the low and high rates of these fertilizer materials are as shown in Table 3.2.

All fertilizers including TSP were ground and sieved through 100 mesh. Appropriate amount of the fertilizers was thoroughly mixed with 200 g air-dry soil and two thirds of the soils’ field capacity water requirement added. The uniformly wetted soil was added into pots (270 cm³) and four maize seeds planted. The remaining one third of the soils’ field capacity water requirement was added. The weight of the pots and contents were recorded. Subsequent watering was done to this weight to re-establish the field capacity of the soils. Each pot was placed on top of a larger pot of 1100 cm³ containing nutrient solution and separated with wire gauze. Pots were covered by a polyethylene sheet to minimize evaporation loss prior to crop emergency and to create warmer conditions for germination. Ten days after planting the plants were thinned to two per pot, soil was covered with sterilized gravel to minimize evaporation loss and new weight recorded for watering purposes. At later growth stages the weight of the plants were taken into account in watering^. To avoid positional effect the pots were rotated daily. Greenhouse

^1 Field capacity of the soils was estimated by progressively adding demineralized water to 100 g soil and simultaneously stirring until there was a free flow of the soil when a cut was made across it with a spoon. Sixty percent (60%) of the water added to this point was considered the field capacity of the soil.

^2 Estimation of plant weight was based on total leaf length of plants on complete nutrient (+P) solution. Using a graph relating plant size to weight, correction was made when plant weight was more than 5 g.
temperatures were maintained at 20 °C during day and night using HPI lamps of 400 watts placed 1.2 m above the pots at one lamp per square meter.

Table 3.2. Treatment details for Experiment 3.2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>No of pots per treatment</th>
<th>P rate mg pot⁻¹</th>
<th>Fertilizer mg pot⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Control</td>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2. Control (+P)</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. TSP</td>
<td>&quot;</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>4. TSP</td>
<td>&quot;</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>5. Mali</td>
<td>&quot;</td>
<td>100</td>
<td>877</td>
</tr>
<tr>
<td>6. Mali</td>
<td>&quot;</td>
<td>200</td>
<td>1754</td>
</tr>
<tr>
<td>7. Minjingu</td>
<td>&quot;</td>
<td>200</td>
<td>1843</td>
</tr>
<tr>
<td>8. Minjingu</td>
<td>&quot;</td>
<td>400</td>
<td>3686</td>
</tr>
<tr>
<td>9. Khouribga</td>
<td>&quot;</td>
<td>200</td>
<td>1567</td>
</tr>
<tr>
<td>10. Khouribga</td>
<td>&quot;</td>
<td>400</td>
<td>3134</td>
</tr>
</tbody>
</table>

The nutrient solution was changed every five days. Plant size was determined by measuring the length of the leaves from the base to the apex (blade and sheath) when plants on the +P solution were at the 4th and 8th leaf stages (Janssen, 1990). At harvest the above ground plant parts (shoots), roots in soil and roots in solution were separately weighed before and after drying at 70 °C for 48 hours for the shoots and 24 hours for the roots. All shoot samples as well as two root samples per treatment were analyzed for P contents. The root samples were selected on the basis of dry-matter yield; for each treatment, pots with the lowest and highest dry-matter yield were considered for root analysis. This was done in order to reduce costs of analysis.

3.2.3 Experiment 3.3. The P supply of Soil S1 from Tanzania

The P supply of the Rhodic Ferralsol (Soil S1 from Tanzania) was compared with that of a Plinthic Ferralsol (Marie IV) from Ivory Coast (low available P), a Luvic Phaeozem (KDM) from Kenya (intermediate available P) and Cumulic Anthrosol from the Netherlands (high available P). Herein after, the soils will be referred to as Tanzania, Ivory Coast, Kenya and Netherlands respectively. Some of the properties of the soils are shown in Table 3.3.

The P supply of a given soil can be estimated from the difference in growth between plants on complete nutrient solution and those on solution missing P. The index used is called sufficiency quotient denoted by SQ (Janssen, 1990). For details on SQ see Appendix 2. The study was conducted for 26 days from 26th October to 21st November 1994 in the greenhouse at WUR using the double pot technique as in Experiment 3.2. Maize (Zea mays var. LG 11) was the test crop. A complete randomized design was used with eight treatments and four replicates. The eight treatments were the four soils on either -P or +P nutrient solution. The soils were sieved through a 2 mm screen. Two thirds of the respective soil field capacity water requirement was added into 200 g air dry soil sieved through a 2 mm screen. The uniformly wetted soil was introduced into 270 cm³ pots as used in Experiment 3.2.

The rest of the procedure and greenhouse conditions are as described for Experiment 3.2 except that smaller bottom pots (750 cm³) were used. All shoot samples as well as two root samples per treatment were analyzed for P contents. The root samples were selected on the basis of SQ values; such that for each treatment, pots with the lowest and highest SQ values were considered for root analysis. This was done in order to reduce costs of analysis.

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Some properties of the different soils used in Experiments 3.2 and 3.3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Tanzaniaa</th>
<th>Ivory Coastb</th>
<th>Kenyac</th>
<th>Netherlandsb</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH H₂O (1:5)</td>
<td>6.8</td>
<td>5.0</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>pH CaCl₂ (1:5)</td>
<td>5.7</td>
<td>4.1</td>
<td>4.9</td>
<td>4.8</td>
</tr>
<tr>
<td>P -Bray 1 (mg kg⁻¹)</td>
<td>1</td>
<td>2.2</td>
<td>7.4</td>
<td>-</td>
</tr>
<tr>
<td>P -Olsen</td>
<td>1</td>
<td>4.6</td>
<td>11.4</td>
<td>-</td>
</tr>
<tr>
<td>P_total (mg kg⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N (g kg⁻¹)</td>
<td>344</td>
<td>83</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Org. C (g kg⁻¹)</td>
<td>20</td>
<td>14</td>
<td>37</td>
<td>11</td>
</tr>
<tr>
<td>CEC (mmol (+) kg⁻¹)</td>
<td>129</td>
<td>35</td>
<td>215</td>
<td>-</td>
</tr>
</tbody>
</table>

- Not determined.

a From Duijkers (1978).
b Sub-department of Soil Science and Plant Nutrition, WUR.
c Also referred to as Soil S1 in other experiments.

Determined colorimetrically (Murphy and Riley, 1962) after extraction with suspension of 0.01 M CaCl₂, with filter paper impregnated with iron oxide and dissolving the iron phosphates in 0.2 N H₂SO₄.

Data analysis

For Experiment 3.1 no formal statistical test was performed on the data except for averages. Data of Experiments 3.2 and 3.3 were subjected to ANOVA using the statistical package STATGRAPHIC Plus version 7.0 to determine the effect of the different sources of P on Rs, dry-matter yield and P content (Experiment 3.2) and the effect of soil available P on Rs, (SQ), dry-matter yield and P content (Experiment 3.3).

3.3 Results

3.3.1 Experiment 3.1. Extraction of phosphate rocks with hydrochloric acid

Overall, more P was extracted from Mali than from Khouribga and Minjingu PRs (Table 3.4). At high HCl concentration (1M), extractable P was high from all the PRs. However, when based on percent of total P content, extractable P from Khouribga was about 10% less than from either Mali or Minjingu PR. Extractable P decreased sharply as HCl concentration decreased. The difference between Mali PR and the others became wider. The greatest difference occurred at 0.1M HCl, where extractable P from Mali was 14 and 24 times higher than from Khouribga and Minjingu PRs, respectively. Corresponding values at 0.01 and 0.001 M HCl concentration were 7.3 and 8.0, with respect to Minjingu, and 2.0 and 1.4 with respect to Khouribga. Shaking time did not have a substantial effect on the amount of P extracted (see Fig. 3.1).

Minjingu PR was also extracted at HCl concentrations of 0.1, 0.01, 0.001, 1, 2, 3, 4 and 5 M HCl) at the Soils laboratory of ARI Mlingano in Tanga. Results are plotted in Fig. 3.1. For the purpose of comparison extractable P values for Minjingu PR obtained from the laboratory at WUR are also plotted on the same chart. At HCl concentration of 1M and above extractable P did not differ markedly between the different shaking times. Between 2 and 5 M HCl it ranged from 106 to 126 g kg⁻¹. Extractable P at 5 M HCl was higher than the total P shown in Table 3.1. This is possibly due to the fact that the samples involved were not drawn from the same lot (see also Table 1.1, Chapter 1). At 0.1 and 0.01 M HCl concentration results from the NSS laboratory

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show an increase in extractable P with increasing shaking time. However, at 0.001 M HCl and 24 hours shaking times it dropped slightly. Results from the WUR laboratory indicate a steady decrease in extractable P with increasing shaking time at acid concentration of 0.1 and 0.01 M.

Table 3.4. Experiment 3.1. Extractable P averaged over the four different shaking times.

<table>
<thead>
<tr>
<th>HCl conc. (M)</th>
<th>Mali (mg kg⁻¹)</th>
<th>% of total</th>
<th>Khouribga (mg kg⁻¹)</th>
<th>% of total</th>
<th>Minjingu (mg kg⁻¹)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>77494</td>
<td>68.0</td>
<td>74202</td>
<td>58.2</td>
<td>73714</td>
<td>67.9</td>
</tr>
<tr>
<td>0.1</td>
<td>5612</td>
<td>4.9</td>
<td>405</td>
<td>0.32</td>
<td>232</td>
<td>0.21</td>
</tr>
<tr>
<td>0.01</td>
<td>16.8</td>
<td>0.01</td>
<td>2.3</td>
<td>0.002</td>
<td>2.1</td>
<td>0.002</td>
</tr>
<tr>
<td>0.001</td>
<td>11.2</td>
<td>0.01</td>
<td>5.6</td>
<td>0.004</td>
<td>8.2</td>
<td>0.008</td>
</tr>
<tr>
<td>Total P content</td>
<td>114000</td>
<td></td>
<td>127600</td>
<td></td>
<td>108500</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.1. Experiment 3.1. Extractable P from Minjingu PR at different HCl concentration and shaking time. Blocks with white edges: ARI Mlingano laboratory, other blocks: WUR laboratory sub-department of Soil Science and Plant Nutrition.

3.3.2 Experiment 3.2. Response of maize to various PRs on a Rhodic Ferralsol (Soil S1) from Tanzania

Severe P deficiency symptoms (purple coloration of the leaves and stems) were observed in the control pots on -P nutrient solution. Maize on the low rate of TSP and both rates of the PRs also showed P deficiency symptoms. The plants were tall and slender except for the pots treated with Mali PR where they were shorter. All pots on +P nutrient solution had healthy green plants.
Phosphate release by PRs and soils

Highest relative increase in plant size ($R_s$ in Appendix 2) were obtained from the Control (+P) treatment and lowest from the Control (-P) treatments. At the high and low rates TSP gave relatively high $R_s$ compared to the PRs but apart from the high rate of Mali PR the difference was not significant ($P < 0.05$). Among the PRs, $R_s$ did not differ significantly although there is an indication that the low rates were performing better than the high rates.

Shoot DM yield was highest at the Control +P treatment (Table 3.5). However, it was not significantly different ($P < 0.05$) from that at the high rate of TSP. The high rate of TSP differed significantly from the PRs. Mali PR behaved like TSP in that yield increased with increasing P rate. There is an indication, though not significant, that the low rates of Minjingu and Khouribga were performing better than the high rates. However, when total DM yield was considered this trend was only true for Minjingu PR. Figure 3.2 shows the relation between DM yield and total P content. The fitted lines for the various P sources are shown in Table 3.6. Essentially, there were no differences between the PR sources with respect to P utilization all showing practically the same linear relationship. Most points in Fig. 3.2 are closer to the line representing maximum dilution of P (YPD), an indication of limited supply of P. Only one point (from the high rate of TSP) is close to the line of maximum accumulation of P (indication of excess availability of P) and that explains why in Table 3.6 the relation for TSP is not linear.

Table 3.5. Experiment 3.2. Relative increase in plant size ($R_s$), dry-matter yield and P content in maize treated with different P sources.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>P rate</th>
<th>$R_s$</th>
<th>Dry-matter yield, g pot$^{-1}$</th>
<th>P content mg pot$^{-1}$</th>
<th>P recovery %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (-P)</td>
<td>0</td>
<td>8.14c</td>
<td>1.13e 1.77c 1.34c 1.74c</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>TSP</td>
<td>20</td>
<td>9.61b</td>
<td>1.77bc 2.40b 2.52b 3.19c 7.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSP</td>
<td>40</td>
<td>9.73b</td>
<td>2.11ab 2.59ab 4.19b 5.23b 8.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>100</td>
<td>8.82bc</td>
<td>1.38de 2.22bc 1.77c 2.28c 0.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mali</td>
<td>200</td>
<td>8.55c</td>
<td>1.51cd 2.31bc 2.16c 2.76c 0.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minjingu</td>
<td>200</td>
<td>8.95bc</td>
<td>1.62cd 2.49b 2.28c 2.90c 0.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minjingu</td>
<td>400</td>
<td>8.95bc</td>
<td>1.47cde 2.19bc 2.11c 2.69c 0.24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khouribga</td>
<td>200</td>
<td>9.00bc</td>
<td>1.59cd 2.36b 2.36c 3.00c 0.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khouribga</td>
<td>400</td>
<td>8.77bc</td>
<td>1.53cd 2.38b 2.08c 2.60c 0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (+P)</td>
<td>0</td>
<td>11.70a</td>
<td>2.36a 3.10a 17.73a 21.80a -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P < 0.05$).

Highest shoot P content was from the Control +P treatment (Table 3.5). P content was significantly higher ($P < 0.05$) at the high rate of TSP compared to the low rate of TSP and the PR treatments. The relationship between total P content and P application is shown in Fig. 3.3. P content increased steadily with P rate when P source was TSP or Mali PR, but higher rates of Minjingu and Khouribga slightly depressed P content. From Fig. 3.3 the substitution value (SV) (Rajan et al., 1996) of the PRs were obtained by dividing the amount of TSP-P (standard P fertilizer) to P required to give the same P content as 200 mg PR-P. There was no difference in SV between the PRs and on average the value was 0.1 for all the PRs.
Recovery of P for TSP was 7.25 percent at the low rate and 8.73 percent at the high rate (Table 3.5). It was much lower for the PRs where it decreased with increasing P rates. However, with Mali the difference between the two rates was slight compared to Minjingu and Khouribga where the difference between the low and the high rates was 2.4 and 2.8 times respectively. Expressing P recovery from the PRs as percent of recovery from TSP, the values at the low and high rates were respectively: 7.45 and 5.84 for Mali, 8.0 and 2.75 for Minjingu and 8.69 and 3.03 for Khouribga. All these values are much lower than the 30 % recovery assumed for TSP, and the 20 % and 10 % recovery fractions, relative to TSP, for Mali and Minjingu and Khouribga, respectively (see Materials and Methods).
3.3.3 Experiment 3.3. The P supply of Soil S1 from Tanzania

Phosphorus deficiency symptoms for plants on -P solution were clearly apparent on both the Tanzania and Ivory Coast soils, slightly on the Kenya soil and absent on the Netherlands soil. On the Tanzania and Ivory Coast soils, the stems and leaves were deep purple in color, erect and narrow, and senescence of the first leaves was apparent. Plants on the Netherlands soil were shorter, with thicker stems compared to plants on the Kenya soil.

$R_s$ and SQ were lowest on the Tanzania soil. Whereas the difference in SQ was only slightly significant ($P < 0.10$), the difference in $R_s$ was stronger ($P < 0.05$) (Table 3.7). Lowest DM yields was on the Ivory Coast soil. On the -P solution, DM yield on the Kenya and Netherlands soils, and on the Netherlands and Tanzania soils did not differ significantly. There was no significant difference in DM yield on the +P solution.

The Tanzania and Ivory Coast soils differed significantly ($P < 0.05$) from the Netherlands and Kenya soils in shoot P content of the plants on the -P solution. On the +P solution, the soils differed in a similar way, but these differences were not significant. The ratios (-P/+P) of DM yield and P content also fell into two groups, the soils from Tanzania and Ivory Coast having lower values than those from Kenya and the Netherlands. The ratios of shoot-P-contents were related to the $P_i$ values of the soils (Tables 3.3 and 3.7).
### Chapter 3

**Table 3.7.** Experiment 3.3. Relative increase in plant size \((Rs)\), sufficiency quotient \((SQ)\), maize dry-matter yield and P content on minus P and plus P nutrient solutions.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Rs</th>
<th>SQ</th>
<th>Dry-matter yield, g pot(^{-1})</th>
<th>Shoot P content mg pot(^{-1})</th>
<th>Ratio -P/+P dry-matter P content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>-P</td>
<td>+P</td>
<td>-P</td>
</tr>
<tr>
<td>Tanzania</td>
<td>13.4c</td>
<td>16.0c</td>
<td>0.84b</td>
<td>1.15bc</td>
<td>1.83bc</td>
</tr>
<tr>
<td>Ivory Coast</td>
<td>14.6b</td>
<td>16.6b</td>
<td>0.88a</td>
<td>1.08c</td>
<td>1.65c</td>
</tr>
<tr>
<td>Kenya</td>
<td>15.9a</td>
<td>17.7a</td>
<td>0.89a</td>
<td>1.52a</td>
<td>2.32a</td>
</tr>
<tr>
<td>Netherlands</td>
<td>15.2ab</td>
<td>16.1bc</td>
<td>0.94a</td>
<td>1.34ab</td>
<td>2.08ab</td>
</tr>
<tr>
<td>LSD(_{0.05})</td>
<td>0.95</td>
<td>0.71</td>
<td>0.09</td>
<td>0.22</td>
<td>0.34</td>
</tr>
<tr>
<td>SE</td>
<td>0.43</td>
<td>0.33</td>
<td>0.04</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>CV (%)</td>
<td>4.2</td>
<td>3.3</td>
<td>5.7</td>
<td>11.4</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different \((P < 0.05)\). For SQ \((P < 0.10)\)

#### 3.4 Discussion

*Extraction of phosphate rocks with hydrochloric acid.*

PRs may contain CaCO\(_3\) and other proton consuming compounds besides apatite. The CaCO\(_3\) present in PRs as an accessory compound is readily soluble in dilute HCl and will dissolve before the inner shells of the PR particle, containing the calcium phosphates, are accessed. Together with the dissolution of CaCO\(_3\) some P will go into solution. Under conditions of limited proton supply, most of them will be used to solve CaCO\(_3\), thereby increasing the concentration of Ca and hampering the dissolution of apatite. As proton supply increases the inner shells of the PR particle are accessed and proportionately more P can be solved than at low proton supply.

Considering Minjingu PR extracted at 1 M HCl, the amount of H\(^+\) used for the dissolution of CaCO\(_3\) and apatite can be found as follows:

In the extraction flask, a solid: solution ratio of 1:7 was used, so per liter of 1 M HCl, 1/7 kg of the PR was added. Minjingu PR contains about 7.1 % CaCO\(_3\) (Table 3.1). In 1 liter of the extraction solution there was 1/7 * 0.071 * 1000 = 10.14 g CaCO\(_3\), or 0.1028 mol CaCO\(_3\). From the reaction

\[
\text{CaCO}_3 + 2\text{H}^+ \rightleftharpoons \text{Ca}^{2+} + \text{CO}_2 + \text{H}_2\text{O}
\]

It follows that 1 mol of CaCO\(_3\) requires 2 mol H\(^+\), and hence the amount of CaCO\(_3\) present requires 0.2028 mol H\(^+\). If CaCO\(_3\) would dissolve first, 0.7972 mol HCl is left for the dissolution of apatite. Dissolution of fluorapatite can be represented by the following equation

\[
\text{Ca}_5(\text{PO}_4)_3\text{F} + 7\text{H}^+ \rightleftharpoons 5\text{Ca}^{2+} + 3\text{H}_2\text{PO}_4^- + \text{HF}
\]

indicating that 1 mol of apatite containing 3 mol PO\(_4\) or 93 g P requires 7 mol H\(^+\). Hence, the remaining quantity of H\(^+\) after dissolution of CaCO\(_3\) would be sufficient to dissolve 0.7972/7 * 93 = 10.6 g of P from 1/7 kg of PR. For 1 kg PR, this will be 10.6 * 7 = 74.4 g P, a value close to the 73.7 g P found in the experiment (Table 3.4).

As Khouribga and Mali have lower CaCO\(_3\) contents than Minjingu (Table 3.1) more H\(^+\) is left for the dissolution of phosphates, explaining the higher amounts of dissolved P found for
these PRs (Table 3.4). Based on citrate soluble P, McClellan and Notholt (1986) ranked Mali PR as medium and Minjingu PR as medium to high in reactivity, but our results suggest that Minjingu and Khouribga PRs have a lower reactivity than Mali PR which should be due in part to the lower CaCO$_3$ contents of Mali PR.

At low HCl concentrations, ($< 0.1$ M) the amount of H$^+$ that was available was not sufficient to solve all CaCO$_3$, and because CaCO$_3$ dissolves more easily than apatite, the portion left for dissolution of phosphates was less than proportionate (Table 3.4). On the basis of the measured amounts of dissolved P, the amounts of dissolved CaCO$_3$ were calculated for the various HCl concentrations. Lines relating solved P or CaCO$_3$ to HCl concentration were drawn (Fig. 3.4). The graph shows that relatively more CaCO$_3$ was dissolved than P, as assumed above. The trend in the effect of shaking time was not systematic; there was some indication of P re-precipitation at longer shaking time (24 hours) when HCl concentration was 0.001 M. According to Amarasiri and Abeyroon (1977) and Deeley et al. (1987) more P should be expected with increasing shaking time. However, the removal of the products of dissolution (Ca and P) from the zone of dissolution is necessary to ensure continuation of the dissolution process according to the law of mass action, otherwise re-precipitation of P by Ca will take place (Kirk and Nye, 1986).

The amounts of P extracted from Minjingu PR at the same H$^+$ concentration differed between the WUR and ARI Mlingano laboratories especially at low H$^+$ concentrations (Fig. 3.1). The samples were not drawn from the same lot and hence could differ in CaCO$_3$ and P content given the fact that the marketed product is not very homogenous (compare the data of Tables 1.1 and 3.1).

![Figure 3.4](image)

**Figure 3.4.** Experiment 3.1. Relation between the solved fractions of total P (measured) or CaCO$_3$ (calculated) and HCl concentration. Reaction times of Minjingu PR and HCl were one minute and 24 hours.
Chapter 3

Response of maize to various PRs on a Rhodic Ferralsol from Tanzania

Dry-matter yield and P content were lower, though not significantly, at 400 mg than at 200 mg P per pot for Minjingu and Khouribga. This may be a consequence of the higher Ca concentration, following the dissolution of CaCO$_3$ in the soil solution, and hence the lower P concentration at the higher P rates, as explained above. Such reactions were not found for TSP and Mali PR because they contain no or less CaCO$_3$ and, moreover, were not applied at rates as high as 400 mg P.

One of the reasons why the recovery of P was lower than assumed could be the short duration of growth. By the time of harvest a large proportion of P was from the seed and soil. Another reason is that uptake did not increase with increasing rate of application as assumed at the derivation of the rates of PR. The substitution value was the same for all the PRs indicating that they did not differ agronomically. Under field conditions a relative agronomic effectiveness (RAE) value for Mali PR of between 85 - 90 % was reported in West Africa (Henao and Baanante, 1997) while in Western Kenya values of between 70 - 75 % have been reported for Minjingu PR (Bromfield et al., 1981; Lijzenga, 1998). Comparison of such results is however, difficult since the PRs were not tested under similar conditions. See also Chapter 5.

The P supply of the soil from Tanzania

Although there was a slight difference in SQ between the Tanzania and the other soils, this index was higher than the critical value of 0.8 found for soils with P-Olsen $< 11$ mg kg$^{-1}$ (Aelterman, 1984). There could be various reasons for this and one of them is the short duration of growth. It is expected that between the two measurements of plant size the plants would be relying solely on the soil for their supply of P. However the contribution of P by seed to total P content was high and it might be that between the two measurements P contribution from the seed still played an important role in plant growth. Consequently any measurement of growth was not assessing P supply from the soil alone but also from the seed. On the Tanzania and Ivory Coast soils the shoot P contents were lower than 1.89 mg, being seed P content and assuming all of it is available for uptake. If root P is also taken into account (see below) total P content is more than seed P. A longer growing period would have ensured that plants were relying more on the soil for their P.

From Table 3.7 it appears that the ratio of P content on -P to P content on +P nutrient solutions is a better criterion for assessing the P status of the soils. This ratio is related to the P$_I$ of the soils. However, the difference between the Netherlands and Kenya soils is still small and does not give a correct picture of the enormous difference in P$_I$ between the two soils. This emphasizes the fact that seed P played a role within the short growth duration of the experiment. To avoid this a longer growing period is necessary. Some calculations illustrate this. Assuming total P content in plant is $1.27 *$ shoot P content (from Table 3.5), total P in the four soils would be 2.02, 2.20, 3.48 and 3.87 mg. Subtracting 1.89 mg from the seed, the supplies by the soils are estimated to be 0.13, 0.31, 1.59 and 1.98 mg per pot, suggesting relatively much bigger differences among the soils than the shoot P contents of Table 3.7 do.

In conclusion, the experiments described in this chapter indicate that CaCO$_3$ content of the PRs was an important factor determining differences among the PRs. Minjingu and Khouribga PRs having relatively high CaCO$_3$ content were hard compared to Mali PR. Differences in dissolution manifested more at low than at high proton supply. Although Mali PR showed a higher reactivity than Minjingu and Khouribga in the extraction experiment, it did not perform better agronomically under conditions of limited proton supply. All had a substitution value (SV) of 0.1. There was an indication (though insignificant) of poor performance at the higher rates of the hard PRs. Anyhow it is obvious that a low availability of PR-P cannot be
compensated for by a high application rate. The P supplies of the Tanzania soil was low, which is in accordance with its low P-Bray-I, P-Olsen and P$_s$ soil test values. The implications of these results are that, high rates of PR are not desirable as they will introduce more CaCO$_3$ hence reducing the amounts of protons that would otherwise be available for solving P from calcium phosphates in the PR. Also, laboratory extractable P does not give a correct picture of the agronomic effectiveness of a PR and that soil and plant properties are important in determining the agronomic effectiveness of a PR. The contribution of plant and soil factors in the dissolution of PR is considered in detail in the next two chapters.
CHAPTER 4

4 Influence of crops on the effectiveness of Minjingu phosphate rock. Pot experiments

4.1 Effects of crop type and dry-matter yield on soil pH

Abstract

In a greenhouse experiment, the effects of crop type and dry-matter yield on soil pH were studied, by growing maize, cowpea and pigeonpea at different plant densities. Dry-matter yield increased with increasing plant density. There was no consistent pattern between dry-matter production and soil pH. Changes in pH between cropped and uncropped pots were negligible due to the high pH buffer capacity of the soils compared to the amounts of protons produced. These results implies that the use of protons produced by growing plants for PR dissolution will require that the PR is in the vicinity of the rhizosphere to intercept the protons before they are neutralized by soil constituents.

4.1.1 Introduction

In the preceding chapter the importance of protons supply for effective PR dissolution and the importance of soil and plant factors in PR effectiveness were demonstrated. High PR rates were shown to have a depressing effect on PR effectiveness. Strategies to produce protons are therefore important in PR effectiveness. In this chapter the contribution of growing plants to proton supply (Chapter 4.1) and the use of these protons in PR dissolution (Chapter 4.2) are studied. Cropping may influence soil pH (Williams, 1980; Lee, 1980; Gahoonia and Nielsen, 1992; Hartemink and Bridges, 1995). When plants take up excess cations over anions, H\(^+\) ions are extruded to the rhizosphere to maintain electro-neutrality. In so doing, rhizosphere pH decreases. This is common in plants utilizing atmospheric N (Aguilar, 1981; Bekele, et al., 1983) for their source of N and when NH\(_4\)-N is taken up (Breterler, 1973). Crops like sisal (Hartemink, 1995) and rapeseed (Bako Boan and van Diest, 1989) whose Ca uptake is large also acidify their rhizosphere. On the other hand, some plant species raises the pH of their rhizosphere when they take up excess of anions over cations. In such cases electro-neutrality is maintained through extrusion of OH\(^-\) ions.

The pH change in the rhizosphere is a function of crop type, dry-matter production and soil factors. Van Beusichem (1984) reported a positive correlation between the amount of dry-matter produced and the amount of H\(^+\) excreted when plants rely on atmospheric N. High dry-matter production of N\(_2\) fixing crops is therefore expected to result in high amount of H\(^+\) excretion and hence a great drop in rhizosphere pH. The extent of the pH decrease is however limited in soils with high pH buffer capacity.

To find out the influence of dry-matter production on some of the soils used in this thesis, two legume crops (cowpea and pigeonpea) and one cereal crop (maize) were grown at different plant densities in a pot experiment at ARI Mlingano, Tanga. The general objective was to study the influence of crop type and dry-matter yield on soil pH. Information on the effects of crop type and dry matter yield on changes in soil pH may help to explain why certain combinations of soil and crop are effective in utilizing phosphate from alkaline rock phosphates and others not.

4.1.2 Materials and Methods

The experiment was conducted between 18/11/1995 and 13/12/1995 for 26 days using a randomized complete block design with three blocks. Two legume crops (cowpea and pigeonpea) and one cereal crop (maize) were used. To achieve different levels of dry-matter production, different plant populations (2, 4, 6, 8, 32 plants per pot) were used. A control of zero
Chapter 4

Plant population was also included. For each crop there were 24 treatment combinations comprising four soils and six different plant populations. The soils coded S1 through S4 represent three Rhodic Ferralsols (S1 to S3) two of which are clay in texture and one sandy clay, and a Cambic Arenosol (S4) which is sandy loam in texture. Their pH (H₂O) values are 6.8, 5.8, 5.0 and 5.7 for S1, S2, S3 and S4, respectively. Detailed properties of the soils are summarized in Table 2.3, Chapter 2. Soils were air dried and sieved through a 2 mm screen. Field capacity was estimated as explained in Footnote 1, Chapter 3. No nutrients were added.

Two thirds of the field capacity water requirement for each soil was added to 1.5 kg of soil, thoroughly mixed to ensure uniform wetting, and then introduced into 2 liters plastic pots. Maize (Zea mais (L.) var. TMV1), cowpea (Vigna unguiculata var. vuli) and pigeonpea (Cajanus cajan var. ICPL 87075) were planted at the different plant populations. For each plant population slightly higher number of seeds were planted and later thinned to the required density. After planting, the rest of the water was added, pots were weighed and then covered by polyethylene sheet to minimize evaporation loss prior to crop emergence. Subsequent water addition was done to the recorded weight to re-establish the field capacity of the soils. The pots were rotated daily to avoid positional effects. After thinning, sterilized gravel was spread on the soil surface to minimize evaporation loss. The new weight was recorded for watering purposes. The increase in weight of the growing plants was also considered in watering. It was estimated as explained in Footnote 2, Chapter 3. Greenhouse temperatures averaged 32 °C during the day and 22 °C at night. At harvest shoots were oven dried at 70 °C for 48 hours and then weighed. Soils from one replicate for each crop were dried, sieved through a 2 mm screen and pH (H₂O) measured at the Soils laboratory of ARI Mlingano in Tanga. The consideration of only one replicate was a cost reduction measure.

In a small experiment cowpea and pigeonpea were grown in the same soils to see whether there was active nodulation. This would ensure that the legumes were relying on symbiotic N fixation for their source of N, an important condition that would result in extrusion of H⁺ into the rhizosphere. Cowpea and pigeonpea were separately planted at 2 and 8 plants per pot for 20 days. At harvest nodules were counted and dissected to examine N fixation activity. Before this small experiment began the two forms of inorganic N that is, NFL⁺⁻N and NCV-N were measured spectrophotometrically after extraction with 1M KCl.

Data analysis

No formal ANOVA was carried out. Averages of dry-matter yield and pH change were calculated and regression of pH change and dry-matter yield determined graphically.

4.1.3 Results

Of the three crops, cowpea showed the highest growth vigor while pigeonpea the least. The later also took long to establish, forcing the cancellation of the highest density of 32 plants per pot. Dry-matter yield increased with increasing plant density (Table 4.1.1). Yield followed the order cowpea ≥ maize > pigeonpea. Lowest yields were obtained from the sandy loam soil (Soil S4) and highest from Soil S1.
Influence of crops on PR effectiveness

Table 4.1.1. Dry-matter yield (g pot⁻¹) of maize, cowpea and pigeonpea at different plant densities (number of plants per pot) in four soils. (Average of three replicates).

<table>
<thead>
<tr>
<th>Crop/Plant density</th>
<th>Soil S1 (pH = 6.8)</th>
<th>Soil S2 (pH = 5.8)</th>
<th>Soil S3 (pH = 5.0)</th>
<th>Soil S4 (pH = 5.7)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maize</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>1.67</td>
<td>1.12</td>
<td>0.87</td>
<td>1.28</td>
</tr>
<tr>
<td>4</td>
<td>2.70</td>
<td>2.65</td>
<td>2.20</td>
<td>1.31</td>
<td>2.22</td>
</tr>
<tr>
<td>8</td>
<td>4.92</td>
<td>4.24</td>
<td>3.55</td>
<td>2.37</td>
<td>3.77</td>
</tr>
<tr>
<td>16</td>
<td>7.13</td>
<td>6.25</td>
<td>5.37</td>
<td>3.30</td>
<td>5.51</td>
</tr>
<tr>
<td>32</td>
<td>9.51</td>
<td>9.86</td>
<td>8.21</td>
<td>4.68</td>
<td>8.07</td>
</tr>
<tr>
<td><strong>Cowpea</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.47</td>
<td>1.06</td>
<td>1.31</td>
<td>1.19</td>
<td>1.26</td>
</tr>
<tr>
<td>4</td>
<td>2.30</td>
<td>1.60</td>
<td>2.76</td>
<td>2.58</td>
<td>2.31</td>
</tr>
<tr>
<td>8</td>
<td>4.28</td>
<td>3.71</td>
<td>4.18</td>
<td>3.44</td>
<td>3.90</td>
</tr>
<tr>
<td>16</td>
<td>6.58</td>
<td>7.54</td>
<td>6.85</td>
<td>6.74</td>
<td>6.93</td>
</tr>
<tr>
<td>32</td>
<td>9.76</td>
<td>9.44</td>
<td>9.80</td>
<td>7.91</td>
<td>9.23</td>
</tr>
<tr>
<td><strong>Pigeonpea</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.86</td>
<td>0.77</td>
<td>0.80</td>
<td>0.47</td>
<td>0.73</td>
</tr>
<tr>
<td>4</td>
<td>1.46</td>
<td>1.43</td>
<td>1.56</td>
<td>1.25</td>
<td>1.43</td>
</tr>
<tr>
<td>8</td>
<td>3.07</td>
<td>2.48</td>
<td>2.52</td>
<td>1.95</td>
<td>2.51</td>
</tr>
<tr>
<td>16</td>
<td>4.23</td>
<td>3.66</td>
<td>4.38</td>
<td>2.93</td>
<td>3.80</td>
</tr>
</tbody>
</table>

† pH in H₂O

Soil pH changes due to cropping.

From the experiment on nodulation, it is clear that the highest number of nodules were found on the sandy loam (Table 4.1.2). The nodules at the time of harvest were however still very small in size. The average number of nodules per plant was higher at low than at high plant density. The general trend was for higher nodulation the lower the initial soil N content. Consequently, highest nodulation was observed in the sandy loam soil which had the lowest N content (Table 4.1.3). Most of the nodules had the characteristic pink coloration associated with nodules active in N fixation.

Table 4.1.2. Average nodulation count per plant densities of 2 and 8 plants per pot.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Density</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowpea</td>
<td>2</td>
<td>8.0</td>
<td>5.5</td>
<td>5.5</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.3</td>
<td>1.6</td>
<td>1.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Pigeonpea</td>
<td>2</td>
<td>2.5</td>
<td>3.0</td>
<td>3.0</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.1</td>
<td>0.9</td>
<td>0.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 4.1.4 shows the original soil pH and soil pH after harvest for uncropped and cropped (corresponding to highest DM production only) pots. The difference in soil pH between cropped and uncropped pots was negligible at the end of the experiment.
Chapter 4

The relations between dry-matter yield and changes in pH are shown in Fig. 4.1.1. The relationships can be described by:

\[ y = -0.036x - 0.056; \quad R^2 = 0.14 \text{ for maize} \]
\[ y = -0.016x - 0.267; \quad R^2 = 0.04 \text{ for cowpea} \]
\[ y = 0.013x + 0.013; \quad R^2 = 0.003 \text{ for pigeonpea}, \]

where \( y \) stands for pH change and \( x \) for DM yield. The low values of \( R^2 \) clearly indicate that there was no relation between DM yield and changes in pH.

\begin{table}[h]
\centering
\caption{NH\textsubscript{4} and NO\textsubscript{3} contents (mg kg\textsuperscript{-1}) in Soils S1, S2, S3 and S4 at the start of the experiment.}
\begin{tabular}{lcccc}
\hline
 & S1 & S2 & S3 & S4 \\
\hline
NH\textsubscript{4} & 6.3 & 8.2 & 9.0 & 5.6 \\
NO\textsubscript{3} & 6.0 & 6.4 & 5.2 & 3.4 \\
Total inorganic N & 12.3 & 14.6 & 14.2 & 9.0 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\centering
\caption{Original soil pH (H\textsubscript{2}O) and soil pH (H\textsubscript{2}O) after harvest for uncropped and cropped\textsuperscript{1} pots.}
\begin{tabular}{lcccc}
\hline
 & S1 & S2 & S3 & S4 \\
\hline
Original & 6.8 & 5.8 & 5.0 & 5.7 \\
Uncropped & 6.2 & 5.8 & 4.8 & 5.5 \\
Maize & 6.2 & 5.5 & 4.8 & 5.2 \\
Cowpea & 6.2 & 5.5 & 4.7 & 5.5 \\
Pigeonpea & 6.3 & 6.1 & 5.2 & 5.6 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{1}pH values corresponding to highest DM production only
Influence of crops on PR effectiveness

Figure 4.1.1. Relation between dry-matter yield and change in pH during the course of the experiment for Soils S1 to S4:
A = Maize, B = Cowpea, C = Pigeonpea.
Chapter 4

4.1.4 Discussion

Although DM yield increased with increasing plant density and for the legume nodulation was evident, the negligible difference in pH between cropped and uncropped pots indicate that dry-matter yield had little or no effect on soil pH. The expectation was a drop in pH by the legumes (when they rely on biological N fixation for their source of N) and an increase of pH by the maize, when NO₃ was the major form of inorganic N. The lack of effect on the pH of the soil could be attributed to the high pH buffer capacity of the soils (Table 2.3 Chapter 2). A simple calculation can indicate what change in pH may be expected given the pH buffering capacities of the soils.

For maize OH⁻ are supposed to be extruded so the pH should rise. The amounts of OH⁻ extruded can be estimated from the following information. Based on the data by Boxman and Janssen (1990), the mass fraction for K, Ca, Mg, P, N, and S are respectively, 24, 9.5, 7, 8, 22 and 2.2. (Unfortunately the plants could not be analyzed, so that we had to rely on general data on nutrient mass fractions in the plants). The charge contribution of cations and anions is respectively, 1673 and 1967 giving a surplus of negative charge of 0.294 mmol per g dry matter. The maximum amount of OH⁻ extruded by maize (32 plants) on Soil S1 is: 9.51 x 0.294 per pot or 9.51 x 0.294 /1.5 = 1.864 mmol(-) per kg of soil. The pH buffer capacity of Soil S1 is 64 mmol(+)/kg⁻¹ per pH unit. (Table 2.3, Chapter 2). Hence, the OH⁻ production is sufficient for a lowering of the pH by 1.864/64 = 0.029 unit. Soil S4 has the lowest pH buffer capacity (54 mmol(+)/kg⁻¹) (Table 2.3, Chapter 2). The maximum OH⁻ production on Soil S4 was 4.68 x 0.294/1.5 = 0.917 mmol(-) per kg soil, sufficient for a lowering of the pH by 0.917/54 = 0.017 unit. The pH changes shown in Fig. 4.1.1.A are within and even a little outside these ranges. The variance in pH, and the estimates of nutrient mass fractions, however, were such that one may conclude that the calculations and experimental data indicate pH changes of similar magnitudes.

The amount of protons extruded by cowpea can be calculated from the following data: per kg dry-matter of cowpea, 1970 mmol(+) are extruded (Chapter 4.2, Section 4.2.4.), or per gram dry matter 1.97 mmol(+). The highest cowpea dry-matter yield in Soil S1 was 9.76 g per pot, i.e. per 1.5 kg soil. The amount of protons extruded per pot is 9.760 x 1.97 = 19.227 mmol(+), and per kg soil this is 12.818 mmol(+). Given a pH buffer capacity of 64 mmol(+)kg⁻¹ per pH unit (Table 2.3, Chapter 2), the maximum increase in pH in Soil S1 could have been: 12.818/64 = 0.2 pH unit. The values obtained were maximally 0.2, but mostly even smaller. Hence, probably proton production was less than maximum, which agrees with the slow start of nodule formation.

Similar calculations for pigeonpea (amount of protons per kg dry-matter is 1041 (Chapter 4.2, Section 4.2.4)), gives an estimate of the amount of protons produced in Soil S1 at the highest density of 16 plants per pot equals to 4.4 * 1.04 = 4.576 mmol(+) or 3.05 mmol(+) per kg soil, sufficient for a change in pH of 0.05 pH unit.

For Soil S4, the amounts of protons extruded by cowpea at 32 plants per pot and pigeonpea at 16 plants per pot were 7.91 x 1.97 = 15.58 and 2.93 x 1.97 = 5.77 mmol(+) per pot. These values come down to 10.39 or 3.85 mmol(+) per kg soil, respectively, which are sufficient for pH changes of 0.19 and 0.07 pH unit, given pH buffer capacity of 54 mmol(+)/kg⁻¹ (Table 2.3, Chapter 2); these values are similar to those calculated for Soil S1.

From Table 4.1.2. it follows that the total number of nodules per pot was hardly affected by plant density, which may indicate that also biological N fixation and proton production were hardly affected by plant density. As a result there was no consistent pattern relating yield with pH changes (Fig. 4.1.1.B and C). Also here it applies that the variance in pH and the roughness
of the estimates of nutrient mass fractions make that one may conclude that the calculations and experimental data indicate pH changes of similar magnitudes.

Summarizing, dry-matter yield increased with increasing plant density but changes in pH due to cropping were negligible because the pH buffer capacities of the soils were high compared to the amounts of protons or hydroxyl-ions produced. The implication of these results is that PR must be in the vicinity of the rhizosphere to intercept the protons, produced by growing plants relying on atmospheric N, before the protons are neutralized by soil constituents. Also roots of non-legume plants must be there if they are to take profit of the proton production by legumes. This is one of the aspects being studied in the next chapter (Chapter 4.2.).

4.2 Effect of intercropping maize with legumes on Minjingu phosphate rock availability in Rhodic Ferralsols

Abstract

The influence of legumes on the effectiveness of Minjingu phosphate rock (MPR) as P source to non-legumes was studied in a greenhouse experiment involving cowpea or pigeonpea intercropped with maize. Cowpea and pigeonpea took up MPR-P better than maize and improved the uptake of MPR-P by maize. The substitution values of MPR were higher for cowpea and pigeonpea than for maize. The better use of PR by the legumes suggests that the rates of PR can be rather low when intercropping involves legume crops capable of fixing N. The use of low rates will ensure efficient use of available protons and also such rates will be within the reach of resource poor farmers. Proper choice of crops in an intercropping system is important to minimize the adverse effects of competition.

4.2.1 Introduction

In Chapter 4.1 growing legume plants failed to influence soil pH due to their lower proton production compared to the pH buffer capacity of the soils. It was then suggested that for PR to make use of such protons for its dissolution it has to be within the vicinity of the rhizosphere. This will ensure that produced protons dissolve PR particles before soil constituents intercept them. In this chapter our interest is focused on exploiting the protons produced by legume plants fixing atmospheric N for Minjingu PR dissolution before soil constituents neutralize them. We are also interested to find out whether a non-legume not capable of producing protons like maize (Chapter 4.1) could have its P nutrition improved when grown together with a legume crop.

There are suggestions that some legume crops such as pigeonpea can increase the soil available P pool to cater for their own needs and those of a subsequent crop (Arihara et al 1991). We failed to observe this in an earlier study involving cowpea-maize rotation in the greenhouse at WUR (Mowo, 1995). Cowpea failed to solubilize enough P for its needs and those of maize grown immediately after it. Part of the reason for this failure we attributed to fixation of solubilized P during the period between cowpea harvest and the time when maize roots were developed enough to absorb nutrients. We therefore hypothesized that intercropping might provide better conditions for a non-legume to benefit from possible proton induced dissolution of PR by the legume. A pot experiment was therefore established in the greenhouse at ARI Mlingano, Tanga, to study the influence of intercropping maize with cowpea or pigeonpea on MPR effectiveness. Specifically the study aimed (i) at finding out whether cowpea or pigeonpea could solubilize enough P from MPR for their needs and those of intercropped maize, (ii) to compare the two legumes in enhancing the effectiveness of MPR under different soil conditions and (iii) to compare the availability of MPR-P, TSP-P and the mixture of MPR + TSP under
different cropping systems. Prompted by the fact that high PR rates were less effective as P source for maize (Chapter 3), we included in this study the effects of a low and a high PR rate on PR dissolution when species capable of producing protons are present. Information from this study will assist in arriving at appropriate crop combinations that will ensure optimum utilization of P fertilizers.

4.2.2 Materials and Methods

To be able to compare MPR and TSP by their effects on dry-matter (DM) yield and P uptake under conditions of sole maize and maize-legume intercropping, appropriate quantities of MPR-P and TSP-P must be used. They had to be estimated beforehand and that required for each crop assumptions on DM yields and P mass fractions, and on P recovery from MPR and TSP.

Expected DM yields, mass fractions and P uptake for maize, cowpea and pigeonpea

Cowpea and pigeonpea were chosen as the leguminous crops because they are among the popular grain legumes in Tanzania (Chapter 2) and are often intercropped with maize. A growth period of 35 days was planned and a population density of six plants per pot. The dry-matter production was estimated at 2.5 g per plant for each of the crops maize, cowpea and pigeonpea. This estimate was based on earlier trials in Wageningen where a dry-matter production of 4 g by either two maize or two cowpea plants was obtained in 26 days on a complete nutrient solution (Mowo, 1995).

Based on former experiments and on literature data, mass fractions of P were assumed to be 0.3 % in maize and 0.8 % in the legumes. Hence, above-ground uptake for sole cropped maize (6 plants) is: 6 * 2500 * 0.003 = 45 mg P per pot, and for intercrops of 3 maize and 3 legume plants: 3 * 2500 * 0.003 + 3 * 2500 * 0.008 = 22.5 + 60 = 82.5 mg P per pot.

Set up of the experiment

Two soils both Rhodic Ferralsols one with a high pH (S2) and the other with a low pH (S3) (Table 2.3, Chapter 2) were used. The experiment was conducted for 35 days from 26/07/1995 to 29/08/1995 using the double pot technique (Janssen, 1974, 1990). The top two liters pot containing the soil had its bottom slit open and wire gauze fixed to separate it from the bottom one liter pot containing nutrient solution. Just below the rim of the bottom pot four holes were made for aeration. A randomized complete block design with four blocks was used. For each soil there were 18 treatments consisting of 3 cropping patterns (sole cropped maize, maize intercropped with cowpea and maize intercropped with pigeonpea), 2 sources of P (MPR and TSP) and 3 rates of P (Table 4.2.1). The P rates included a control, a low and a high P application rate and a mixture of the high rate of MPR and the low rate of TSP. The 18 treatments were on minus P (-P) and minus N (-N), the later when maize was intercropped with the legumes. Nine extra treatments on plus P (+P) nutrient solution were added for reference. The composition of the nutrient solution is shown in Appendix 3.

Air dry soil (2 kg) passed through a 2 mm sieve was thoroughly mixed with ground (100 mesh) MPR or TSP or their combinations. Two thirds of the water required to reach the field capacity of the soils (see Footnote 1, Chapter 3) was added into the soil fertilizer mixture. The mixture was introduced into the 2 liters plastic pots and planted with maize (Zea mais (L.) var. TMV1) either as sole crop or intercropped with cowpea (Vigna unguiculata var. Vuli) or pigeonpea (Cajanus cajan var. ICPL 87075). Plant population per pot was six, that is either six maize plants or three maize and three legume plants. For the sole maize crop, ten seeds were sown and later thinned to six. For the intercropped maize, six seeds of each crop were sown and later thinned to three per crop. The rest of the water was added and pots plus their contents weighed.
Influence of crops on PR effectiveness

Subsequent additions of water were done to this weight to re-establish the field capacity of the soils. The pots were then placed above the 1 liter pots which contained the nutrient solution. Changing of this solution was done at intervals of 5 days. The pots were covered by polyethylene sheet to minimize evaporation loss prior to crop emergence. The cover was removed after germination. Greenhouse temperatures averaged 28 °C during the day and 23 °C at night. To avoid positional effect the pots were rotated daily. After thinning sterilized gravel was spread above the soil to minimize evaporation loss. The new weight was recorded for the purposes of watering. Also at a later stage when the plants had grown substantially their weight was estimated using a graph relating maize plant size to weight (see Footnote 2, Chapter 3). At harvest shoots and roots were separated and oven dried at 70 °C for 48 hours (shoots) and 24 hours (roots) and dry weight determined. To reduce costs in analysis, shoot samples from the highest and lowest yielding pots were analyzed for P contents at the Soils laboratory of ARI Mlingano in Tanga.

Table 4.2.1. Rates of MPR-P and TSP-P (mg pot\(^{-1}\)) used in Soil S3 and Soil S2.

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Control</th>
<th>MPR-P</th>
<th>TSP-P</th>
<th>M2 + T1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>low (M1)</td>
<td>high(M2)</td>
<td>low(T1)</td>
</tr>
<tr>
<td><strong>Soil S2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize sole (ms)</td>
<td>0</td>
<td>750</td>
<td>1500</td>
<td>90</td>
</tr>
<tr>
<td>Maize intercropped</td>
<td>0</td>
<td>75</td>
<td>150</td>
<td>75</td>
</tr>
<tr>
<td><strong>Soil S3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize sole (ms)</td>
<td>0</td>
<td>1500</td>
<td>3000</td>
<td>90</td>
</tr>
<tr>
<td>Maize intercropped</td>
<td>0</td>
<td>150</td>
<td>300</td>
<td>75</td>
</tr>
</tbody>
</table>

1 In Soil S3 MPR-P rates were double those used in Soil S2. For reasons see text.

Derivation of fertilizer rates

For the calculation of appropriate P application rates, it was assumed that the added fertilizer P should be sufficient for the above ground P uptake. Based on former experience, P recovery by sole maize was set at 3 % from MPR and 25 % from TSP or from solubilized MPR-P. The uptake of 45 mg P for sole cropped maize requires 1,500 mg MPR-P and 180 mg TSP-P. Therefore the amount of MPR (11 %) required is 13,636 mg and the amount of TSP (20 %) is 900 mg. These were taken as the high rates, the low rates being half these amounts for Soil S2. Given the lower pH of Soil S3 we anticipated higher fixation of dissolved P. Therefore to be able to compensate for P fixation and hence cover the expected P range (since we were not sure of the rates to use), the rate of MPR in Soil S3 was doubled both under sole and intercropping (Table 4.2.1).

The calculation for the intercropping is more complicated. From the estimates above, the legume crop in the intercropping requires 60 mg P per pot. Considering that MPR dissolution will take place in the rhizosphere of the legume, we assumed a 100 % recovery of P solubilized from MPR. Therefore the amount of MPR-P required by the legume crop is 60 mg per pot. The P requirement by intercropped maize is 22.5 mg per pot (see above). The recovery of P solubilized from MPR was set at 25 %. Therefore, intercropped maize will require 22.5 * 100/25 = 90 mg MPR-P per pot. The total MPR-P required under intercropping is therefore 60 mg (legume) + 90 mg (maize) or 150 mg per pot. This was considered the high rate of MPR-P and half that the low rate. It was assumed that legumes would recover as much of the added TSP-P as maize, that is 25 %. The required amount of TSP-P in the intercropping would be 82.5/0.25 = 330 mg per pot. By mistake, however, the same rates as calculated for MPR-P were applied (Table 4.2.1).
Chapter 4

Statistical analysis and equations for the assessment of fertilizer effectiveness

The procedure NLIN for non-linear least squares fitting of the SAS program version 6.12 (SAS Institute, 1997) was used to estimate the parameters in equations 1 to 15 developed below for shoot DM and P content through iteration and successive approximation. The relation between P rate and DM yield or between P rate and P uptake systems can be represented by parabolic equations. We assumed that the nature of the relation between fertilizer and crop was essentially the same for TSP and for MPR and that the fertilizers behaved as different dilutions of the same active ingredient (Black and Scott, 1956). TSP was considered as the test fertilizer, and its effectiveness was described by Equation 1, where $y_m$ stands for expected dry-matter yield or expected P uptake by maize sole, $x$ for the rate of TSP-P, $a_i$ and $b_i$ are regression coefficients, and $k$ is a constant referring to yield or uptake at zero P application.

From TSP: \[ y_m = k_i + a_1x + b_1x^2 \] (1)

For MPR the same equation applies but the quantity of applied MPR-P has to be multiplied by the so-called substitution value (SV). It is the ratio of applied P in standard fertilizer (TSP) to P required from the test fertilizer (in this case MPR) to give the same yield or P uptake. In the equations SV is denoted by $s_1$ for sole maize:

\[ y_m = k_i + a_1s_1x + b_1(s_1x)^2 \] (2)

For combinations of MPR and TSP (MPR + TSP), the equation is:

\[ y_m = k_i + a_1(x_1 + s_1x_2) + b_1(x_1 + s_1x_2)^2 \] (3)

Where $x_1$ and $x_2$ refer to the rates of TSP-P and MPR-P, respectively.

For maize under intercropping, similar equations as under sole cropping are valid with an additional factor ($q_1$ for maize-cowpea, $q_2$ for maize-pigeonpea) to take care of the effects in growth caused by the lower number of maize plants and the interaction with the legumes, and with different substitution values ($s_2$ for maize with cowpea, $s_3$ for maize with pigeonpea).

**Maize in maize-cowpea intercropping ($y_{mc}$)**

From TSP: \[ y_{mc} = (k_i + a_1x + b_1x^2) \times q_1 \] (4)

From MPR: \[ y_{mc} = (k_i + a_1s_2x + b_1(s_2x)^2) \times q_1 \] (5)

From MPR + TSP: \[ y_{mc} = (k_i + a_1(x_1 + s_2x_2) + b_1(x_1 + s_2x_2)^2) \times q_1 \] (6)

**Maize in maize-pigeonpea intercropping ($y_{mp}$)**

From TSP: \[ y_{mp} = (k_i + a_1x + b_1x^2) \times q_2 \] (7)

From MPR: \[ y_{mp} = (k_i + a_1s_3x + b_1(s_3x)^2) \times q_2 \] (8)

From MPR + TSP: \[ y_{mp} = (k_i + a_1(x_1 + s_3x_2) + b_1(x_1 + s_3x_2)^2) \times q_2 \] (9)

The relationships for cowpea and pigeonpea are essentially the same, and only the regression coefficients $k$, $a$ and $b$, and the substitution values $s$ differ from those of maize.

**Cowpea ($y_{cp}$)**

From TSP: \[ y_{cp} = k_2 + a_2x + b_2x^2 \] (10)

From MPR: \[ y_{cp} = k_2 + a_2s_4x + b_2(s_4x)^2 \] (11)

From MPR + TSP: \[ y_{cp} = k_2 + a_2(x_1 + s_4x_2) + b_2(x_1 + s_4x_2)^2 \] (12)
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Pigeonpea ($y_{pp}$)

From TSP: \[ y_{pp} = k_3 + a_3 x + b_3 x^2 \] (13)

From MPR: \[ y_{pp} = k_3 + a_3 s_5 x + b_3 (s_5 x)^2 \] (14)

From MPR + TSP: \[ y_{pp} = k_3 + a_3 (x_1 + s_5 x_2) + b_3 (x_1 + s_5 x_2)^2 \] (15)

According to the assumptions made for deriving the appropriate rates of TSP and MPR, the coefficients in the equations for P uptake would have the following values: \( a_1 = 0.25, a_2 = 0.25, a_3 = 0.25, b_1 = 0, b_2 = 0, b_3 = 0, s_1 = 0.03/0.25 = 0.12, s_2 = 1, s_3 = 1, s_4 = 1.00/0.25 = 4, s_5 = 1.00/0.25 = 4, q_1 = 0.5, q_2 = 0.5 \). No assumptions were made for \( k_1, k_2 \) and \( k_3 \).

4.2.3 Results

At similar rates of fertilizer-P, maize shoot dry-matter yield (average of four replicates) was higher in Soil S2 than in Soil S3 irrespective of the cropping system (Table 4.2.2). Practically the same is true for cowpea, but not for pigeonpea. Of the three crops, yields of pigeonpea were the lowest. Maize DM yield was lower when intercropped with cowpea, than when intercropped with pigeonpea. Similarly, P content of maize was lower when intercropped with cowpea than when intercropped with pigeonpea (Table 4.2.3).

The estimated parameters in equations 1 to 15 for shoot DM yield are shown in Table 4.2.4. For cowpea and pigeonpea, the negative quadratic coefficients (\( b_2 \) and \( b_3 \), respectively) were negligible; the 95 % confidence intervals include the value zero. The confidence interval of the coefficient for maize (\( b_1 \)) did not include zero, but the value of \( b_1 \) was small. Shoot DM yield response of sole cropped maize to TSP-P can be described by \( 0.013x - 1.8 \times 10^{-5} x^2 \) for Soil S3 and by \( 0.026x - 3.0 \times 10^{-5} x^2 \) for Soil S2 (\( x = \) rate of P), implying a better response on Soil S2, as long as \( x \) is less than 1083.3 mg P per pot. The values of \( s_1 \) are less than 1 in both soils, implying that for maize TSP performed better than MPR; its value was lower in Soil S3 than Soil S2 implying that more MPR-P was required in Soil S3 than in Soil S2 to give the same maize DM yield as TSP-P.

Also the yield response of intercropped maize to TSP was higher in Soil S2 than in Soil S3 as follows from the nearly equal values of \( q_1 \) and \( q_2 \) on both soils. In Soil S3, the performance of MPR, as expressed in DM yield, was similar when maize was sole cropped or intercropped with cowpea (\( s_1 = s_2 \)), and better when maize was sole cropped than when it was intercropped with pigeonpea (\( s_1 < s_3 \)). In Soil S2, both \( s_2 \) and \( s_3 \) were higher than \( s_1 \), and even much higher than 1, indicating that under intercropping the performance of MPR was much better than the performance of TSP.
Table 4.2.2. Shoot dry-matter yield (g pot\(^{-1}\)) of maize, cowpea and pigeonpea on minus P solution.

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>Soil</th>
<th>Crop</th>
<th>Shoot dry-matter yield (g pot(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>P rate (mg pot(^{-1}))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>750</td>
</tr>
<tr>
<td>Sole</td>
<td>S3</td>
<td>maize</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
<td>5.07</td>
</tr>
<tr>
<td>Mixed cropping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize + cowpea</td>
<td>S3</td>
<td>maize</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>cowpea</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
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Table 4.2.3. Shoot P content (average of low and high yielding pots) on minus P solution.

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na = not applicable
Chapter 4

Shoot DM yield response of cowpea to TSP-P can be described by $0.018x - 1.5 \times 10^{-5} x^2$ for Soil S3 and by $0.016x + 4.6 \times 10^{-5} x^2$ for Soil S2 ($x =$ rate of P), showing no marked difference in response between the two soils as long as $x$ is less than 32.8 mg P per pot. Shoot DM yield response of pigeonpea to TSP-P can be described by $0.004x - 0.5 \times 10^{-5} x$ for Soil S3 and by $0.015x - 8.2 \times 10^{-5} x^2$ for Soil S2 ($x =$ rate of P), implying a slightly better response on Soil S2, as long as $x$ is less than 142.9 mg P per pot. The values of $s_4$ of 2.1 and 0.95 indicate that the response of cowpea to MPR was better than or at least similar to the response to TSP. The values of $s_5$ of 1.9 and 0.3 for pigeonpea are too irregular and values of $R^2$ are too low to allow for clear conclusions about the performance of MPR with this crop. Except for $s_4$ and $s_5$, the above remarks on the parameter values of shoot DM yield are also applicable to those of shoot P content.

Table 4.2.4. Estimates of the parameters in equations 1 to 15 for shoot DM yield and shoot P content.

| Crop            | Soil S3 | Parameter | Estimate | S.E. ± | $R^2$ | Soil S2 | Estimate | S.E. ± | $R^2$
|-----------------|---------|-----------|----------|--------|------|---------|----------|--------|------
| Shoot dry-matter yield, g per pot |         |           |          |        |      |         |          |        |      |
| Maize           |         | $k_1$     | 3.728    | 0.222  | 0.89 | 5.249  | 0.380    | 0.87   |      |
|                 |         | $a_1$     | 0.013    | 0.003  |      | 0.026  | 0.005    |        |      |
|                 |         | $b_1$     | -1.765 $\times 10^{-5}$ | 0.727 $\times 10^{-5}$ |      | -3.042 $\times 10^{-5}$ | 0.976 $\times 10^{-5}$ |        |      |
|                 |         | $s_1$     | 0.107    | 0.030  |      | 0.344  | 0.068    |        |      |
|                 |         | $q_1$     | 0.401    | 0.038  |      | 0.382  | 0.028    |        |      |
|                 |         | $s_2$     | 0.106    | 0.197  |      | 3.277  | 1.062    |        |      |
|                 |         | $q_2$     | 0.671    | 0.043  |      | 0.819  | 0.035    |        |      |
|                 |         | $s_3$     | 0.442    | 0.185  |      | 3.643  | 0.719    |        |      |
| Cowpea          |         | $k_2$     | 2.116    | 0.421  | 0.85 | 2.688  | 0.647    | 0.68   |      |
|                 |         | $a_3$     | 0.018    | 0.005  |      | 0.016  | 0.013    |        |      |
|                 |         | $b_2$     | -1.507 $\times 10^{-5}$ | 0.081 $\times 10^{-5}$ |      | 4.558 $\times 10^{-5}$ | 5.966 $\times 10^{-5}$ |        |      |
|                 |         | $s_4$     | 2.182    | 0.610  |      | 0.949  | 0.194    |        |      |
| Pigeonpea       |         | $k_3$     | 0.829    | 0.127  | 0.46 | 0.807  | 0.215    | 0.23   |      |
|                 |         | $a_4$     | 0.004    | 0.002  |      | 0.015  | 0.007    |        |      |
|                 |         | $b_3$     | -0.486 $\times 10^{-5}$ | 0.405 $\times 10^{-5}$ |      | -8.236 $\times 10^{-5}$ | 4.364 $\times 10^{-5}$ |        |      |
|                 |         | $s_5$     | 1.863    | 0.891  |      | 0.266  | 0.178    |        |      |
| Shoot P content, mg per pot |         |           |          |        |      |         |          |        |      |
| Maize           |         | $k_1$     | 6.294    | 0.757  | 0.98 | 8.623  | 1.701    | 0.94   |      |
|                 |         | $a_1$     | 0.041    | 0.008  |      | 0.092  | 0.023    |        |      |
|                 |         | $b_1$     | -0.297 $\times 10^{-4}$ | 0.107 $\times 10^{-4}$ |      | -1.232 $\times 10^{-4}$ | 0.545 $\times 10^{-4}$ |        |      |
|                 |         | $s_1$     | 0.282    | 0.057  |      | 0.266  | 0.078    |        |      |
|                 |         | $q_1$     | 0.276    | 0.035  |      | 0.400  | 0.088    |        |      |
|                 |         | $s_2$     | 3.389    | 0.788  |      | 1.010  | 0.791    |        |      |
|                 |         | $q_2$     | 0.659    | 0.070  |      | 0.671  | 0.060    |        |      |
|                 |         | $s_3$     | 0.762    | 0.235  |      | 3.002  | 0.925    |        |      |
| Cowpea          |         | $k_2$     | 9.162    | 4.436  | 0.24 | 3.503  | 0.404    | 0.99   |      |
|                 |         | $a_2$     | 0.105    | 0.139  |      | 0.048  | 0.006    |        |      |
|                 |         | $b_2$     | -6.872 $\times 10^{-4}$ | 2.826 $\times 10^{-4}$ |      | -0.348 $\times 10^{-4}$ | 0.190 $\times 10^{-4}$ |        |      |
|                 |         | $s_4$     | 0.187    | 0.224  |      | 1.489  | 0.134    |        |      |
| Pigeonpea       |         | $k_3$     | 1.606    | 0.308  | 0.89 | 1.325  | 0.239    | 0.92   |      |
|                 |         | $a_3$     | 0.004    | 0.004  |      | 0.006  | 0.005    |        |      |
|                 |         | $b_3$     | -0.021 $\times 10^{-4}$ | 0.035 $\times 10^{-4}$ |      | -0.044 $\times 10^{-4}$ | 0.211 $\times 10^{-4}$ |        |      |
|                 |         | $s_5$     | 5.624    | 4.657  |      | 0.956  | 0.282    |        |      |
4.2.4 Discussion

Theoretically the amount of P that can be solubilized from MPR through extrusion of H⁺ ions by the legumes can be found by first estimating the amount of protons extruded by the legumes in reaction to excess uptake of cations. The charge balance per unit of DM weight can be derived from knowledge of the mass fraction of the important cations. According to Nijhof (1987) the mass fraction of K, Ca, Mg, N and P in a growing cowpea crop are 37, 22, 7.4, 70 and 8.0 g kg⁻¹ respectively. Corresponding values for pigeonpea (Johansen, 1990) are respectively, 17.2, 13.2, 2.6, 32 and 2.4. The charge contribution of cations and anions is respectively, +2660 and -696 for cowpea and +1318 and -277 for pigeonpea. The charge balance is therefore +1970 for cowpea and +1041 for pigeonpea. The charge balance of sodium to chloride was considered zero although there might have been a slight excess of Cl. Nitrogen is suggested to come from biological nitrogen fixation and not from the soils; so it does not influence the ionic uptake. For the purpose of this study, however, the extrusion of H⁺ ions by cowpea and pigeonpea were assumed the same: 1.970 mmol H⁺ per gram dry-matter, and hence 14.775 mmol H⁺ for the three legume plants (under intercropping) producing 7.5 g of dry-matter (see Materials and Methods).

From the simplified equation of the dissolution of a fluorapatite:

\[
\text{Ca}_5(\text{PO}_4)_3\text{F} + 7\text{H}^+ \rightarrow 5\text{Ca}^{2+} + 3\text{H}_2\text{PO}_4^- + \text{HF}
\]

7 mmol H⁺ are required for 3 mmol H₂PO₄⁻ containing 93 mg P. Hence, the maximum amount of P that can be solubilized by three legume plants is \(93 \times 14.775/7 = 196.3\) mg. It should be pointed out that proton consumption by the dissolution of CaCO₃ present in MPR (Chapter 3) was not taken into account. Hence, the calculated solubilization of 196.3 mg P per pot by the legume plants must be considered as an upper limit. This means that the amounts of protons available for the dissolution of calcium phosphates in MPR is lower than our calculations show. The consequence of this is lower availability of MPR-P than assumed.

A decline in yield under intercropping is attributed to the failure of each crop to fully realize its growth potential due to competition for resources. Cowpea depressed maize yield more than pigeonpea because of the higher growth vigor of cowpea as is clearly expressed by the fact that the values of \(q_1\) of cowpea are lower than those of \(q_2\) of pigeonpea (see also Chapter 4.1). Dry-matter yield and P uptake were linearly related to P application. The higher maize yield response per unit of P applied as TSP than as MPR when maize was sole cropped indicate that TSP-P was more available than MPR-P.

In Table 4.2.5 the results obtained are compared with the assumptions made when designing the experiment. Not included are the values of \(b_1\), \(b_2\) and \(b_3\), as they were close to zero, like was assumed. There are considerable differences between assumed and realized values; moreover the realized values were different for the two soils. The recovery of TSP-P was much lower than anticipated, especially on Soil S3. This is at least partly due to the fact that our assumptions neglected the contribution of soil and seed to P uptake. The better growth conditions in Soil S2 meant higher P demand and this may have lead to the higher P recovery on this soil. They may also be responsible for the higher substitution value of MPR (\(s_1\), \(s_2\) and \(s_3\)) and the higher values of the reduction factors (\(q_1\) and \(q_2\)) on Soil S2 than on Soil S3. Similar observations were made by Ahlawat and Saraf (1981) who reported increased P demand and response by pigeonpea when biomass production was high.
Chapter 4

Table 4.2.5. Comparison of assumed and realized values concerning P recovery, the relative performance of MPR and the influences of intercropping.

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</table>

The substitution values of MPR are higher for cowpea ($s_4$) and pigeonpea ($s_5$) than for maize, and also higher for maize under intercropping ($s_2$ and $s_3$), than for sole maize ($s_1$) except for $s_2$ on Soil S3. There may be two different causes. The application rates of MPR were much higher under sole maize than under intercropped maize; taking into account the general law of diminishing returns and reduced dissolution at higher application rates (Chapter 3), lower substitution values for sole maize than for intercropped maize were to be expected in this experiment, even if legumes would not produce protons. Nevertheless, it is likely that the legumes have produced protons and by that improved the dissolution of MPR.

Summarizing, the main hypotheses of this experiment, namely that leguminous crops are able to take up rock P better than non-legumes and may even improve the uptake of rock P by accompanying non-legume crops have then been confirmed. This means that the rate of PR can be rather low when intercropping involve legume crops capable of fixing N. Also, the effective use of PR by non-legumes can be improved when they are intercropped with legume crops and thus avoid or reduce the needs for soluble P fertilizers to cater for the non-legumes.

Maize was more depressed when intercropped with cowpea than with pigeonpea because of the higher growth vigor of cowpea. These results suggest that proper combination of crops in an intercropping system is important to minimize the adverse effects of competition between the crops. This study has shown that the combination maize with pigeonpea would for that reason be better than maize with cowpea.
5 Comparison of Minjingu phosphate rock and triple superphosphate under different soil conditions. Pot experiments

5.1 Response of maize, cowpea and pigeonpea to MPR and TSP in soils varying in pH

Abstract

The response of maize, cowpea and pigeonpea to MPR and TSP was studied in the greenhouse using two Rhodic Ferralsols differing in pH. Response to MPR was stronger in the low than in the high pH soil. In maize treated with MPR, P rates corresponding to maximum yields were between 46.5 and 93 mg pot\textsuperscript{-1} (31 and 62 mg kg\textsuperscript{-1} soil respectively). Maize DM yield did not show an obvious optimum with TSP. Cowpea and pigeonpea did not show a clear optimum with both sources of P. Both legumes gave a higher DM production with MPR than with TSP on the high pH soil and yields were higher on the high than on the low pH soil. This indicates that the legumes prefer a high pH (around pH (H\textsubscript{2}O) = 6) to a low pH (around pH (H\textsubscript{2}O) = 5) and are able to make use of MPR at a pH (H\textsubscript{2}O) of 6. The later is possible when the legumes can modify rhizosphere soil conditions with respect to pH. Such modifications could be exploited in enhancing the effectiveness of phosphate rocks.

5.1.1 Introduction

In the preceding chapters it was shown that the CaCO\textsubscript{3} content of a PR and the availability of sufficient amounts of protons were important factors influencing the dissolution of PR. Further, high PR rates were observed to depress PR dissolution. For example, results of Experiment 3.2 (Chapter 3) showed that maize yield at 400 mg MPR-P per pot (2000 mg MPR-P kg\textsuperscript{-1}) was lower than at 200 mg MPR-P per pot (1000 mg MPR-P kg\textsuperscript{-1}). Similarly, P uptake and percent P recovery was higher at the low than at the high MPR rate. Meanwhile growing legume plants relying on atmospheric N were better in PR utilization than non-legume plants (Chapter 4.2). Vigorously growing plants have high demand for nutrients such as P and Ca. This will favor PR dissolution. The soil properties of pH, reserve acidity, available P and exchangeable Ca (Bolland and Gilkes, 1990) are all important in the dissolution of PR. It is therefore to be expected that the optimum PR rate to be used in a given soil and for a particular crop or crop combination will be dictated by the interrelationships of the soil, plant and PR properties. In this chapter soil pH (Chapter 5.1) and interaction of pH and available P (Chapter 5.2) are considered in details with respect to P availability from Minjingu PR. In Chapter 5.1 we were interested in establishing the response curves of maize, cowpea and pigeonpea to MPR and TSP. Specifically the study aimed at establishing the optimum MPR and TSP-P rates for the three crops on Rhodic Ferralsols of different pH, compare the three crops in their ability to utilize soluble and less soluble sources of P, and to compare MPR and TSP performance in the different crops and soils.

5.1.2 Materials and methods

In this experiment the rates of TSP-P and MPR-P were the same, as a consequence of the finding in Chapters 3 and 4 that high rates of MPR cannot compensate for a low substitution value. The rates of P were arrived at after a preliminary study (Mowo, 1997) involving 7 rates of P (24.0, 46.5, 93.0, 187.5, 375, 750 and 1500 mg P pot\textsuperscript{-1}) applied as MPR or TSP, and three crops (maize, cowpea and pigeonpea) was conducted to establish appropriate rates to test in this experiment. From the study five P rates (46.5, 93.0, 187.5, 375 and 750 mg P pot\textsuperscript{-1}) were selected.

The experiment was conducted for 26 days from 05/04/1996 to 01/05/1996. The experimental design was a randomized complete block with five rates of MPR and TSP as selected from
the preliminary study, two soils and three crops; maize (*Zea mais* (L.) var. TMV1), cowpea (*Vigna unguiculata* var. Vuli) and pigeonpea (*Cajanus cajan* var. ICPL 870750. There were 10 treatments for each soil and crop combination replicated three times, and a control treatment replicated six times. The two soils were Rhodic Ferralsols; Soil S2 (pH (KCl) 5.0, P-Bray-I = 4.0 mg kg\(^{-1}\)) and Soil S3 (pH (KCl) 4.1, P-Bray-I = 2.0 mg kg\(^{-1}\)).

Properties of the soils are shown in Table 2.3, Chapter 2. TSP was included as reference P fertilizer. Both fertilizers were ground and sieved through 100 mesh. Appropriate weights of the fertilizers were thoroughly mixed with 1.5 kg air-dry soil previously passed through 2 mm sieve. Two thirds of the soils' field capacity water requirement (Footnote 1, Chapter 3) was added into the soil plus fertilizer mixture and then introduced into 2 liters plastic pots. Ten seeds of either maize, cowpea or pigeonpea were sown per pot (later thinned to 6), the rest of the water added and pots and contents weighed. Subsequent watering was done to this weight. The pots were covered with a polyethylene sheet to minimize evaporation loss prior to crop emergency. After thinning, sterilized gravel was spread over the soil for the same purpose and new weight recorded for watering purposes. The increase in plant weight as they grew was estimated (Footnote 2, Chapter 3) and taken into account during watering. Pots were rotated daily to minimize positional effects. Greenhouse temperatures averaged 28 °C during the day and 23 °C during the night. At harvest shoots were separated from roots and dried at 70 °C for 48 hours for shoots and 24 hours for roots. The dried plant materials were weighed and for each treatment shoot and root samples from the highest yielding pots were analyzed for P contents. The reduction of the number of samples considered for analysis was aimed at cutting down costs.

**Statistical analysis**

The general Linear Model's procedure (GLM) of the SAS program version 6.12 (SAS Institute, 1997) was used to conduct analysis of variance to determine the influence of soil pH, P source and P rate on dry-matter yield of maize, cowpea and pigeonpea.

### 5.1.3 Results

#### Maize

Maize dry-matter yields from the control treatments in Soil S3 were lower than in Soil S2 (Table 5.1.1). There was no significant difference in DM yield between the two soils when P was applied. However, type of P fertilizer and rate of P application (Table 5.1.2) significantly influenced yield. Relation between maize DM yield response and P rate is shown in Fig. 5.1.1. Maize yield response to P was stronger in Soil S3 than in Soil S2. On both soils DM yield response to MPR was stronger than to TSP especially at low application rates. Response to TSP did not show an obvious optimum but for MPR in Soil S3 there was a possible optimum at P rates of between 46.5 and 93 mg pot\(^{-1}\) (31 and 62 mg kg\(^{-1}\) soil respectively). Total P contents are shown in Table 5.1.3 and the relationship between P uptake response and P rate in Fig. 5.1.2. Generally, uptake response was stronger in Soil S3 than in Soil S2. Whereas uptake response to MPR was stronger than to TSP in Soil S3, it was just the opposite in Soil S2 where it was higher to TSP than to MPR. Uptake response was higher at the low than at the high rates of MPR. The pattern with TSP in Soil S3 is not clear but in Soil S2 there is a general trend of increasing uptake response with increasing P rates.

#### Cowpea

As for maize, cowpea DM yields of the control treatments were lower on Soil S3 than on Soil S2 (Table 5.1.1) but did not differ significantly between the soils when P was applied (Table
5.1.2). The effect of P rate was highly significant (P < 0.01) while the interactions soil * type of P and soil * rate of P were significant at P < 0.05. Dry-matter yield response to applied P is shown in Fig. 5.1.3. In Soil S3 there is no clear pattern with regard to response to MPR while in Soil S2, increasing MPR rates resulted in increasing DM yield response. There was no clear optimum, neither for MPR nor for TSP.

Total P contents are shown in Table 5.1.3 while P uptake response in relation to P rate is shown in Fig. 5.1.4. In both soils the uptake response to MPR and TSP increased with increasing P rate. In Soil S2 uptake response to MPR was stronger than to TSP. Uptake response increased about linearly with an increase in P application.

Table 5.1.1. Average (three replicates) dry-matter yield (g pot\(^{-1}\)) of maize, cowpea and pigeonpea treated with MPR or TSP.

<table>
<thead>
<tr>
<th>P rate mg pot(^{-1})</th>
<th>DM yield maize</th>
<th>cowpea</th>
<th>pigeonpea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPR</td>
<td>TSP</td>
<td>MPR</td>
</tr>
<tr>
<td>Soil S3: pH (KCl) = 4.1; P-Bray-I = 2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.06</td>
<td>3.63</td>
<td>1.49</td>
</tr>
<tr>
<td>46.5</td>
<td>8.85</td>
<td>6.43</td>
<td>5.30</td>
</tr>
<tr>
<td>93.0</td>
<td>10.13</td>
<td>7.14</td>
<td>4.56</td>
</tr>
<tr>
<td>187.5</td>
<td>9.13</td>
<td>7.99</td>
<td>5.94</td>
</tr>
<tr>
<td>375.0</td>
<td>8.73</td>
<td>7.29</td>
<td>5.31</td>
</tr>
<tr>
<td>750.0</td>
<td>7.75</td>
<td>7.38</td>
<td>5.99</td>
</tr>
<tr>
<td>Mean yield</td>
<td>8.44</td>
<td>7.05</td>
<td>5.12</td>
</tr>
<tr>
<td>Mean response</td>
<td>2.86</td>
<td>1.19</td>
<td>1.79</td>
</tr>
<tr>
<td>Soil S2: pH(KCl) = 5.0; P-Bray-I = 4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>6.92</td>
<td>4.75</td>
<td>2.11</td>
</tr>
<tr>
<td>46.5</td>
<td>8.70</td>
<td>7.63</td>
<td>5.04</td>
</tr>
<tr>
<td>93.0</td>
<td>8.66</td>
<td>7.53</td>
<td>5.64</td>
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<tr>
<td>187.5</td>
<td>8.35</td>
<td>8.06</td>
<td>5.91</td>
</tr>
<tr>
<td>375.0</td>
<td>8.64</td>
<td>7.76</td>
<td>6.18</td>
</tr>
<tr>
<td>750.0</td>
<td>8.90</td>
<td>8.89</td>
<td>6.44</td>
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<tr>
<td>Mean yield</td>
<td>8.36</td>
<td>7.80</td>
<td>5.66</td>
</tr>
<tr>
<td>Mean response</td>
<td>1.73</td>
<td>1.05</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Pigeonpea

Pigeonpea DM yields of the control treatments were lower in Soil S3 than in Soil S2 (Table 5.1.1), a trend similar to maize and cowpea yields. Yields were strongly influenced by soil and P rate (P < 0.01). Yields from Soil S2 were higher than those from Soil S3 (Table 5.1.1) when P was applied which is different from maize and cowpea. There was a slight significant effect of type of P (P < 0.10) and the interaction soil * P rate (P < 0.05). Dry-matter yield response to applied P is shown in Fig. 5.1.5. It increased in Soil S3 with respect to increasing MPR-P with no clear optimum. In Soil S2 the pattern with MPR is not clear. Total P contents are shown in Table 5.1.3. Pigeonpea P uptake response (Fig. 5.1.6) to MPR in Soil S3 followed almost a similar pattern like DM yield response while in Soil S2 it was irregular. Uptake response to TSP in both soils was also irregular.
Chapter 5

Figure 5.1.1. Relation between maize dry-matter (DM) yield response and P rate (average of 3 replicates): A = Soil S3, B = Soil S2. (P rates: 1 = 46.5, 2 = 93.0, 3 = 187.5, 4 = 375 and 5 = 750 mg pot\(^{-1}\)).

Figure 5.1.2. Relationship between P uptake response by maize and P rate (one replicate): A = Soil S3, B = Soil S2. For actual P rates see Fig. 5.1.1.

P recovery

P recovery was rather low except at the low rates of MPR for maize and cowpea in Soil S3 (Table 5.1.4). More P was recovered from MPR than TSP and from Soil S3 than Soil S2. Comparing the legumes and maize more P was recovered by maize which could be attributed to the relatively higher DM yield of the later. Lowest P recovery was from pigeonpea, which had the lowest DM production.
Comparison of Minjingu PR and TSP

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maize</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replication</td>
<td>2</td>
<td>10.417</td>
<td>5.209</td>
<td>4.610</td>
<td>0.0149</td>
</tr>
<tr>
<td>Soil</td>
<td>1</td>
<td>1.433</td>
<td>1.433</td>
<td>1.265</td>
<td>0.2663</td>
</tr>
<tr>
<td>Fertilizer treatments</td>
<td>10</td>
<td>58.588</td>
<td>5.859</td>
<td>5.171</td>
<td>0.0001</td>
</tr>
<tr>
<td>Type P</td>
<td>1</td>
<td>20.780</td>
<td>20.780</td>
<td>18.341</td>
<td>0.0001</td>
</tr>
<tr>
<td>Rate P</td>
<td>5</td>
<td>30.979</td>
<td>6.196</td>
<td>5.469</td>
<td>0.0005</td>
</tr>
<tr>
<td>Type P * rate P</td>
<td>4</td>
<td>6.829</td>
<td>1.707</td>
<td>1.507</td>
<td>0.2151</td>
</tr>
<tr>
<td>Soil * fertilizer</td>
<td>10</td>
<td>12.498</td>
<td>1.250</td>
<td>1.103</td>
<td>0.3790</td>
</tr>
<tr>
<td>treatments</td>
<td>Error</td>
<td>48</td>
<td>54.380</td>
<td>1.133</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>71</td>
<td>137.908</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CV(%) = 13.5, R² = 0.61

| **Cowpea**                |                    |                |             |         |             |
| Replication               | 2                  | 0.032          | 0.016       | 0.044   | 0.9569      |
| Soil                      | 1                  | 0.328          | 0.328       | 0.896   | 0.3488      |
| Fertilizer treatments     | 10                 | 30.400         | 3.040       | 8.306   | 0.0001      |
| Type P                    | 1                  | 0.998          | 0.998       | 2.736   | 0.1052      |
| Rate P                    | 5                  | 28.075         | 5.615       | 15.342  | 0.0001      |
| Type P * rate P           | 4                  | 1.327          | 0.332       | 0.907   | 0.4682      |
| Soil * fertilizer         | 10                 | 8.020          | 0.802       | 2.191   | 0.0347      |
| treatments                | Soil * type P      | 1              | 2.212       | 2.212   | 6.044       |
|                           | Soil * rate P      | 5              | 5.447       | 1.089   | 2.975       |
|                           | Soil * type P * rate P | 4 | 0.361 | 0.090 | 0.246 | 0.9104 |
| Error                     | 48                 | 17.580         | 0.366       |         |             |
| Total                     | 71                 | 56.904         |             |         |             |

CV(%) = 11.5, R² = 0.69

| **Pigeonpea**             |                    |                |             |         |             |
| Replication               | 2                  | 0.112          | 0.056       | 0.311   | 0.7352      |
| Soil                      | 1                  | 5.675          | 5.675       | 31.528  | 0.0001      |
| Fertilizer treatments     | 10                 | 12.445         | 1.245       | 6.917   | 0.0001      |
| Type P                    | 1                  | 0.559          | 0.559       | 3.106   | 0.0846      |
| Rate P                    | 5                  | 10.527         | 2.105       | 11.694  | 0.0001      |
| Type P * rate P           | 4                  | 1.360          | 0.340       | 1.889   | 0.1281      |
| Soil * fertilizer         | 10                 | 4.168          | 0.417       | 2.317   | 0.0259      |
| treatments                | Soil * type P      | 1              | 0.024       | 0.024   | 0.133       |
|                           | Soil * rate P      | 5              | 2.606       | 0.521   | 2.894       |
|                           | Soil * type P * rate P | 4 | 1.538 | 0.384 | 2.133 | 0.0910 |
| Error                     | 48                 | 8.649          | 0.180       |         |             |
| Total                     | 71                 | 31.368         |             |         |             |

CV(%) = 19.4, R² = 0.72
Figure 5.1.3. Relation between cowpea dry-matter (DM) yield response and P rate (average of 3 replicates). A = Soil S3, B = Soil S2. For actual P rates see Fig. 5.1.1.

Figure 5.1.4. Relation between P uptake response by cowpea and P rate (one replicate): A = Soil S3, B = Soil S2. For actual P rates see Fig. 5.1.1.
Comparison of Minjingu PR and TSP

Figure 5.1.5. Relation between pigeonpea dry-matter (DM) yield response and P rate (average of 3 replicates). A = Soil S3, B = Soil S2. For actual P rates see Fig. 5.1.1.

Figure 5.1.6. Relation between P uptake response by pigeonpea and P rate (one replicate): A = Soil S3, B = Soil S2. For actual P rates see Fig. 5.1.1.
### Table 5.1.3. Total P contents of maize, cowpea and pigeonpea on Soils S3 and S2 treated with MPR and TSP

<table>
<thead>
<tr>
<th>P rate, mg pot⁻¹</th>
<th>P content, mg pot⁻¹</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MPR</td>
<td>TSP</td>
<td>MPR</td>
<td>TSP</td>
<td>MPR</td>
<td>TSP</td>
<td>MPR</td>
<td>TSP</td>
</tr>
<tr>
<td>Soil S3: pH (KCl) = 4.1, P-Bray-I = 2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5.60</td>
<td>5.05</td>
<td>2.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.5</td>
<td>12.83</td>
<td>8.93</td>
<td>10.13</td>
<td>7.44</td>
<td>1.52</td>
<td>3.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>93.0</td>
<td>26.71</td>
<td>9.65</td>
<td>8.18</td>
<td>7.08</td>
<td>7.89</td>
<td>1.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>187.5</td>
<td>22.54</td>
<td>15.82</td>
<td>11.46</td>
<td>8.98</td>
<td>7.52</td>
<td>1.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>375.0</td>
<td>9.54</td>
<td>8.60</td>
<td>11.51</td>
<td>12.22</td>
<td>8.07</td>
<td>8.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>750.0</td>
<td>10.35</td>
<td>8.99</td>
<td>12.29</td>
<td>13.75</td>
<td>5.47</td>
<td>10.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean P content</td>
<td>14.60</td>
<td>9.60</td>
<td>9.77</td>
<td>9.09</td>
<td>5.50</td>
<td>4.56</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean response</td>
<td>10.79</td>
<td>4.80</td>
<td>5.66</td>
<td>4.84</td>
<td>3.56</td>
<td>2.44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Soil S2: pH (KCl) = 5.0, P-Bray = 4.0 |         |         |         |         |         |         |         |         |         |
| 0                | 7.64                | 5.40    | 3.24    |         |         |         |         |         |         |
| 46.5             | 11.08               | 11.50   | 6.51    | 4.96    | 6.59    | 1.84    |         |         |         |
| 93.0             | 13.55               | 15.12   | 9.58    | 6.04    | 3.82    | 2.70    |         |         |         |
| 187.5            | 11.87               | 15.36   | 10.68   | 7.49    | 2.92    | 5.59    |         |         |         |
| 375.0            | 10.96               | 12.83   | 11.99   | 9.15    | 6.38    | 3.66    |         |         |         |
| 750.0            | 10.70               | 19.24   | 14.62   | 13.56   | 5.77    | 6.78    |         |         |         |
| Mean P content   | 10.97               | 13.62   | 9.80    | 7.78    | 4.79    | 3.97    |         |         |         |
| Mean response    | 3.99                | 7.17    | 5.28    | 2.84    | 1.85    | 0.87    |         |         |         |

*Data from highest yielding pots only.*

### Table 5.1.4. P recovery (%) by maize, cowpea and pigeonpea from MPR and TSP in Soils S3 and S2.

<table>
<thead>
<tr>
<th>P rate, mg pot⁻¹</th>
<th>MPR</th>
<th>TSP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>maize cowpea pigeonpea mean</td>
<td>maize cowpea pigeonpea mean</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.5</td>
<td>15.5</td>
<td>10.9</td>
</tr>
<tr>
<td>93.0</td>
<td>22.6</td>
<td>3.4</td>
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<td>3.4</td>
</tr>
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<td>375.0</td>
<td>1.0</td>
<td>1.7</td>
</tr>
<tr>
<td>750.0</td>
<td>0.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

| S2               |     |     |     |     |     |     |     |     |     |
| 46.5             | 7.4 | 2.4 | 7.2 | 5.7 | 8.3 | -0.9| -3.0| 2.4 |
| 93.0             | 6.4 | 4.5 | 0.6 | 3.8 | 8.0 | 0.7 | -0.6| 2.7 |
| 187.5            | 2.3 | 2.8 | -0.2| 1.6 | 4.1 | 1.1 | 1.3 | 2.2 |
| 375.0            | 0.9 | 1.8 | 0.8 | 1.2 | 1.4 | 1.0 | 0.1 | 0.8 |
| 750.0            | 0.4 | 1.2 | 0.3 | 0.6 | 1.5 | 1.1 | 0.5 | 1.0 |

**5.1.4 Discussion**

The stronger response to applied P observed in Soil S3 compared to Soil S2 can be attributed to the difference in available P of this soil. (See also Chapter 5.2). The stronger response to MPR compared to TSP especially at the low rates of application could be an effect of CaCO₃ in the former. With regard to maize this was more prominent in Soil S3 which has a lower pH than
Comparison of Minjingu PR and TSP

Soil S2. Because CEC and pH buffer capacity of the two soils are of similar magnitude (Table 2.3, Chapter 2), Soil S3 has a higher proton supply than Soil S2. Relatively better performance of low compared to high rates of PR was reported in Chapter 3 and also by Rajan et al. (1991) and Kanabo and Gilkes (1988). Different from high rates, low PR rates have low amounts of CaCO₃ and other proton consuming compounds. Hence relatively more protons will be available for PR dissolution than when high rates of PR are used.

In Soil S3, P uptake response by maize was higher with MPR than with TSP while in Soil S2 TSP performed better. This could be because of the relatively better conditions of pH in Soil S2 offering conducive environment for the performance of TSP. A graph relating DM yield and P contents in maize (Fig. 5.1.7) shows, however, that the increase in P uptake above 15 mg pot⁻¹ was not reflected in extra DM production. Apparently more P was taken up than could be utilized by the plant. Maximum DM production seemed to be 12 g pot⁻¹, and likely other factors than P have set this maximum. A similar trend was also shown by cowpea (Fig. 5.1.8), where dry-matter yields could not surpass 7 g pot⁻¹ at P contents beyond about 13 mg P pot⁻¹. Pigeonpea did not show a similar pattern like maize and cowpea (Fig. 5.1.9). Dry-matter yield was still increasing with increase in P content. Highest DM production reached only 3.5 g pot⁻¹. Apparently there was still room for increasing DM production as P uptake increased.

The main effect of soil and interactions of soil with either type of P or P rate were not significant in maize, whereas in cowpea there was a significant interaction of soil * type P and rate of P and in pigeonpea a significant main effect of soil and an interaction effect of soil * P rate. Both legumes had a higher DM production with MPR than with TSP on Soil S2, while yields were higher on Soil S2 than on Soil S3. This indicates that the legumes (i) prefer a pH (H₂O) around 6 above a pH (H₂O) around 5, (ii) are able to make use of MPR-P at a pH (H₂O) of 6. Cowpea and pigeonpea are capable of fixing atmospheric N. In the course of utilizing this source of N they may extrude protons, which can modify rhizosphere soil conditions mainly with respect to pH (Dodor et al. 1999). Probably this process worked even better in Soil S2 than in Soil S3.

Figure 5.1.7. Relation between maize DM yield and P contents (one replicate):
In conclusion the low available P and pH of Soil S3 compared to Soil S2 provided better environment for response to applied P. In Soil S3 response was always better to MPR than to TSP due mainly to the low pH of the soil. For maize P rates corresponding to maximum yields were between 46.5 and 93 mg pot\(^{-1}\) MPR-P. Maize DM yield did not show an obvious optimum with TSP. Cowpea and pigeonpea did not show a clear optimum with both sources of P. Both legumes gave a higher DM production with MPR than with TSP on the high pH soil and yields were higher on the high than on the low pH soil. This indicates that the legumes prefer a high pH (around pH (H\(_2\)O) = 6) to a low pH (around pH (H\(_2\)O) = 5) and are able to make use of MPR at a pH (H\(_2\)O) of 6. The later is possible when in the course of utilizing atmospheric N, the legumes can modify rhizosphere soil conditions with respect to pH. Such modifications could be exploited in improving the P nutrition of crops when less soluble sources like PRs are used (see also Chapter 4.2).
5.2 Response of maize to application of Minjingu phosphate to soils varying in pH and available phosphorus

Abstract

This study focuses on the influence of interactions of soil pH and soil available P on the effectiveness of Minjingu phosphate rock (MPR). The experiment was carried out in the greenhouse at ARI Mlingano. Nine soils were used together forming the combinations of three levels of pH and three levels of available P. Triple superphosphate (TSP) was included as reference P fertilizer. There were significant interactions of soil pH and available P with fertilizer P on maize dry-matter yield and shoot P content. The effects of fertilizer P on shoot P content were far more significant than on dry-matter yield. Dry-matter yield response to MPR was lower than to TSP. Yield response occurred in soils low in available P and was absent when P-Bray-I was > 7 or P-Olsen > 10 mg P kg\(^{-1}\) soil. In low pH soils, absorbed P from MPR was better utilized than from TSP an indication of a liming effect by MPR. Difference in P uptake between MPR and TSP was narrow in low pH than in high pH soils reflecting higher MPR solubility at low than at high soil pH.

5.2.1 Introduction

In Chapter 5.1 a stronger response to MPR-P was observed in the low pH Soil S3 which is also low in available P compared to Soil S2. Soil factors therefore are important in influencing the effectiveness of less soluble P sources. The recovery of P from applied P fertilizers is usually low. For soluble P fertilizers it is about 10 % for above ground parts (Janssen, 1998) while for less soluble P fertilizers like PRs, it is even less. In addition to limited diffusion from the center of the PR particles, P entering the soil solution from a dissolving PR particle is susceptible to form less soluble P compounds rendering it unavailable to plants (Hammond et al., 1986). Important soil factors influencing the availability of P from a dissolving PR particle include soil pH (Kanabo and Gilkes, 1987), soil buffering capacity and P status (Smyth and Sanchez, 1982; Syers and Mackay, 1986) reserve acidity (Bolland and Gilkes, 1990), Ca concentration (Mackay et al., 1986) and soil organic matter (Chien et al., 1990).

It was hypothesized that pH and soil available P across different soil types will influence the effectiveness of PR differently. This was tested in a pot experiment carried out in the greenhouse at ARI Mlingano using nine different soils together forming the combinations of three levels of pH and three levels of available P. In this case, maize was grown and three rates of P were applied. The general objective was to study the influence of interactions of soil pH and soil available P on the performance of MPR and TSP. Specifically the study aimed at establishing soil pH and available P levels suitable for effective use of MPR and TSP, to compare MPR and TSP under different soil conditions of pH and available P and to establish whether MPR has any liming effect. Such information is required in arriving at appropriate rates of MPR or TSP for different soils, given the strong influence soils has on P availability.

5.2.2 Materials and Methods

From analytical data of client samples brought to the Soils Laboratory at ARI Mlingano, nine sites were identified representing the combinations of low, medium, high pH (pH (H\(_2\)O): 5.0 - 5.2; 5.6 - 6.2; 6.7 - 7.4; pH (KCl) 4.1 - 4.2; 4.6 - 5.3; 6.0 - 6.7, respectively, and low, medium and high available P (P-Bray-I: 1.3 - 4.0; 7.2 - 8.5; 29.6 - 31.7; P-Olsen: 2.0 - 6.0; 10.8 - 12.8; 44.4 - 47.6 mg kg\(^{-1}\), respectively. Their properties and the sites from where they were collected (mainly from sisal estates in Tanga), are shown in Table 5.2.1.
The experiment was conducted for 26 days from 06/07/1998 to 01/08/1998. Six fertilizer treatments including a zero P control, 62.5 and 125 mg pot\(^{-1}\) MPR-P (ground to 100 mesh), 62.5 and 125 mg pot\(^{-1}\) granular TSP-P, and 62.5 mg pot\(^{-1}\) powder TSP-P (ground to 100 mesh) were tested. A randomized complete block design in a 3 x 3 x 6 factorial combination with four replicates was used. Factors were three levels of soil pH, three levels of available P and 6 fertilizer treatments. Soils were taken from a depth of 0 - 20 cm at different points of the respective sites, thoroughly mixed and transported to ARI Mlingano where they were air dried and sieved through a 2 mm screen. Appropriate weights of the fertilizers were thoroughly mixed with 1 kg of soil followed by two thirds of the respective soils' field capacity water requirement (Footnote 1, Chapter 3). The mixture was introduced into one-liter plastic pots. Four maize seeds (Zea mais var. Staha) were planted per pot (later thinned to two per pot) and the remaining amount of water added. Variety Staha differs from variety TMV1 used in Chapter 5.1 in that it takes 10 days longer to reach maturity (Variety TMV1 takes 85 days to maturity). Also it is more suited to the long season while TMV1 is suited to both the short and long seasons. The rest of the procedure is as detailed in Chapter 5.1. Greenhouse temperatures averaged 30 °C during the day and 22 °C at night. At harvest above ground parts and roots were separated, the later washed and both dried in the oven at 70 °C for 48 hours for shoots and 24 hours for the roots. Dry weights were taken and shoot samples from the highest and lowest yielding pots analyzed for P contents. This was done to minimize costs.

Analysis of variance (ANOVA) was conducted using the general linear models' procedure (GLM) of the SAS program version 6.12 (SAS Institute, 1997) to determine the effects of treatments on shoot DM yield (four replicates) and P uptake from the low and high yielding pots.

### 5.2.3 Results

Severe P deficiency symptoms were observed in the control pots on soils low in available P at all pH levels. In soils with high pH and either low or medium available P, slight P deficiency symptoms were observed when the high rate of MPR (125 mg P pot\(^{-1}\)) was used. Granular TSP at the high rate gave healthy plants especially on soils with low pH and medium available P while TSP powder performed well on the medium pH and medium available P soils and poorly on soils low in pH.

Table 5.2.2 gives the data on dry-matter yield (average of 4 replicates) and Table 5.2.3 gives the data on P content of the maize shoots that had been analyzed (average of the highest and lowest yielding pots per treatment) (corresponding data on shoot DM are shown in Appendix 4). The P contents were calculated by multiplying dry-matter yield with P mass fraction.
Table 5.2.1. Some physico-chemical properties of the soils from the selected sites.

<table>
<thead>
<tr>
<th>pH range</th>
<th>Avail. P range</th>
<th>Site Name</th>
<th>Soil Name</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>pH 1:2.5</th>
<th>OC</th>
<th>TN</th>
<th>P mg kg⁻¹</th>
<th>CEC</th>
<th>Ca</th>
<th>Mg</th>
<th>K</th>
<th>Al</th>
<th>H</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>low</td>
<td>MAT13 (Furaha)</td>
<td>43</td>
<td>4</td>
<td>53</td>
<td>5.0</td>
<td>4.1</td>
<td>2.5</td>
<td>16</td>
<td>1.2</td>
<td>4.0</td>
<td>6.0</td>
<td>70</td>
<td>16</td>
<td>13</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>Kwaraguru 12</td>
<td>46</td>
<td>10</td>
<td>44</td>
<td>5.1</td>
<td>4.2</td>
<td>2.5</td>
<td>17</td>
<td>1.1</td>
<td>7.8</td>
<td>11.7</td>
<td>185</td>
<td>34</td>
<td>26</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>Kwaraguru 21/22</td>
<td>42</td>
<td>8</td>
<td>50</td>
<td>5.2</td>
<td>4.1</td>
<td>2.5</td>
<td>21</td>
<td>1.2</td>
<td>31.7</td>
<td>47.6</td>
<td>231</td>
<td>54</td>
<td>39</td>
<td>2.6</td>
</tr>
<tr>
<td>medium</td>
<td>low</td>
<td>Kwaraguru 24/25</td>
<td>40</td>
<td>10</td>
<td>50</td>
<td>5.6</td>
<td>4.6</td>
<td>2.5</td>
<td>20</td>
<td>1.2</td>
<td>3.5</td>
<td>5.3</td>
<td>152</td>
<td>43</td>
<td>31</td>
<td>7.0</td>
</tr>
<tr>
<td>medium</td>
<td></td>
<td>Sakura 285</td>
<td>88</td>
<td>2</td>
<td>10</td>
<td>6.2</td>
<td>5.3</td>
<td>2.5</td>
<td>4</td>
<td>0.3</td>
<td>7.2</td>
<td>10.8</td>
<td>34</td>
<td>18</td>
<td>5</td>
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<td>high</td>
<td>Kwaraguru 24/25</td>
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<td>6</td>
<td>56</td>
<td>5.7</td>
<td>4.7</td>
<td>2.5</td>
<td>24</td>
<td>1.5</td>
<td>31.0</td>
<td>46.5</td>
<td>164</td>
<td>72</td>
<td>21</td>
<td>1.1</td>
</tr>
<tr>
<td>high</td>
<td>low</td>
<td>Sakura 259</td>
<td>38</td>
<td>4</td>
<td>58</td>
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<td>6.0</td>
<td>2.5</td>
<td>22</td>
<td>1.3</td>
<td>1.3</td>
<td>2.0</td>
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<td>238</td>
<td>63</td>
<td>1.5</td>
</tr>
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<td>Mwera 268</td>
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<td>4</td>
<td>62</td>
<td>7.4</td>
<td>6.7</td>
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<td>16</td>
<td>0.9</td>
<td>8.5</td>
<td>12.8</td>
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<td>228</td>
<td>77</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>high</td>
<td>Sakura 345A</td>
<td>11</td>
<td>2</td>
<td>87</td>
<td>6.7</td>
<td>6.0</td>
<td>2.5</td>
<td>22</td>
<td>1.3</td>
<td>29.6</td>
<td>44.4</td>
<td>194</td>
<td>129</td>
<td>35</td>
<td>7.7</td>
</tr>
</tbody>
</table>

nd = not determined.
Chapter 5

Table 5.2.2. Maize shoot dry-matter yield (g pot⁻¹) (average of 4 replicates) as a function of P application via MPR and TSP. (TSPg = granular TSP, TSPp = powder TSP).

<table>
<thead>
<tr>
<th>Soil pH (KCl)</th>
<th>P-Bray-I, mg kg⁻¹</th>
<th>Control</th>
<th>MPR-P</th>
<th>TSPg-P</th>
<th>TSPp-P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>62.5</td>
<td>125</td>
<td>62.5</td>
<td>125</td>
</tr>
<tr>
<td>4.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>1.25</td>
<td>1.49</td>
<td>1.29</td>
<td>1.09</td>
</tr>
<tr>
<td>8</td>
<td>2.62</td>
<td>2.67</td>
<td>2.66</td>
<td>2.50</td>
<td>2.57</td>
</tr>
<tr>
<td>31</td>
<td>1.87</td>
<td>1.92</td>
<td>2.14</td>
<td>1.75</td>
<td>1.84</td>
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<td>1.83</td>
<td>1.95</td>
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</tr>
<tr>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2.06</td>
<td>1.48</td>
<td>1.76</td>
<td>1.76</td>
<td>1.80</td>
</tr>
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<td>8</td>
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<td>1.36</td>
<td>1.08</td>
<td>1.67</td>
<td>1.22</td>
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<td>31</td>
<td>1.88</td>
<td>2.16</td>
<td>1.75</td>
<td>1.65</td>
<td>2.21</td>
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<tr>
<td>average</td>
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<td>1.67</td>
<td>1.53</td>
<td>1.69</td>
<td>1.74</td>
</tr>
<tr>
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<td>1.39</td>
<td>1.47</td>
<td>1.88</td>
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<td>1.32</td>
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<td>1.79</td>
<td>1.74</td>
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<tr>
<td>average</td>
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<td>1.61</td>
<td>1.69</td>
<td>1.72</td>
<td>2.02</td>
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<tr>
<td>Average over pH</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.48</td>
<td>1.40</td>
<td>1.71</td>
<td>1.79</td>
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<td>1.81</td>
<td>1.86</td>
<td>1.73</td>
<td>1.83</td>
<td>1.81</td>
</tr>
<tr>
<td>31</td>
<td>1.80</td>
<td>1.96</td>
<td>1.88</td>
<td>1.64</td>
<td>1.94</td>
</tr>
<tr>
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<td></td>
<td>1.70</td>
<td>1.74</td>
<td>1.77</td>
<td>1.75</td>
</tr>
</tbody>
</table>

* P rate in mg pot⁻¹.

Dry-matter yield was significantly influenced by soil pH, available P, the interactions soil pH * available P, soil pH * fertilizer P, available P * fertilizer P and soil pH * available P * fertilizer P (Table 5.2.4) (detailed contrasts analysis are shown in Appendix 5). Yield response to fertilizer P was practically absent when P-Bray-I was > 7.0 or P-Olsen > 10 mg kg⁻¹ soil, irrespective of the pH of the soil. Yield response was observed in two soils with low available P (P-Bray ≤ 4.0 or P-Olsen ≤ 6 mg kg⁻¹).

The results of the statistical analysis on maize shoot P contents (Table 5.2.5) were quite similar at low and high DM production. Shoot P content was influenced by pH, fertilizer treatment and the interaction pH * available P. The average shoot P content in the controls was highest at medium pH and did not increase with soil available P (Table 5.2.3). The uptake from MPR was lower than that from TSP and on the average better from the powder than from the granular TSP, at a rate of 62.5 mg pot⁻¹.
Comparison of Minjingu PR and TSP

Table 5.2.3. Average maize shoot P contents (mg pot\(^{-1}\)) of the highest and lowest yielding pots per treatment. Data have been calculated per pot. Corresponding shoot DM yield are shown in Appendix 5.

<table>
<thead>
<tr>
<th>Soil pH (KCl)</th>
<th>Control</th>
<th>MPR-P(^{f})</th>
<th>TSPg-P(^{f})</th>
<th>TSPp-P(^{f})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>1.34</td>
<td>1.98</td>
<td>2.72</td>
<td>2.39</td>
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<td>3.46</td>
<td>3.88</td>
<td>4.04</td>
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<td></td>
<td>31</td>
<td>2.98</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
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<td>3.17</td>
<td>2.97</td>
<td>3.78</td>
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<td>1.98</td>
<td>2.19</td>
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<tr>
<td></td>
<td>average</td>
<td>2.40</td>
<td>3.01</td>
<td>2.92</td>
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<td>3.55</td>
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<td></td>
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<td>1.65</td>
<td>2.31</td>
<td>2.54</td>
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<tr>
<td></td>
<td>average</td>
<td>1.65</td>
<td>2.36</td>
<td>2.69</td>
</tr>
<tr>
<td>Average over pH</td>
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<td>2.33</td>
<td>3.13</td>
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<td></td>
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<td>1.86</td>
<td>2.60</td>
<td>3.06</td>
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<td></td>
<td>31</td>
<td>1.99</td>
<td>3.02</td>
<td>3.51</td>
</tr>
<tr>
<td>General average</td>
<td>1.95</td>
<td>2.65</td>
<td>2.91</td>
<td>3.05</td>
</tr>
</tbody>
</table>

\(^{f}\) P rate in mg pot\(^{-1}\).

Table 5.2.4. ANOVA table for the influence of MPR and TSP on maize shoot DM yields under different conditions of soil pH and available P.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replication</td>
<td>3</td>
<td>0.877</td>
<td>0.292</td>
<td>3.074</td>
<td>0.0296</td>
</tr>
<tr>
<td>Soil pH (pH)</td>
<td>2</td>
<td>2.010</td>
<td>1.005</td>
<td>10.559</td>
<td>0.0001</td>
</tr>
<tr>
<td>Available P (P)</td>
<td>2</td>
<td>1.908</td>
<td>0.954</td>
<td>10.042</td>
<td>0.0001</td>
</tr>
<tr>
<td>pH * P</td>
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<td>29.035</td>
<td>7.259</td>
<td>76.411</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fertilizer treatments (F)</td>
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<td>0.118</td>
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<td>0.2924</td>
</tr>
<tr>
<td>pH * F</td>
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<td>0.237</td>
<td>2.495</td>
<td>0.0086</td>
</tr>
<tr>
<td>P * F</td>
<td>10</td>
<td>2.136</td>
<td>0.214</td>
<td>2.253</td>
<td>0.0179</td>
</tr>
<tr>
<td>pH * P * F</td>
<td>20</td>
<td>3.778</td>
<td>0.189</td>
<td>1.989</td>
<td>0.0106</td>
</tr>
<tr>
<td>Error</td>
<td>159</td>
<td>15.144</td>
<td>0.095</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>215</td>
<td>57.843</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CV (%) = 17.5, \(R^2 = 0.74\)
Chapter 5

Table 5.2.5. ANOVA table for the influence of MPR and TSP on maize shoot P contents for pots analyzed for P contents. I. At low DM production. II. At high DM production.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I. At low DM production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil pH (pH)</td>
<td>2</td>
<td>0.890</td>
<td>0.445</td>
<td>2.528</td>
<td>0.1048</td>
</tr>
<tr>
<td>Available P (P)</td>
<td>2</td>
<td>0.058</td>
<td>0.029</td>
<td>0.165</td>
<td>0.8492</td>
</tr>
<tr>
<td>pH * P</td>
<td>4</td>
<td>6.433</td>
<td>1.608</td>
<td>9.136</td>
<td>0.0002</td>
</tr>
<tr>
<td>Fertilizer treatments (F)</td>
<td>5</td>
<td>9.104</td>
<td>1.821</td>
<td>10.347</td>
<td>0.0001</td>
</tr>
<tr>
<td>pH * F</td>
<td>10</td>
<td>1.606</td>
<td>0.161</td>
<td>0.915</td>
<td>0.5396</td>
</tr>
<tr>
<td>P * F</td>
<td>10</td>
<td>1.415</td>
<td>0.142</td>
<td>0.807</td>
<td>0.6265</td>
</tr>
<tr>
<td>Error</td>
<td>20</td>
<td>3.515</td>
<td>0.176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>53</td>
<td>23.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 17.6, $R^2 = 0.85$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II. At high DM production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil pH (pH)</td>
<td>2</td>
<td>3.515</td>
<td>1.758</td>
<td>7.295</td>
<td>0.0042</td>
</tr>
<tr>
<td>Available P (P)</td>
<td>2</td>
<td>0.886</td>
<td>0.443</td>
<td>1.838</td>
<td>0.1856</td>
</tr>
<tr>
<td>pH * P</td>
<td>4</td>
<td>17.381</td>
<td>4.345</td>
<td>18.029</td>
<td>0.0001</td>
</tr>
<tr>
<td>Fertilizer treatments (F)</td>
<td>5</td>
<td>19.919</td>
<td>3.984</td>
<td>16.531</td>
<td>0.0001</td>
</tr>
<tr>
<td>pH * F</td>
<td>10</td>
<td>2.523</td>
<td>0.252</td>
<td>1.046</td>
<td>0.4441</td>
</tr>
<tr>
<td>P * F</td>
<td>10</td>
<td>2.570</td>
<td>0.257</td>
<td>1.066</td>
<td>0.4309</td>
</tr>
<tr>
<td>Error</td>
<td>20</td>
<td>4.828</td>
<td>0.241</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>53</td>
<td>51.621</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 14.5, $R^2 = 0.91$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.4 Discussion

The results of Tables 5.2.2 to 5.2.5 show (i) that the responses to MPR and TSP are not in a simple unambiguous way related to pH and soil P, and (ii) that the response in terms of shoot P content is much stronger than the response in terms of dry-matter production. Apparently plants were able to take up P but not or only partly to use the absorbed P for DM production. This raised the hypothesis that there was a maximum amount of P that could be utilized. If this were the case the response to applied P would be a function of the amount of P that was supplied by the soils. The shoot P content of the control treatments can indicate this amount. To test this hypothesis the responses to fertilizer P in terms of DM production and shoot P content were plotted to shoot P contents of the controls in Figures 5.2.1 and 5.2.2, respectively. Separate graphs were made for MPR and TSP (granular) and for the difference in response between TSP and MPR. The responses are the averages of the responses at 62.5 and 125 mg P per pot rates. Soil pH is taken into account as indicated in the graphs.
Figure 5.2.1. Dry-matter (DM) yield response to MPR and TSP granular in relation to shoot P contents of controls. A = response to MPR, B = response to TSP granular, C = Difference (TSP - MPR).
Figure 5.2.2. P- uptake response to MPR and TSP granular in relation to shoot P contents of controls. A = response to MPR, B = response to TSP granular, C = Difference (TSP - MPR).
Figure 5.2.3: Relation between DM yield and shoot P contents at low (A), medium (B) and high (C) pH. Each point is averaged over three P Bray-1 values.

Comparison of Minjiangu PR and JSP
Figure 5.2.1 shows negative relationships between DM yield response and shoot P contents of the control, and differences in the pH effect between MPR and TSP. The response to TSP is clearly lower at pH 4.1 than at pHs 4.9 and 6.2. As a result the difference between TSP and MPR is always negative at low pH (indicating higher response to MPR than to TSP at low pH) and positive or negative at higher pH. The P uptake (shoot P contents) responses are less affected by pH and shoot P contents of the control than the DM yields responses (Fig. 5.2.2). The P uptake responses are never negative, and always higher for TSP than for MPR, except for the combination of low pH with low P-Bray-I (Soil 1) where both fertilizers have the same response.

Figure 5.2.2.C shows that the difference between TSP and MPR in P uptake response is lower at pH 4.1 than at higher pH. One likely cause is that the solubility of MPR is higher at low than at high pH (Chapter 3; Admont, et al., 1986; Bolland and Gilkes, 1998). This is shown in Fig. 5.2.3 where DM yields have been plotted against P contents. Each point represents the average of three soils (low, medium and high P-Bray-I). The ranges of shoot P contents of the TSP and MPR treatments overlap at pH 4.1 (low), while at pH 4.9 (medium) and 6.2 (high) the ranges for TSP are situated at higher values than those for MPR. At the low pH, the MPR curve lies clearly above the TSP line (Fig. 5.2.3.A), while at pH 4.9 and 6.2 the difference is small and the curves practically coincide. This points to a liming effect of MPR at low pH. Similar results were obtained by Semoka (1989) who observed relatively better performance of Minjingu PR compared to TSP in a low acid soil although P uptake was higher from the later.

Figure 5.2.4. Relationship between shoot P contents of control treatment and soil pH (H$_2$O). The values of pH (H$_2$O) are about one unit higher than those of pH (KCl) (see Table 5.2.1). The open round and squares symbols stand for Soil 5 and Soil 7 respectively, two soils situated really below the parabolic curve. Soil 5 has low clay and organic C contents while soil 7 is the only really P-deficient soil.

Because the pots did not receive any nutrient except P, lack of another nutrient may have reduced the P uptake in the control pots. It was tried to relate shoot P contents to the soil parameters given in Table 5.2.1, but the only clear relation was again with pH. In Fig. 5.2.4 the highest points are found around pH (H$_2$O) = 5.7. It is hypothesized that the relation between
Comparison of Minjingu PR and TSP

shoot P content and pH follows a parabola-like curve: the optimum is close to pH (H₂O) = 6, in agreement with the relationships found in Kenya (Janssen et al., 1990; Janssen and Van der Eijk, 1990). There are two soils situated really below the parabolic curve: Soil 5 with low content of clay and organic C content, and Soil 7 which was the only really P-deficient soil.

The uptake response to TSP-granular (Table 5.2.3) usually was lower than to TSP-powder. The better absorption of the powder form of TSP compared to the granular form likely is a result of the more even distribution of P in the soil, increasing the availability. The uptake response to the granular form of TSP was higher when control P uptake and pH were low. These are conditions with higher risks of P fixation. Because very high P concentrations are found around TSP granules (Van der Eijk, 1997), likely less P is fixed than when TSP is applied in powder form.

In conclusion, dry-matter yield responded to P only in soils low in available P and on average, response to MPR was lower than to TSP. Yield response was absent when P-Bray-I was greater than 7 or P-Olsen greater than 10 mg kg⁻¹ soil. The difference in P uptake response to P between MPR and TSP was narrow in low than in high pH soils, reflecting higher solubility of MPR at low than at high pH. Optimum P uptake occurred at pH (H₂O) = 5.7. Utilization of absorbed P was better from MPR than from TSP in low pH soils indicating a liming effect. There were significant interactions of soil pH and/or available P with fertilizer P pointing to the importance of these soil factors on the performance of P fertilizers. One of the aspects being studied in the next chapter is the influence of soil pH and soil available P on MPR and TSP under field conditions.
CHAPTER 6

6 Spatial variability in crop performance in relation to soil properties

Abstract

The influence of spatial soil variability on the effectiveness of MPR and crop performance was studied in four field trials at ARI Mlingano on two contrasting sites during the long and short rains of 1997. The Post-mortem Residual Analysis and the Nearest Neighbor Means techniques were used. Variation in maize yields was more explained by soil pH than by soil available P. Soil pH influenced the relationship between P values determined by Bray-I and by Olsen. P-Bray-I tended to be higher than P-Olsen in the low pH soil and lower than P-Olsen in the high pH soil. At low pH P-Bray-I was > 0.65 * P-Olsen. Therefore, to be able to correctly identify the important factors influencing soil variability especially when P is involved, the choice of appropriate method of P determination in relation to the pH of the soil is important.

Post-mortem Residual Analysis and the Nearest Neighbor Means techniques were more effective in isolating environmental from treatment effects in the large trials. Reorientation of some of the large trials to allow blocks accommodate the variability will lower the within blocks variations. There was more variability in the first than the second season due to the uniform management and the treatments applied. Post-mortem Residual Analysis and the Nearest Neighbor Means techniques should therefore be used in large trials to isolate environmental effects beyond what normal blocking can do.

6.1 Introduction

The preceding Chapters (Chapters 3 to 5) dealt with single factors influencing PR effectiveness under controlled conditions. In the next two chapters more than one factor influencing the effectiveness of PR are studied under field conditions. In this chapter the influence of spatial soil variability on the effectiveness of PR and on crop performance was studied in the four field trials covered under Chapter 7.

High variability in plant growth within and between fields in the tropics is common especially on recently cleared land, even when the soil has been subjected to uniform management intervention. Working in the Sahel, Brouwer and Bouma (1997) observed large spatial variability in millet growth over short distances. Similar trends have been reported from Kenya on maize (Jama et al., 1997; van der Eijk, 1997). Short distance variability is sometimes so high that it may hinder detection of treatment effects in field experiments (Wilding and Hossner, 1989; Wendt et al., 1993), as well as leading to erroneous conclusions about the efficacy of a given treatment (Govindaraju et al., 1995). Variability in plant growth can be due to spatial soil variability arising from inherent properties, it can be man made or a result of naturally occurring processes. Soil pH (Franzen and Berglund, 1997), differences in soil available P (Wendt et al., 1993; Franzen and Berglund, 1997; Van der Eijk, 1997), slaking and soil depth (Janssen, 1970) and differences in landscape are among the inherent factors, while man made factors include variation in land preparation, livestock keeping and management, fertilizer application and household waste disposal. Natural factors include termite activity (Brouwer, et al., 1992; Mando and van Rhenen, 1998, crustling (Geiger et al., 1992; Buerkert et al., 1995) and soil erosion and deposition by wind and water (Chase and Boudouresque 1987; Wendt et al., 1993).

Although it is known that treatment effects can interact with spatial variability in plant growth (Buerkert and Stern, 1995), most field studies on fertilizer response do not incorporate the influence of spatial soil variability. This is mainly because of limitations in the available experimental designs, which cannot cope well with unexplained variation from patchy
environment. Variation in some of the soil chemical properties does not necessarily conform to a regular pattern, which would be simple to take care of through blocking. Significant soil trends can be taken care of using geostatistical techniques like semi-variograms and kriging (Warrick et al., 1986), which are more suited to regular and predictable environmental variations than to the random patchiness that is common in the tropics.

In this chapter the influence of spatial soil variability on treatment effects in each of the field trials discussed under Chapter 7 was studied using the Post-mortem Residual Analysis (PRA) and the Nearest Neighbor Means (NNM) techniques. The objective was to find out to what extent the natural variability of the soils influenced the effectiveness of Minjingu PR and triple superphosphate. Individual soil properties were also used to try to explain within-treatment yield variability. Soil factors considered to have strong influence on MPR effectiveness were soil pH and available P. Results from this study will help in clarifying some of the treatment effects and hence allow for better interpretation of some of the findings from the field trials. Understanding of the influence of spatial soil variability on MPR effectiveness might offer opportunity in improving the effectiveness of the PR through appropriate management hence contributing to improved crop performance.

6.2 Materials and Methods

In this study yield data of maize from field trials conducted on Soils S2 and S3 for two seasons during 1997 were used. Properties of the soils are covered in Chapter 2. All the trials focus on enhancing the effectiveness of MPR under field conditions. A brief description of the materials and methods for each trial is given below. In all these trials the gross plot size was 27 m$^2$ while net plot size was 16.2 m$^2$.

**In Trial 7.1** (Chapter 7.1) the effect of method and rate of application of MPR and TSP was studied using a randomized complete block design in a 2 x 2 x 6 factorial. Each of the 24 treatments was replicated four times to make a total of 96 experimental units (plots) per site. MPR or TSP was either broadcast or applied in the planting hole at six different P rates that is; 0, 5, 10, 20, 40, 80 kg ha$^{-1}$.

**Trial 7.2** (Chapter 7.2) examines the influence of two sources of N fertilizers (Sulfate of ammonia (SA), and calcium ammonium nitrate (CAN)) on the effectiveness of MPR and TSP. A randomized complete block design in a 2 x 2 x 4 x 4 factorial arrangement of treatments was used. Factors were N source (levels: SA and CAN), P source (levels: MPR and TSP) and rates of N and P (four rates). N was applied at 0, 20, 40, and 80 kg ha$^{-1}$ and P at 0, 10, 20, and 40 kg ha$^{-1}$. Each treatment was replicated two times to make a total of 128 experimental units per site.

**In Trial 7.3** (Chapter 7.3) different application methods of combinations of MPR and a soluble P source (TSP) were studied. The experimental design was a randomized complete block in a 2 x 2 factorial arrangement of treatments with four replicates. Factors were application method of MPR (levels: broadcast and application in the planting hole) and application method of TSP (levels: broadcast and application in the planting hole).

**Trial 7.4** (Chapter 7.4) investigates the possible role of farmyard manure in enhancing the effectiveness of MPR and TSP. The experimental design was a randomized complete block with nine treatments each replicated four times to make a total of 36 plots per site. The treatments formed $3^2$ treatment combinations with factors: type of P (levels: MPR and TSP) and type of farmyard manure (levels: fresh and incubated).
Spatial variability in crop performance

Calculation and maps of NNM

The NNM of an individual plot is the average of the residuals of the neighboring plots. Residuals were calculated using the statistical package STATGRAPHIC Plus version 7.0. It involves the calculation of the predicted yield from the full statistical model, including all main effects and interactions. We also included block effects with the exception of Trial 7.2 in the first season. Residuals are then obtained by subtracting the predicted yield from the observed yield. The equations used for the predicted yields are shown below for each trial. In the interaction term the interactions with blocks were not included.

Trial 7.1.  \[ y = \text{General mean} + \text{block} + \text{type P} + \text{method P} + \text{rate P} + \text{interaction terms}, \]
where \( y \) is the expected yield and \( P \) is either MPR-P or TSP-P.

Trial 7.2.  \[ y = \text{General mean} + \text{block} + \text{type P} + \text{type N} + \text{rate P} + \text{rate N} + \text{interaction terms}, \]
where \( y \) is the expected yield, \( P \) is either MPR-P or TSP-P and \( N \) is either SA-N or CAN-N.

Trial 7.3.  \[ y = \text{General mean} + \text{block} + \text{method M} + \text{method T} + \text{interaction term}, \]
where \( y \) is the expected yield, \( M \) is MPR-P and \( T \) is TSP-P.

Trial 7.4.  \[ y = \text{General mean} + \text{block} + \text{type P} + \text{type F} + \text{interaction term}, \]
where \( y \) is the expected yield, \( P \) is either MPR-P or TSP-P and \( F \) either incubated or fresh farmyard manure.

It is assumed that environmental conditions not captured by the model effects are present in the residuals. If we assume that plots closer together are more similar or are affected by more similar conditions than those far apart, the average of the residuals of the neighboring plots is a representation of the environmental factors influencing the individual plot. The NNMs were used to explain differences in response to soil properties.

Maps of NNM were made for each trial by entering the NNM values in their respective plots and demarcating different strata representing areas of similar NNM (such as high, intermediate or low NNM).

Sampling

The residuals were grouped into classes or strata representing similar values. For each stratum soils on the paths bordering the highest and lowest yielding plots of the same treatment were sampled at 0 - 20 cm (28 samples each for Soils S2 and S3). This was done during the second cropping season prior to harvesting. Sampling was done on the paths to avoid influence of treatments on the soil in the plots themselves. The soils were dried and passed through 2 mm screen, and sub-samples of 200 g were sent to Wageningen University for analysis of pH, P-Olsen and P-Bray-I.

6.3 Results

Soil pH, P-Olsen, P-Bray-I, their interrelations and the relations with yield

Soil S3 has a lower pH than Soil S2 (Table 6.1). Soil pH was less variable in Soil S2 (CV = 3.6 %) compared to Soil S3 (CV = 8.6 %). Both soils are low in available P, averaging 3.1 mg kg\(^{-1}\) (P-Olsen) but in Soil S2 maxima for P-Olsen were higher than in Soil S3, and above the value of 5 mg kg\(^{-1}\), which is often used as critical value. For both soils P-Bray-I was more variable than P-Olsen; both soil indices were more variable in Soil S2 than Soil S3.
Chapter 6

Table 6.1. Descriptive statistics of soil pH and available P for Soils S3 and S2 used in the field trials (n = 28).

<table>
<thead>
<tr>
<th>Statistic</th>
<th>pH (KCl)</th>
<th>P-Olsen (mg kg(^{-1}))</th>
<th>P-Bray-I (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil S3</td>
<td>Soil S2</td>
<td>Soil S3</td>
</tr>
<tr>
<td>Mean</td>
<td>4.6</td>
<td>5.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>4.1</td>
<td>5.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.7</td>
<td>5.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Range</td>
<td>1.6</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>CV (%)</td>
<td>8.6</td>
<td>3.6</td>
<td>34.6</td>
</tr>
</tbody>
</table>

In Fig. 6.1 the values of P-Bray-I have been plotted against those of P-Olsen for four pH classes. Three lines were drawn: the 1:1 line, Line A bordering the highest points, and Line B bordering the lowest points in the graph.

In Fig. 6.2 it is shown that there was a weak negative relation between P-Bray-I and pH, but also that P-Olsen was not related to pH. In Fig. 6.3, the ratio P-Bray-I/P-Olsen was plotted against soil pH for different P-Bray-I classes. When soil pH was < 5.0, which practically coincided with P-Bray-I classes higher than 2.1 mg P kg\(^{-1}\), the ratio was > 0.65 meaning that at low pH, P-Bray-I was higher than P-Olsen (P-Bray-I > 0.65 * P-Olsen).
Figure 6.2. Relationship between P-Bray-I and pH \( (y = -1.6x + 10.7; R^2 = 0.19) \) and between P-Olsen and pH \( (y = 0.2x + 2.1; R^2 = 0.01) \) in Soils S3 and S2. \( (y = P\text{-Bray-I or P-Olsen and } x = \text{pH}) \).

Figure 6.3. Relation between the ratio P-Bray-I to P-Olsen and pH at various P-Bray-I classes in soils S2 and S3.

Wherever possible, maize grain yields were compared to soil pH across the different trials from both soils (Fig. 6.4). Regression analysis was carried out although there were only two clusters of pH values, with values around 4.3 and 5.3, respectively. Generally yield increased with increasing soil pH. For the control treatment the relation was \( y = 4.3x - 17.7 \) (y = maize grain yield in tons per hectare and x = pH (KCl)) indicating a yield increase of 4.3 ton per hectare per pH unit.
Figure 6.4. Relationship between maize grain yield and soil pH for different treatments in Soils S3 and S2. The P rates are shown in Table 6.3.

Of the treatments considered in Fig. 6.4, maize grain yield per unit of pH change was highest when TSP was banded (5.6 tons per hectare). The other treatments had lower yield per unit of pH change than the control treatment, the lowest coming from the MPR + fresh FYM treatment (1.5 tons per hectare) followed by the TSP + incubated FYM treatment (2.0 tons per hectare). On average the yield increase between pH (KCl) 4.3 and 5.3 was 4 tons per hectare, but when FYM was applied the yield increase was 1.5 to 2 tons per hectare.
Maps of Nearest Neighbor Means (NNMs)

Schematic field maps for the NNMs of first and second seasons grain yields in t ha\(^{-1}\) are shown in Figures 6.5, and 6.7 to 6.11 for three of the field trials (Trials 7.1, 7.2 and 7.4) discussed in Chapter 7. Trial 7.3 was too small for NNM to have a significant role in refining the results, so no maps were made. Shaded plots (with negative NNM) have lower yields than predicted by the model. Very poorly yielding plots are shaded black. Stars indicate plots with very good yields. The criteria used to categorize the yields were arbitrarily set after the NNMs were sorted in ascending order. Plots with NNMs very far from zero were considered either very poor (highly negative) or very good (highly positive). The same criteria were used in both seasons for the same trial. Bold numbers are average of the NNMs per row or column. Roman number indicates block number and adjacent to it actual average block yield.

The NNMs for Trial 7.1 are shown for Soil S3 in Fig. 6.5. The variation in the north-south direction was stronger and smoother than in the east-west direction. Very poor (NNM < -1.15) and very good (NNM > +1.21) plots were diagonally opposite to each other. The number of plots in these two categories was lower in the second compared to the first season. Some plots belonged to the same categories in both seasons. Linear regression analysis (\(y = a + bx\), with \(y = \text{NNM of the first season and } x = \text{NNM of the second season}\)) showed that of all the field trials, the relation between the NNMs of both seasons was the strongest in this trial (\(R^2 = 0.75\)) (Table 6.2 and Fig. 6.6). The distribution of the difference in NNMs between the two seasons was almost normal (Fig. 6.6).

<table>
<thead>
<tr>
<th>Trial</th>
<th>a</th>
<th>b</th>
<th>(R^2)</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>Normality test*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil S3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>+0.04</td>
<td>1.12</td>
<td>0.75</td>
<td>+0.04</td>
<td>0.45</td>
<td>P &gt; 0.479</td>
</tr>
<tr>
<td>7.2</td>
<td>-0.02</td>
<td>0.97</td>
<td>0.37</td>
<td>-0.02</td>
<td>0.15</td>
<td>P &gt; 0.508</td>
</tr>
<tr>
<td>7.4</td>
<td>-0.01</td>
<td>0.51</td>
<td>0.40</td>
<td>+0.01</td>
<td>0.28</td>
<td>P &gt; 0.062</td>
</tr>
<tr>
<td>Soil S2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>-0.02</td>
<td>0.57</td>
<td>0.30</td>
<td>-0.03</td>
<td>0.40</td>
<td>P &gt; 0.487</td>
</tr>
<tr>
<td>7.2</td>
<td>+0.04</td>
<td>0.48</td>
<td>0.14</td>
<td>+0.05</td>
<td>0.36</td>
<td>P &gt; 0.605</td>
</tr>
<tr>
<td>7.4</td>
<td>+0.01</td>
<td>0.24</td>
<td>0.05</td>
<td>+0.02</td>
<td>0.29</td>
<td>P &gt; 0.299</td>
</tr>
</tbody>
</table>

* Shapiro-Wilks' test.

The same trial was laid in Soil S2 between contours bounding a narrow piece of land, so it had to extend lengthwise. NNM maps are shown in Fig. 6.7. There was high variability within blocks in the first season with very poor plots (NNM < -0.62) occurring in all blocks and very good plots (NNM > +0.59) in three blocks (Blocks I, III and IV). Interesting is the occurrence directly on either side of the termite mound of very poor and very good plots in Blocks I and III. In the second season there was only one very good plot while there were no very poor plots. The NNMs of both seasons were only weakly related (\(R^2 = 0.30\)) (Table 6.2).

The NNMs for Trial 7.2 in Soil S3 are shown in Fig. 6.8. Plots with negative and positive NNMs appeared to be randomly distributed. Several plots changed from positive to negative
Chapter 6

NNM and vice versa in the second season. Very poor (NNM < -0.19) plots were more in the first than the second season. There were no very good (NNM > +0.25) plots in the second season. The absolute values of the NNM in Soil S3 however, were generally smaller than in Soil S2 (Fig. 6.9). Relation between the NNM of both seasons was weak (R² = 0.37) in Soil S3 but relatively stronger than in Soil S2 (R² = 0.14), (Table 6.2).

Negative NNM s for Trial 7.2 in Soil S2 during the first season were distributed almost entirely along the periphery with very poor plots (NNM < -0.59) (Fig. 6.9) on the corners. Plots with NNM > + 0.56 were considered very good. The number of very poor plots in the second season was reduced from eight to only one while very good plots dropped from six to two. None of the very good or very poor plots in the first season showed a similar trend in the second season.

The NNM maps for Trial 7.4 are shown for Soil S3 in Fig. 6.10. The number of very poor (NNM < -0.34) and very good (NNM > + 0.56) plots was lower in the second compared to the first season and in some instances plots which were in either category in the first season behaved similarly in the second season. There was a weak relation (R² = 0.40) between the NNMs of both seasons (Table 6.2) but like in the previous trials this relation was relatively stronger in this soil than in Soil S2.

In Soil S2 (Fig. 6.11) the number of very poor plots was higher in the second than the first season, a trend different from the other trials. The number of very good plots (NNM > + 0.28) decreased by one in the second season. None of the plots which were very poor (NNM < -0.28) in the first season remained in the same category in the second season, and the relation of NNM between the two seasons was the weakest (R² = 0.05) in this trial (Table 6.2 and Fig. 6.12). The distribution of their difference was far from normal (Fig. 6.12). This distribution is shown as an example of the other extreme compared to Trial 7.1 in Soil S3 (Fig. 6.6), with a normal distribution.
### Spatial variability in crop performance

<table>
<thead>
<tr>
<th>N</th>
<th>-1.28</th>
<th>-1.25</th>
<th>1.58</th>
<th>1.88</th>
<th>1.90</th>
<th>-0.74</th>
<th>-0.62</th>
<th>-0.48</th>
<th>-0.61</th>
<th>-0.91</th>
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<td>-1.07</td>
<td>1.17</td>
<td>-0.81</td>
<td>-0.90</td>
<td>-0.59</td>
<td>-0.81</td>
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<tr>
<td></td>
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<td>-1.07</td>
<td>-0.88</td>
<td>-1.13</td>
<td>-0.90</td>
<td>-0.55</td>
<td>-0.58</td>
<td>-0.81</td>
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<td>-0.10</td>
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<td>-0.99</td>
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<td>-0.71</td>
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<td>-0.58</td>
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</tr>
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<td>-0.38</td>
<td>-0.72</td>
<td>-0.95</td>
<td>-0.80</td>
<td>-0.12</td>
<td>0.25</td>
<td>-0.48</td>
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<tr>
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<td>0.07</td>
<td>-0.90</td>
<td>-0.91</td>
<td>-0.52</td>
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<td>0.20</td>
<td>0.19</td>
<td>-0.16</td>
<td></td>
</tr>
<tr>
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<td>0.06</td>
<td>0.24</td>
<td>-0.78</td>
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<td>-0.80</td>
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<td>1.07</td>
<td>1.16</td>
<td>-0.04</td>
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<td>-0.44</td>
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<td>0.59</td>
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<td>0.93</td>
<td>0.91</td>
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<td>0.25</td>
<td>0.78</td>
<td>0.84</td>
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<td>1.07</td>
<td>0.43</td>
<td>1.12</td>
<td>0.95</td>
<td>0.71</td>
<td>0.68</td>
<td>0.89</td>
<td>1.60</td>
<td>0.93</td>
<td></td>
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<tr>
<td></td>
<td>0.55</td>
<td>0.35</td>
<td>1.50</td>
<td>1.09</td>
<td>1.44</td>
<td>1.05</td>
<td>1.18</td>
<td>1.47</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.62</td>
<td>0.63</td>
<td>1.22</td>
<td>1.03</td>
<td>1.44</td>
<td>1.54</td>
<td>2.16</td>
<td>1.57</td>
<td>1.21</td>
<td></td>
</tr>
</tbody>
</table>

|    | -0.06 | -0.18 | -0.10 | -0.17 | -0.14 | -0.07 | 0.38  | 0.44 |       |       |
| IV | 3.99  | 3.52  | 3.60  | 4.69  | 4.09  |       |       |       |       |       |

|    | -0.50 | -0.27 | -1.48 | -1.60 | -0.58 | -0.48 | -0.74 | -1.12 | -0.79 |       |
|    | -0.36 | -0.43 | -0.81 | -0.86 | -0.58 | -0.38 | -0.42 | -0.59 | -0.55 |       |
|    | -0.42 | -0.58 | -0.71 | -0.82 | -0.68 | -0.36 | -0.76 | -0.67 |       |       |
|    | -0.31 | -0.25 | -0.09 | -0.14 | -0.77 | -0.87 | -0.60 | -0.42 | -0.43 |       |
|    | -0.33 | -0.09 | -0.43 | -0.41 | -0.57 | -0.38 | -0.65 | -0.64 | -0.44 |       |
|    | -0.62 | 0.14  | -0.76 | -0.55 | -0.37 | -0.45 | -0.25 | -0.34 |       |       |
|    | 0.32  | 0.43  | -0.53 | -0.43 | -0.32 | -0.27 | -0.01 | 0.12  | -0.08 |       |
|    | 0.61  | 0.46  | -0.09 | -0.03 | -0.30 | 0.14  | 0.12  |       | 0.05  |       |
|    | 0.84  | 0.91  | 0.71  | 0.72  | 0.04  | 0.37  | 0.56  | 0.51  | 0.58  |       |
|    | 0.99  | 0.74  | 0.53  | 0.60  | 0.60  | 0.49  | 0.43  | 0.61  |       |       |
|    | 0.63  | 0.56  | 0.80  | 0.84  | 1.11  | 1.55  | 1.15  | 1.23  | 0.99  |       |
|    | 0.61  | 0.70  | 0.24  | -0.05 | 1.87  | 1.05  | 0.84  | 1.17  | 0.80  |       |

|    | 0.17  | 0.19  | -0.20 | -0.21 | -0.05 | -0.03 | -0.04 | -0.02 |       |       |
| IV | 2.99  | 2.66  | 2.60  | 2.69  | 2.82  |       |       |       |       |       |

**Figure 6.5.** Schematic NNM field maps for Trial 7.1 in Soil S3: Left: First season, Right: Second season. Shaded plots have negative NNM. Very poor plots (in black), NNM < -1.15; Very good plots (with stars), NNM > +1.21.
Figure 6.6. Relation between NNM of the second and first season (top) and frequency distribution of the difference in NNM between the two seasons (bottom) in Trial 7.1, Soil S3.
Figure 6.7. Schematic NNM field maps for Trial 7.1 in Soil S2: First season. Shaded plots have negative NNM. Very poor plots (in black), NNM < -0.62; very good plots (with stars), NNM > +0.59.
Chapter 6

Figure 6.7. contd. Second season.
Spatial variability in crop performance

Figure 6.8. Schematic NNM field maps for Trial 7.2 in Soil S3. Top: First season. Bottom: Second season. Shaded plots have negative NNM. Shaded plots have negative NNM. Very poor plots (in black), NNM < -0.19: Very good plots (with stars), NNM > +0.25.
Figure 6.9. Schematic NNM field maps for Trial 7.2 in Soil S2. Left: First season, Right: Second season. Shaded plots have negative NNM. Very poor plots (in black), NNM < -0.59; Very good plots (with stars), NNM > 0.56.
Spatial variability in crop performance

Figure 6.10. Schematic NNM field maps for Trial 7.4 in Soil S3: Left: First season. Right: Second season. Shaded plots have negative NNM. Very poor plots (in black), NNM < -0.34, very good plots (with stars), NNM > +0.56.

Figure 6.11. Schematic NNM field maps for Trial 7.4 in Soil S2. Top: First season. Right: Second season. Shaded plots have negative NNM. Very poor plots (in black), NNM < -0.28, very good plots (with stars), NNM > +0.28.
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Figure 6.12. Relation between NNMs of the second and first season (top) and frequency distribution of the difference in NNM between the two seasons (bottom) in Trial 7.4, Soil S2.
6.4 Discussion

Relations between yields and soil pH

Soil pH was more important in explaining variability in crop performance than available P which in both soils is low (Table 6.1). Landon (1991) considers P-Olsen values less than 4 mg kg\(^{-1}\) to be low for maize. Because no relationship was found between pH and available P (Fig. 6.2), it can be deduced that pH was independently responsible for the variability observed. The choice of method for the determination of available P is important in order to be able to identify with certainty the important factors responsible for soil variability when P is involved. In this study the relation between P values determined by P-Olsen and P-Bray-I were somewhat influenced by soil pH. The P-Bray-I method uses a combination of HCl and NH\(_4\)F and is designed to remove easily acid-soluble forms of P, mainly Ca-P and part of P held by Al and Fe. The Olsen method uses NaHCO\(_3\) at pH 8.5. This extractant decreases the concentration of Ca in solution through precipitating Ca as CaCO\(_3\). It is thought more suitable for high pH soils with high amounts of Ca-P and free CaCO\(_3\) (Thomas and Peaslee, 1973). The P-Olsen method is also considered suitable across extreme soil types because it is least affected by soil type (Simonis, 1998).

The relatively high pH of Soil S2 (Table 6.1) means that pH is not a constraint in this soil. Consequently, variability in crop performance is expected to be lower than in the low pH Soil S3. (see for example Figures 6.8 and 6.9 for Trial 7.2). The relation between yield and pH shown in Fig. 6.4 and summarized in Table 6.3 for some treatments across the different trials show that yield was linearly positively related to pH in all the treatments. From Table 6.3 negative or low responses to P were mainly associated with low pH (< 4.4) or high pH (>5.2) suggesting a possible critical pH range below or above which response to P by maize decline.

Plots that were very poor (black in NNM maps) or very good (stars) and which came from either side of a sampled point, were selected to further look into their residuals in relation to pH and available P. The residuals of the two plots were calculated, averaged per sampling point and sorted in ascending order. This data is summarized in Table 6.4. In Soil S3 lower residuals were associated with low pH and higher residuals with high pH. The two were weakly related (Fig. 6.13), \(y = 1.5x - 7.0; R^2 = 0.51\); where \(y = \text{residuals in t ha}^{-1}, x = \text{pH}\). The trend in Soil S2 is impossible to ascertain given the narrow pH range (5.2 to 5.3). There was no systematic relation between residuals and either P-Olsen or P-Bray-I, suggesting again that the influence of pH on variability was independent of P.
### Table 6.3. Maize grain yields response in relation to soil pH for different treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Trial</th>
<th>Soil</th>
<th>P rate kg ha(^{-1})</th>
<th>pH KCl</th>
<th>P, mg kg(^{-1})</th>
<th>Maize grain yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bray-I</td>
<td>Olsen</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>7.2</td>
<td>S3</td>
<td>0</td>
<td>4.3</td>
<td>3.7</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3</td>
<td>4.4</td>
<td>3.1</td>
<td>3.8</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S2</td>
<td>5.2</td>
<td>1.0</td>
<td>3.6</td>
<td>4.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S2</td>
<td>5.2</td>
<td>2.3</td>
<td>2.0</td>
<td>4.94</td>
</tr>
<tr>
<td>TSP in planting hole</td>
<td>7.1</td>
<td>S3</td>
<td>10</td>
<td>4.4</td>
<td>5.7</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3</td>
<td>4.6</td>
<td>5.0</td>
<td>4.0</td>
<td>2.41 +0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S2</td>
<td>5.3</td>
<td>1.1</td>
<td>2.8</td>
<td>4.26 -0.83</td>
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<td>TSP banded</td>
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<td>S3</td>
<td>20</td>
<td>4.3</td>
<td>4.4</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>3.1</td>
<td>3.8</td>
<td>2.22 +1.00</td>
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<tr>
<td></td>
<td></td>
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<td>5.2</td>
<td>0.4</td>
<td>2.0</td>
<td>5.99 +1.33</td>
</tr>
<tr>
<td>TSP x FYM incubated (5 t ha(^{-1}) FYM)</td>
<td>7.4</td>
<td>S3</td>
<td>46.5(^{1})</td>
<td>4.4</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>4.5</td>
<td>2.7</td>
<td>2.2</td>
<td>4.69 +3.04</td>
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<tr>
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<td></td>
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<td>1.4</td>
<td>3.1</td>
<td>5.31 +1.51</td>
</tr>
<tr>
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<td></td>
<td>S2</td>
<td>5.3</td>
<td>2.9</td>
<td>8.5</td>
<td>5.68 +0.59</td>
</tr>
<tr>
<td>MPR x Fresh FYM (5 t ha(^{-1}) FYM)</td>
<td>7.4</td>
<td>S3</td>
<td>46.5(^{2})</td>
<td>4.3</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S3</td>
<td>4.4</td>
<td>2.7</td>
<td>2.9</td>
<td>2.35 +1.13</td>
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<tr>
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<td></td>
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<td>2.0</td>
<td>4.9</td>
<td>4.51 +0.71</td>
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<td></td>
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<td>5.4</td>
<td>2.9</td>
<td>8.5</td>
<td>3.33 -2.19</td>
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<td>MPR in hole, TSP broadcast</td>
<td>7.3</td>
<td>S3</td>
<td>40(^{*})</td>
<td>4.6</td>
<td>2.2</td>
<td>1.9</td>
</tr>
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<td>4.9</td>
<td>3.0</td>
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<td>5.2</td>
<td>1.0</td>
<td>2.6</td>
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<td>3.3</td>
<td>5.80 +0.28</td>
</tr>
</tbody>
</table>

\(^{1}\) Calculated. For explanation see text.

\(^{2}\) Including P in the FYM.

\(^{*}\) 20 kg\(^{-1}\) P ha\(^{-1}\) each for MPR-P and TSP-P.

### NNM maps and Blocks

The NNM analysis showed that in some cases the blocks could better have been in a direction perpendicular to the one used (Figures 6.5, 6.9, 6.10) or in a diagonal direction (Fig. 6.10). In other fields it was practically impossible to design blocks in an effective way (Fig. 6.8). This holds more for the larger than for the smaller trials. The smaller the field trial the less the chances of having large variability because blocks can be squeezed in a small area. For example in Trial 7.4 on Soil S3 (Fig. 6.10) blocking was comparatively more effective given its relatively small size although there were still some few patches of good and bad areas within each block. In Soil S2 (Fig. 6.11) however, this was not found. In both it would have been better to make square blocks instead of the present oblong ones. In the large trials the influence of the many scattered patches of good and bad areas on treatment effects can be minimized by sub-blocking. Alternatively blocks should not necessarily be clustered together but rather be spatially distributed to accommodate the variability. Hoosbeek et al. (1998) tried with success to use the spatially randomized block design where blocks were distributed across the catena. They observed that the ability of the design in detecting treatment effects was enhanced.
Spatial variability in crop performance

Table 6.4. Residuals of some of selected plots and corresponding pH, P-Olsen and P-Bray-I values. The way of selection is explained in the text.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Plot no.</th>
<th>Residual*</th>
<th>pH (KCl)</th>
<th>P-Olsen mg kg⁻¹</th>
<th>P-Bray-I mg kg⁻¹</th>
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<td>Soil S3</td>
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<td></td>
</tr>
<tr>
<td>7.1</td>
<td>62/74</td>
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<td>4.4</td>
<td>3.7</td>
<td>5.7</td>
</tr>
<tr>
<td>7.2</td>
<td>65/66</td>
<td>-0.47</td>
<td>4.3</td>
<td>2.9</td>
<td>4.4</td>
</tr>
<tr>
<td>7.4</td>
<td>30/31</td>
<td>+0.09</td>
<td>4.1</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>7.2</td>
<td>127/128</td>
<td>+0.30</td>
<td>4.6</td>
<td>4.9</td>
<td>3.4</td>
</tr>
<tr>
<td>7.1</td>
<td>24/36</td>
<td>+0.55</td>
<td>5.6</td>
<td>2.2</td>
<td>3.4</td>
</tr>
<tr>
<td>7.1</td>
<td>60/48</td>
<td>+1.24</td>
<td>5.7</td>
<td>4.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

| Soil S2 |          |           |          |                 |                 |
| 7.1   | 1/2      | -1.29     | 5.3      | 2.8             | 1.1             |
| 7.1   | 60/61    | -0.08     | 5.3      | 2.8             | 0.8             |
| 7.4   | 9/8      | -0.05     | 5.3      | 8.5             | 2.9             |
| 7.4   | 34/35    | +0.31     | 5.2      | 2.3             | 0.8             |
| 7.2   | 92/103   | +0.78     | 5.2      | 6.0             | 2.0             |
| 7.2   | 112/121  | +0.92     | 5.2      | 3.6             | 1.0             |

* Average of two plots on either side of sampled points.

Seasonal effects on variability

Generally there was less variability in the second than the first season, and except for Trial 7.1 in Soil S3 the NNMs of both seasons were weakly related (Table 6.2). For each trial however, this relation was always relatively stronger in Soil S3 than Soil S2 which indicates relatively less variability across the seasons in Soil S3. This is possible because pH was more important in Soil S3 than in Soil S2 as a factor influencing variability. It is not expected that pH differs appreciably between the two seasons. The lower variability in the second compared to the first season could be due to the applied treatments and uniform management. Similar observations were made by Buerkert and Stern (1995) who reported reduced variability resulting from application of P and crop residues. Boxman (1990) found that variation of P-Bray-I, pH and exchangeable cations 12 years after clearing was remarkably lower than 3 years after clearing.

The contrasting differences in NNM in the first season between the plots on either side of the termite mound (Trial 7.1, Soil S2, Fig. 6.7) could have been caused by termite activity influencing the two sides differently, for example, by transferring organic residues from one side to the other, which would affect the physical properties of the soils apart from nutrients stocks. However, these differences were absent in the second season, which could be due to the uniform management employed. Spatial variability in soils due to termite activities has been observed to be an important factor in modifying soil physical properties in the Sahel (Brouwer et al., 1992; Mando and van Rhenen 1998).

Relations between yield responses to P application and soil pH

Yield responses to applied P at different pH is also shown in Table 6.3. It was calculated by subtracting yields at zero fertilizer application \( y = 4.3x - 17.7 \), where \( y = \) yield in ton per hectare at zero fertilizer application and \( x = \) pH (KCl), from the actual yields at the respective pH (Table 6.3). Generally, response to P decreased with increase in pH when TSP was applied with incubated FYM or when it was applied in the planting hole. In the latter case negative yield responses were observed at pH higher than 4.6. When TSP was band applied yield response increased with pH. Meanwhile when TSP was mixed with Minjingu PR (TSP broadcast and
Minjingu PR in the planting hole) the overall trend was that of increasing response with increase in pH. Mixtures of soluble P source and PR have been shown to perform well. For example Hagin and Katz (1985) observed that mixtures of superphosphates and up to 50% PR were as effective as superphosphates on calcareous and slightly alkaline soils. When MPR was mixed with fresh manure response to P decreased with increase in pH. At the highest pH response to MPR - fresh manure mixture was highly negative (-2.19) perhaps a reflection of limitation of protons given that both FYM and MPR are also high in pH and hence high in proton consumption (Kpomblekou-A and Tabatabai, 1994a; Wong, et al., 1998; Chapter 3).

In conclusion, variation in maize yield in the soils used in this study was more explained by pH than available P. This influence of pH on variability was not confounded with available P. When no fertilizers were applied yield increased by about 4 tons per hectare between pH (KCl) 4.3 and 5.5. Soil pH influenced the relationship between P values determined by Bray-I and by P-Olsen. P-Bray-I tended to be higher than P-Olsen in low pH soils and lower than P-Olsen in high pH soils. Knowledge of the pH of the soils is therefore important in that it can be used as a guide to fertilizer use for example, use of PRs since they rely on the availability of protons for their dissolution, and decision on where neutral or acidifying fertilizers could be used. To be able to correctly identify the important factors influencing soil variability especially when P is involved, the choice of appropriate method of P determination in relation to the pH of the soil is important.

The NNM analysis showed that large trials run the risk of increasing the chances of increased variability. It also showed that reorientation of some of the larger trials to allow blocks accommodate the variability could have lowered the within blocks variations. There was more variability in the first than the second season, because of the uniform management and the treatments applied. The use of NNM should be employed in large trials especially in the tropics to isolate environmental effects beyond what normal blocking can do.
CHAPTER 7

7 Exploiting different management options in enhancing the effectiveness of Minjingu phosphate rock. Field trials

7.0 Common characteristics and operations for all the field trials

Introduction

The importance of adequate supply of protons for PR dissolution and the depression of PR dissolution when high rates are used were demonstrated in Chapter 3. In the same chapter, the laboratory extraction experiment (Experiment 3.1) showed that extractable P was influenced by the content of CaCO₃ in the PRs. It was lower the higher the CaCO₃ content. However, this was not reflected in the agronomic effectiveness of the PRs tested in the pot experiment of Chapter 3 (Experiment 3.2) possibly because of the influence of the soils and the interactions of soil and plants (Chapters 4 and 5) on the availability of P from PR. In Chapter 5 it was also demonstrated that utilization of absorbed P was better from PR than from TSP in low pH soils. This chapter focuses on integral testing of the hypothesis and results of the greenhouse experiments in the field with emphasis on fertilizer management. A total of four field trials were established at ARI Mlingano, Tanga, Tanzania during the long rains of March to May and the short rains of October to December in 1997. In all these trials fertilizer P was applied only once during the first season while the effects of P were examined over two cropping periods. In Chapter 7.0 operations and information common to all the field trials are explained while the trials are covered in detail in Chapters 7.1 to 7.4.

Trial sites

The trials were conducted on two Rhodic Ferralsols, Soils S2 and S3. Soil S2 is in the farm of ARI Mlingano and Soil S3 near Mzambaraoni village some 2.5 km from S2 (Fig. 2.1, Chapter 2). The general characteristics of the soils are shown in Table 2.3, Chapter 2. Soil S2 has a relatively high pH (pH (H₂O) = 5.8; pH (KCl) = 5.0) and relatively high available P (P-Olsen = 6; P-Bray-I = 4 mg kg⁻¹) while Soil S3 has a relatively low pH (pH (H₂O) = 5.0; pH KCl = 4.1) and low available P (P-Olsen = 3; P-Bray-I = 2 mg kg⁻¹).

Land preparation and layout

Previous land use in both sites was fallow, with a dense grass and shrub vegetation. Land preparation was done by first clearing the land using a tractor-mounted mower. This was followed by plowing and harrowing. Experimental treatments were randomly allocated to plots of gross area 4.5 m x 6.0 m (27 m²). Each plot had six rows of 6 meters long. The net plot area was 3.0 m x 5.4 m (16.2 m²) and consisted of the four inner rows minus the last hills at both ends of the rows.

Planting

Two maize seeds (Zea mais (L.) var. TMV1) were planted per hill at a spacing of 75 x 30 cm and later thinned to one per hill. Where necessary gap filling was done between 8 and 10 days after planting. Gross plant population was 120 per plot (44,444 plants per hectare) at 20 plants per row. Plant population per net plot was 72 at 18 plants per row. Planting holes about 10 cm deep were made using a hand hoe. When fertilizer was applied in the planting hole it was covered by a thin layer of soil about 2.5 cm thick. Planting was done between 25/03/1997 and 29/03/1997 in the first season and between 07/10/1997 and 11/10/1997 in the second season. To ensure that the plants of the second crop were planted in the same positions as the plants of the first crop, permanent markers were placed at the corners of each trial in the first season.
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Weed and Pest Control

Weeds were controlled by one application of Fermanin 72 (2,4-D amine), a pre-emergence herbicide, followed by two hand weeding. A high rate of the herbicide (3 liters per hectare) was used in view of the high clay content of the soils and a known history of striga in the area. The first hand weeding essentially aimed at re-working the soil to break surface crust in order to improve aeration and water infiltration since weed pressure was still low. Insect pests mainly the maize stalk borer (Busceolla fusca) were controlled using thiodan (endosulfan 35% emulsifiable concentrate) sprayed once during the first season and twice in the second season due to higher stalk borer incidence.

To put off domestic animals, mainly cattle, the fields were fenced using barbed wire. Especially for trials on Soil S3 near the village, vermin such as monkeys and wild pigs were scared away by watchmen posted at the site. Whereas monkeys were a problem during the day throughout the growing season, wild pigs were a major problem at night mainly at the later stages of growth of the maize. In the second season rats were a problem but were put under control using a zinc phosphate based rodenticide mixed with maize bran and fishmeal. The mixture was spread at various points throughout the fields. Termite attack was another problem especially in the second season but was minimized by raising maize plants that had fallen to the ground and supporting them on wooden stands.

N application

For trials where N fertilizer was not a treatment, calcium ammonium nitrate (CAN) at the recommended rate of 50 kg N ha⁻¹ (Mowo et al., 1993) was applied 5 to 6 weeks after planting depending on soil moisture. Fertilizer N was applied in a furrow (about 2.5 cm deep) made about 5 cm from a maize row and then covered with a thin layer of soil.

Observations and measurements

During both seasons visual observations of crop performance was done throughout the growing period. This included growth vigor, deficiency symptoms, diseases, and insect pests' damage. In the second season some plots were sampled for soils and plant materials for analysis. (see Materials and Methods section of Chapter 6 on how plots were selected for sampling). Maize grain and stover were separately sampled, dried and milled. Sub-samples of 200 g for soils and 3 g for plant materials were sent to WUR for analysis of pH, P-Olsen and P-Bray-I for soils and P content for plant materials.

Harvesting

The first season crop was harvested between 01/07/1997 and 04/07/1997 and the second season crop between 02/02/1998 and 05/02/1998. Harvesting was done after maize was dry. For each trial the guard rows were harvested first to avoid mixing with the net plot. Using a knife the ear was opened and cob removed leaving the husk on the plant. The stover was cut at the base, bundled and fresh weight taken in the field. The oven dry weight of the stover was derived from some few samples of stover, which were oven dried at 70 °C for 48 hours. Each plot was allocated a well-labeled harvesting bag whose weight was measured prior to harvesting. The weighing of the cobs was made in the field and the weight of the harvesting bag subtracted. In Season I the dry weight of the maize was derived from few (56) plots, which had their cobs dried to the required storage moisture of 13 %. The 56 plots were picked at random, each trial being represented. The maize from these plots was shelled and weight of grain and axis determined. A graph of grain weight against cob weight was made from which the grain yield of all the plots was derived at 13 % moisture. In Season II a hand driven
Sheller was acquired and maize from individual plots was shelled and weighed separately after the maize had dried to the required storage moisture.

Statistical analysis

Data for Trials 7.1 and 7.2 (Chapters 7.1 and 7.2) were statistically analyzed using regression analysis. The procedure REG from the statistical program SAS, version 6.12 (SAS Institute Inc., 1997) was used. For the Trials 7.3 and 7.4 (Chapters 7.3 and 7.4) the general linear model procedure (GLM), of the same statistical program SAS version 6.12 was used.

7.1 Influence of rate, type of P fertilisers and method of application

Abstract

The influence of rate and method of application of MPR and TSP on maize yield were studied in a field trial on two Rhodic Ferralsols at ARI Mlingano during the long and short rains of 1997. Initially, TSP-P performed better than MPR-P but their residual effects were almost the same on both soils. Optimum rate of P application for the low pH Soil S3 was 38 kg ha\(^{-1}\) for MPR-P and 49 kg ha\(^{-1}\) for TSP-P. In the high pH Soil S2 method of application was important, particularly for MPR. When MPR was applied in the planting hole it performed poorly. Optimum P rates for MPR on Soil S2 were 146 kg ha\(^{-1}\) when broadcast and 35 kg ha\(^{-1}\) when applied in the planting hole. Corresponding values for TSP were 123 kg ha\(^{-1}\) when broadcast and 105 kg ha\(^{-1}\) when applied in the planting hole. Response to P was low in both soils. When applied in the planting hole in the high pH Soil S2, response to TSP-P was 3 times more than to MPR-P. The results indicate that best response to MPR will be obtained at modest rates with broadcast application.

7.1.1 Introduction

The decrease in PR effectiveness at increasing rate of application (Chapters 3, 4, and 5; Brenes and Bornemisza, 1992) points at an optimum application rate. Optimal PR rates will be dictated by the amount of available protons and the demand for fertilizer P by the crop. The rate should not be too low for a sufficient supply of P to crops and it should not be too high to depress the dissolution of the PR. It is therefore necessary to establish optimum PR application rates depending on the properties of the soils. Such knowledge is necessary given the current drive towards high PR rates (high input strategy) to compensate for the low P content and recovery of PRs (Buresh et al., 1997). Apart from depression of PR at high rates such a strategy is not feasible for the majority of farmers whose purchasing power is low.

Equally important in PR effectiveness is the method of application. Broadcasting and incorporation is reported to be more effective than banding especially in soils medium in P and low in P sorption capacity (Alston and Chin, 1974). Although broadcasting may ensure maximum use of soil protons, substantial part of dissolved P remains out of reach of plant roots. Such P can be considered unavailable for uptake in the first season. Applying PR near the plant roots would ensure exploitation of rhizosphere acidification. However, only a small fraction of the bulk soil acidity can be used for PR dissolution. Therefore, there must be a balance between rate and method of application in relation to the relevant soil properties. This was studied in field trials involving different rates of MPR and TSP applied in two different methods that is, broadcast and application in the planting hole. The trials were established on two Rhodic Ferralsols (Chapter 7.0) during the long and short rains of 1997 at ARI Mlingano. The general objective was to establish appropriate rates and methods of application that will ensure optimum use of MPR. Specifically the trial aimed at establishing...
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the effects of increasing rates of MPR on maize yield, at comparing the performance of MPR with TSP, at comparing the two methods of application and at studying the residual effects of MPR and TSP. Results from this study will enable formulation of optimal MPR application.

Weather conditions

As mentioned in Section 2.4 Chapter 2, rainfall in the months of October and November 1997 was exceptionally high (see Table 2.1 and Fig. 2.3 in Chapter 2). The short rains coincided with the El Niño phenomena. Due to this, yields were much lower in the second season than in the first season.

7.1.2 Materials and Methods

A randomized complete block design in a 2 (types) x 2 (methods) x 6 (rates) factorial arrangement was used for Soils S2 and S3 in two seasons. Each treatment was replicated four times to make a total of 96 experimental units per site. MPR (100 mesh) or TSP was either broadcast or applied in the planting hole at six different P rates, that is 0, 5, 10, 20, 40, 80 kg ha⁻¹ in the first season only. When broadcast, MPR or TSP was pre-mixed with a small amount of surface soil taken from the respective plot and the mixture spread uniformly on the plots. Pre-mixing of the fertilizer with surface soil was done to make it easy to apply uniformly as well as minimize the problem of the powdery nature of MPR. After spreading the fertilizer and working it into the soil, planting holes were made using a hand hoe. Calcium ammonium nitrate (CAN) at the recommended rate of 50 kg N ha⁻¹ was applied in each season to all plots six weeks after planting. The residual effects of P were studied in the second season.

Data were statistically analyzed using regression analysis to determine effects of source of P, method of application and rate of P and their interactions on maize grain yield. The procedure REG from the statistical program SAS, version 6.12 (SAS Institute Inc., 1997) was used. Quadratic regression models with respect to P were assumed for maize grain yield. Allowance was made for blocks effect and Nearest Neighbor Means (NNM, see Chapter 6) of residuals. The regression model for each of the four soil and season combinations is:

\[
y = \alpha + \beta_i + \gamma \text{NNM} + \pi_{ij} P + \pi_{2j} P^2 + \varepsilon,
\]

where \(y\) is observed yield, \(\alpha\) is expected yield if no P is applied, \(\beta_i\) is block effect (\(i = 1, \ldots, 4\)), \(\gamma\) is coefficient for nearest neighbor mean, \(\pi_{ij}\) is coefficient of P rate at treatment \(j\) (\(j = 1, \ldots, 4\), coding for type of P and method of P application), \(\pi_{2j}\) is coefficient of square of P rate at treatment \(j\) and \(\varepsilon\) is unexplained error.

7.1.3 Results

Maize grain yields both observed and corrected for NNM (see Chapter 6) are summarized in Table 7.1.1. Control yields are averages of 16 observations (4 replicates * 4 zero P treatments, while the rest are averages of 4 replicates). Data averaged over the two application methods for each type of P are also shown. In both soils and both seasons NNM proved by far the most important factor affecting yields. Except for Soil S2 in the first season there were no significant differences between the two methods of application, that is broadcast and application in the planting hole (Table 7.1.2). In Soil S3 first season, P and the interaction P * type P had significant positive linear effects on maize grain yields while the quadratic effect of P was significantly negative (\(P < 0.1\)) (Tables 7.1.2 and 7.1.3). From Table 7.1.1 it is clear that TSP performed better than MPR at high but not at low rates. The residual
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effects of P were significant (P < 0.1). However, there was no significant difference between residual TSP-P and residual MPR-P (Tables 7.1.1 and 7.1.2).

In Soil S2 first season, P effect on maize grain yield was not very significant (P = 0.14). However, the interactions P * type P, P * method of application had significant effects (P < 0.05) on maize grain yield (Table 7.1.2). The three factor interaction, P * type P * method of application was significant at P < 0.1. From Table 7.1.1 it follows that broadcasting MPR or TSP was better than application in the planting hole. Further, TSP was better than MPR. There was no significant quadratic effect of P but the interaction P^2 * type P had significant effect (P < 0.05) on maize grain yield. The residual effect of P was highly significant (P < 0.01) (Table 7.1.2), but the differences between MPR and TSP and those between application methods had disappeared in the second season. The quadratic effect of residual P was highly significantly negative (Tables 7.1.2 and 7.1.3).

The responses to P fertilizer (ΔY) (t ha⁻¹) are summarized in the expressions below.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Season</th>
<th>ΔY</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>1</td>
<td>0.029P - 3.840 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to MPR-P)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.038P - 3.840 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to TSP-P)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.018P (MPR or TSP, broadcast or in hole)</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>0.025P - 0.857 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to MPR broadcast)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.006P - 0.857 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to MPR in hole)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.021P - 0.857 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to TSP broadcast)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.018P - 0.857 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(to TSP in hole)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.026P - 2.970 * 10⁻⁴ P²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(MPR or TSP, broadcast or in hole)</td>
</tr>
</tbody>
</table>

From the first derivative to P the P rate for maximum yield and the response to P were calculated (Table 7.1.4). Rates of P to attain maximum yields were lower in Soil S3 than in Soil S2 while average yield response per unit of P were higher in Soil S3 than in Soil S2. Response to TSP was higher than to MPR in Soil S3. In Soil S2 response to broadcast MPR was almost the same as response to TSP broadcast. When applied in the planting hole, response to TSP was three times higher than to MPR. The responses to P were in the low part of the range of responses of 0 - 60 kg per kg P given by (Janssen et al., 1990), when a recovery fraction of 0.1 for fertilizer P is considered.

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Table 7.1.1: Observed and corrected (for NNM) maize grain yields in t ha\(^{-1}\). B and H means broadcast and application in the planting hole respectively.

<table>
<thead>
<tr>
<th>P rate, kg ha(^{-1})</th>
<th>Observed yields</th>
<th>Corrected yields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MPR</td>
<td>TSP</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>Soil S3, First season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.57</td>
<td>2.57</td>
</tr>
<tr>
<td>5</td>
<td>4.42</td>
<td>3.78</td>
</tr>
<tr>
<td>10</td>
<td>4.71</td>
<td>5.08</td>
</tr>
<tr>
<td>20</td>
<td>2.64</td>
<td>2.57</td>
</tr>
<tr>
<td>40</td>
<td>4.90</td>
<td>3.10</td>
</tr>
<tr>
<td>80</td>
<td>4.34</td>
<td>2.34</td>
</tr>
<tr>
<td>Average*</td>
<td>2.57</td>
<td>3.78</td>
</tr>
<tr>
<td>Response*</td>
<td>0.85</td>
<td>0.61</td>
</tr>
<tr>
<td>Soil S3, Second season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.28</td>
<td>2.28</td>
</tr>
<tr>
<td>5</td>
<td>3.55</td>
<td>2.53</td>
</tr>
<tr>
<td>10</td>
<td>3.78</td>
<td>2.77</td>
</tr>
<tr>
<td>20</td>
<td>2.90</td>
<td>2.29</td>
</tr>
<tr>
<td>40</td>
<td>3.49</td>
<td>3.07</td>
</tr>
<tr>
<td>80</td>
<td>3.13</td>
<td>2.36</td>
</tr>
<tr>
<td>Average*</td>
<td>2.28</td>
<td>2.99</td>
</tr>
<tr>
<td>Response*</td>
<td>0.41</td>
<td>0.18</td>
</tr>
<tr>
<td>Soil S2, First season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>3.83</td>
<td>3.83</td>
</tr>
<tr>
<td>5</td>
<td>4.19</td>
<td>4.00</td>
</tr>
<tr>
<td>10</td>
<td>5.02</td>
<td>4.25</td>
</tr>
<tr>
<td>20</td>
<td>4.36</td>
<td>4.03</td>
</tr>
<tr>
<td>40</td>
<td>4.09</td>
<td>3.66</td>
</tr>
<tr>
<td>80</td>
<td>5.95</td>
<td>4.31</td>
</tr>
<tr>
<td>Average*</td>
<td>3.89</td>
<td>3.89</td>
</tr>
<tr>
<td>Response*</td>
<td>0.41</td>
<td>0.10</td>
</tr>
<tr>
<td>Soil S2, Second season</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.70</td>
<td>2.70</td>
</tr>
<tr>
<td>5</td>
<td>2.87</td>
<td>2.99</td>
</tr>
<tr>
<td>10</td>
<td>3.39</td>
<td>3.66</td>
</tr>
<tr>
<td>20</td>
<td>3.32</td>
<td>3.38</td>
</tr>
<tr>
<td>40</td>
<td>3.21</td>
<td>3.41</td>
</tr>
<tr>
<td>80</td>
<td>3.18</td>
<td>3.32</td>
</tr>
<tr>
<td>Average*</td>
<td>3.19</td>
<td>3.35</td>
</tr>
<tr>
<td>Response*</td>
<td>0.36</td>
<td>0.48</td>
</tr>
</tbody>
</table>

* Excluding the zero treatment.

† Average response averaged over all P rates (Corrected yields only).
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Table 7.1.2. ANOVA table for the effects of type of P (MPR or TSP) method of application (Broadcast or in planting hole) and rate of P on maize grain yield (corrected yields). CV stand for coefficient of variation and in %.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil S3, First season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replication</td>
<td>3</td>
<td>0.174</td>
<td>0.058</td>
<td>0.043</td>
<td>0.9881</td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>74.202</td>
<td>74.202</td>
<td>54.641</td>
<td>0.0001</td>
</tr>
<tr>
<td>P</td>
<td>1</td>
<td>5.211</td>
<td>5.211</td>
<td>3.837</td>
<td>0.0534</td>
</tr>
<tr>
<td>P * type</td>
<td>1</td>
<td>4.052</td>
<td>4.052</td>
<td>2.984</td>
<td>0.0878</td>
</tr>
<tr>
<td>P * method</td>
<td>1</td>
<td>1.453</td>
<td>1.453</td>
<td>1.070</td>
<td>0.3039</td>
</tr>
<tr>
<td>P * type * method</td>
<td>1</td>
<td>1.399</td>
<td>1.399</td>
<td>1.030</td>
<td>0.3131</td>
</tr>
<tr>
<td>P²</td>
<td>1</td>
<td>4.838</td>
<td>4.838</td>
<td>3.563</td>
<td>0.0625</td>
</tr>
<tr>
<td>P² * type</td>
<td>1</td>
<td>2.572</td>
<td>2.572</td>
<td>1.894</td>
<td>0.1725</td>
</tr>
<tr>
<td>Error</td>
<td>85</td>
<td>115.458</td>
<td>1.358</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>95</td>
<td>236.872</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV = 31.5, R² = 0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Soil S3, Second season    |                    |                |             |         |             |
| Replication               | 3                  | 0.255          | 0.085       | 0.184   | 0.9071      |
| NNM                       | 1                  | 53.915         | 53.915      | 116.447 | 0.0001      |
| P                         | 1                  | 1.501          | 1.501       | 3.242   | 0.0752      |
| P * type                  | 1                  | 0.048          | 0.048       | 0.104   | 0.7469      |
| P * method                | 1                  | 1.129          | 1.129       | 2.438   | 0.1219      |
| P * type * method         | 1                  | 0.202          | 0.202       | 0.436   | 0.5106      |
| P²                        | 1                  | 1.095          | 1.095       | 2.365   | 0.1277      |
| P² * type                 | 1                  | 0.034          | 0.034       | 0.073   | 0.7877      |
| Error                     | 85                 | 39.313         | 0.463       |         |             |
| Total                     | 95                 | 164.477        |             |         |             |
| CV = 24.2, R² = 0.62      |                    |                |             |         |             |

| Soil S2, First season     |                    |                |             |         |             |
| Replication               | 3                  | 6.051          | 2.017       | 2.997   | 0.0352      |
| NNM                       | 1                  | 18.265         | 18.265      | 27.140  | 0.0001      |
| P                         | 1                  | 1.490          | 1.490       | 2.214   | 0.1405      |
| P * type                  | 1                  | 4.763          | 4.763       | 7.077   | 0.0093      |
| P * method                | 1                  | 4.040          | 4.040       | 6.003   | 0.0164      |
| P * type * method         | 1                  | 2.413          | 2.413       | 3.585   | 0.0618      |
| P²                        | 1                  | 0.260          | 0.260       | 0.386   | 0.5235      |
| P² * type                 | 1                  | 4.136          | 4.136       | 6.146   | 0.0152      |
| Error                     | 85                 | 57.226         | 0.673       |         |             |
| Total                     | 95                 | 95.984         |             |         |             |
| CV = 18.7, R² = 0.40      |                    |                |             |         |             |

| Soil S2, Second season    |                    |                |             |         |             |
| Replication               | 3                  | 0.114          | 0.038       | 0.224   | 0.8798      |
| NNM                       | 1                  | 5.920          | 5.920       | 34.824  | 0.0001      |
| P                         | 1                  | 3.277          | 3.277       | 19.276  | 0.0001      |
| P * type                  | 1                  | 0.156          | 0.156       | 0.918   | 0.3403      |
| P * method                | 1                  | 0.269          | 0.269       | 1.582   | 0.2116      |
| P * type * method         | 1                  | 0.055          | 0.055       | 0.324   | 0.5698      |
| P²                        | 1                  | 2.988          | 2.988       | 17.576  | 0.0001      |
| P² * type                 | 1                  | 0.145          | 0.145       | 0.853   | 0.3582      |
| Error                     | 85                 | 14.444         | 0.170       |         |             |
| Total                     | 95                 | 23.709         |             |         |             |
| CV = 13.2, R² = 0.39      |                    |                |             |         |             |
Table 7.1.3. Parameters estimate for the influence of different rates of MPR and TSP on maize grain yield.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter estimate</th>
<th>Standard error (±)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil S3, First season</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>3.369</td>
<td>0.214</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>0.022</td>
<td>0.208</td>
<td>0.8867</td>
</tr>
<tr>
<td>NNM</td>
<td>0.709</td>
<td>0.097</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR (B)</td>
<td>0.036</td>
<td>0.018</td>
<td>0.0531</td>
</tr>
<tr>
<td>MPR (H)</td>
<td>0.022</td>
<td>0.018</td>
<td>0.2177</td>
</tr>
<tr>
<td>TSP (B)</td>
<td>0.038</td>
<td>0.018</td>
<td>0.0366</td>
</tr>
<tr>
<td>TSP (H)</td>
<td>0.038</td>
<td>0.018</td>
<td>0.0404</td>
</tr>
<tr>
<td>P²</td>
<td>-3.840 * 10⁻⁴</td>
<td>2.040 * 10⁻⁴</td>
<td>0.0634</td>
</tr>
<tr>
<td><strong>Soil S3: Second season</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>2.641</td>
<td>0.124</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>-0.002</td>
<td>0.121</td>
<td>0.6898</td>
</tr>
<tr>
<td>NNM</td>
<td>0.752</td>
<td>0.069</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR (B)</td>
<td>0.019</td>
<td>0.010</td>
<td>0.0710</td>
</tr>
<tr>
<td>MPR (H)</td>
<td>0.016</td>
<td>0.010</td>
<td>0.1276</td>
</tr>
<tr>
<td>TSP (B)</td>
<td>0.022</td>
<td>0.010</td>
<td>0.0315</td>
</tr>
<tr>
<td>TSP (H)</td>
<td>0.014</td>
<td>0.010</td>
<td>0.1807</td>
</tr>
<tr>
<td>P²</td>
<td>-1.820 * 10⁻⁴</td>
<td>1.178 * 10⁻⁴</td>
<td>0.1250</td>
</tr>
<tr>
<td><strong>Soil S2: First season</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>4.085</td>
<td>0.153</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>-0.130</td>
<td>0.150</td>
<td>0.5464</td>
</tr>
<tr>
<td>NNM</td>
<td>0.615</td>
<td>0.125</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR (B)</td>
<td>0.025</td>
<td>0.013</td>
<td>0.0560</td>
</tr>
<tr>
<td>MPR (H)</td>
<td>0.006</td>
<td>0.013</td>
<td>0.6647</td>
</tr>
<tr>
<td>TSP (B)</td>
<td>0.021</td>
<td>0.013</td>
<td>0.1081</td>
</tr>
<tr>
<td>TSP (H)</td>
<td>0.018</td>
<td>0.013</td>
<td>0.1586</td>
</tr>
<tr>
<td>P²</td>
<td>-0.857 * 10⁻⁴</td>
<td>1.464 * 10⁻⁴</td>
<td>0.5600</td>
</tr>
<tr>
<td><strong>Soil S2: Second season</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>2.880</td>
<td>0.074</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>-0.003</td>
<td>0.073</td>
<td>0.6553</td>
</tr>
<tr>
<td>NNM</td>
<td>0.603</td>
<td>0.103</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR (B)</td>
<td>0.025</td>
<td>0.006</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR (H)</td>
<td>0.027</td>
<td>0.006</td>
<td>0.0001</td>
</tr>
<tr>
<td>TSP (B)</td>
<td>0.024</td>
<td>0.006</td>
<td>0.0003</td>
</tr>
<tr>
<td>TSP (H)</td>
<td>0.028</td>
<td>0.006</td>
<td>0.0001</td>
</tr>
<tr>
<td>P²</td>
<td>-2.970 * 10⁻⁴</td>
<td>0.708 * 10⁻⁴</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
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Table 7.1.4. Fertilizer P rates (kg ha\(^{-1}\)) for maximum yield and corresponding average yield response per kg fertilizer P (kg kg\(^{-1}\)).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Season</th>
<th>P Type</th>
<th>Method</th>
<th>Rate</th>
<th>Average response</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>1</td>
<td>MPR</td>
<td>na</td>
<td>38</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>TSP</td>
<td>na</td>
<td>49</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>na</td>
<td>na</td>
<td>∞</td>
<td>na</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>MPR</td>
<td>Broadcast</td>
<td>146</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>MPR</td>
<td>In hole</td>
<td>35</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>TSP</td>
<td>Broadcast</td>
<td>123</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>TSP</td>
<td>In hole</td>
<td>105</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>na</td>
<td>na</td>
<td>44</td>
<td>13</td>
</tr>
</tbody>
</table>

na = Not applicable.

7.1.4 Discussion

The method of P application was important in the high pH Soil S2. This was mainly due to the poor performance of MPR when applied in the planting hole (Table 7.1.3). Apparently, at the high pH of the soil, proton availability was a limiting factor to MPR dissolution and availability. Method of application was not important for TSP. In Soil S3, P application increased yield, which should be expected given its low P status (Chapter 2, Table 2.3). The type of P was important as can be deduced from the significant P * type P effect, TSP being the better source of P compared to MPR (Table 7.1.3). In Soil S2 the significant interaction of P * type P masked the main effect of initial P application. The residual effects of P on maize grain yield were significant in both soils and there were no differences between the types of P or between the two methods of application. The equally good performance of MPR compared with TSP in the second crop (Fig. 7.1.1) could be attributed to increased dissolution of MPR with increase in contact time with the soil (see also Chapter 7.3) and reduced effectiveness of the soluble TSP with time (Bolland et al., 1988b; Rajan et al., 1996). The later should be more important in the low pH Soil S3. Similar results of residual effects of PRs and soluble P
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fertilizers being equally good have been reported by various workers (Bromfield et al., 1981; Chien et al., 1987; Kumar et al., 1992; Kimbi et al., 1996).

To conclude, response to P was low in both soils. TSP performed better than MPR in the first season but their residual effects were almost equally good. The results of this study clearly indicate that the best response to MPR will be obtained at modest rates of application. In the high pH soil (Soil S2), method of application was important particularly for MPR. MPR applied in the planting hole performed poorly suggesting that the ratio of soil to amount of MPR should be large for a good performance of MPR. Maize grain yield per kg of P applied was higher for TSP than for MPR in the low pH soil (Soil S3). In Soil S2, when the two were broadcast maize grain yield per kg of P was almost the same and higher than when applied in the planting hole; response to TSP-P was 3 times more than to MPR-P. The residual effects of MPR and TSP were almost the same for both soils.

7.2 Influence of different sources and amounts of N fertilizers on the effectiveness of Minjingu phosphate rock in the field

Abstract

The influence of different amounts of SA-N and CAN-N on the availability of MPR-P was studied in a field trial at ARI Mlingano during the long and short rains of 1997. The role of SA as an acidifying fertilizer and stimulator of MPR availability could not be confirmed in this study, because MPR was already as available as TSP on the acid Soil S3, and because demand for fertilizer P was weak in the more basic Soil S2. Apart from that the pattern of application did not ensure intimate contact between the particles of the used N and P fertilizers. Responses to N and P were moderate. Both sources of P had significant residual effects on maize grain yield. The results of this study show that there is little scope for improving the effectiveness of MPR by combined application of MPR and sulfate of ammonia.

7.2.1 Introduction

The use of acidifying fertilizers has been shown to improve the effectiveness of PR (Terman et al., 1969; Chien, 1979; Fotyma et al., 1996; Peryea and Burrows, 1999). Sulfate of ammonia apart from supplying the important N and S nutrients, acidifies the soil, hence creating conducive environment for PR dissolution. Further, the supply of important plant nutrients improves crop growth, creating a P concentration gradient through increased P demand. The consequence of this is increase in PR dissolution. To realize the effects of acidifying N fertilizers on PR dissolution, the two fertilizers must be applied at the same place and at the same time to ensure intimate contact with the PR (Rajan et al., 1996). However, this is not the case in the agricultural practice in Tanzania. For example, to obtain the highest effectiveness of N and P fertilizers in maize it is recommended to apply P before planting and N about six weeks after planting. Further, most of the results in literature have been obtained under semi-controlled conditions with rather homogenous soil, while farmers' fields may show large spatial variability in both soil pH and soil P (Chapter 6). Moreover, in most studies relatively large amounts of PR have been applied, whilst our studies have shown that PR performs relatively well when small amounts are applied (Chapters 3, 4, 5, 7.1). It is not for sure that the positive effect of acidifying also hold when small amounts of PR are applied, but is obvious that the above considerations greatly complicate the establishment of straight fertilizer recommendation for N and P.

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The field trials presented in this chapter (7.2) were set up to verify the interaction between N fertilizer type and P fertilizer type under practical conditions in the field. It was hypothesized that application of PR with acidifying fertilizers will extend the use of PR to soils low in proton supply. To test this, a field trial was established at two contrasting sites at ARI Mlingano, with the general objective of studying the influence of two sources of N on the effectiveness of MPR. Triple superphosphate was included as a standard P fertilizer. Specifically the trial aimed at studying the influence of increasing rates of sulfate of ammonia or calcium ammonium nitrate on the effectiveness of MPR, to establish appropriate combinations of N and P sources for optimum crop production and to study the residual effects of MPR and TSP applied once in two seasons.

7.2.2 Materials and Methods

The study was carried out on two soils (S2, a high pH soil and S3, a low pH soil) for two consecutive seasons (Chapter 7.0). A randomized complete block design in a 2 x 2 x 4 x 4 factorial arrangement of treatments was used. Factors were: source of N (levels: CAN and SA) and source of P (levels: MPR and TSP). N and P sources were applied at four rates. N was applied at 0, 20, 40, and 80 kg ha⁻¹ and P at 0, 10, 20, and 40 kg ha⁻¹. Each treatment was replicated two times to make a total of 128 experimental units per site. Minjingu PR (100 mesh) was uniformly broadcast by mixing with a small amount of surface soil taken from the respective plot and the mixture spread uniformly on the plots and worked into the soil. Triple superphosphate was band applied in a furrow at planting about 2.5 cm deep adjacent to the planting hole and then covered by soil. N fertilizers were band applied when maize was six weeks old.

Maize grain yields (13 % moisture content) were analyzed statistically using the statistical program SAS, version 6.12 (SAS Institute Inc., 1997). Linear regression models were used to study the relationship between maize grain yield and P source, rate of P, N source and rate of N. First a full regression model was fitted averaged over the two replicates and allowing for a separate regression model for each of the four groups (MPR/CAN, MPR/SA, TSP/CAN and TSP/SA). The regression model for each group defines quadratic response surfaces with respect to P and N, corrected for blocks and Nearest Neighbor Means (NNM) of the residuals. The full regression model was:

\[ y = \alpha + \beta_i + \gamma * \text{NNM} + \pi_{ij} * P + \pi_{2j} * P^2 + \nu_{ik} * N + \nu_{2k} * N^2 + \lambda_{jk} * P * N + \varepsilon, \]

where \( y \) is observed yield, \( \alpha \) is expected yield if no P or N is applied, \( \beta_i \) is block effect, \( \gamma \) is coefficient for nearest neighbor mean (NNM), \( \pi_{ij} \) is coefficient of P rate of P source j and \( \pi_{2j} \) coefficient of square of P rate of P source j, \( \nu_{ik} \) coefficient of N rate of N source k and \( \nu_{2k} \) coefficient of square of N rate of N source k, and \( \lambda_{jk} \) coefficient of cross product term P*N of P source j and N source k, and \( \varepsilon \) unexplained error. The four regression lines were then tested to see if they are the same. This was followed by reduced regression models where terms which were not significant were dropped. The final model contained only terms that were significant at least in one season (\( P < 0.1 \)). Parameter estimates from the regression models are also given.

7.2.3 Results

There was a statistical significant effect of N and P application at both sites and in both seasons. However, there were no statistical effects of fertilizer type. The four regression lines representing the four combinations of MPR + CAN, MPR + SA, TSP + CAN, and TSP + SA were essentially the same indicating that the types of N and P fertilizers were not significantly different. Maize grain yields, both observed and corrected for NNM (Chapter 6)
are presented in Appendix 6. There was a statistical significant effect of N and P application at both sites and in both seasons. Only in Soil S2 in the first season the performance of MPR was significantly less than that of TSP. Because of the near absence of an effect of N and P fertilizer type in grain yield the data of the four fertilizer combinations have been averaged (Table 7.2.1). The values in that table are thus averages of 8 individual observations (2 reps * 2 * 2). Figure 7.2.1 clearly shows lower yields and stronger response to N in the second season compared to the first season. These differences are likely the result of the very heavy rains in October 1997 (see Table 2.1 and Fig. 2.3 in Chapter 2).

Table 7.2.2 presents the parameter estimates for the influence of the different rates of N (SA or CAN) and P (MPR or TSP) on maize grain yield. They were not exactly the same in the two seasons. The explained variation is low, especially for Soil S2. The coefficient of variation (CV) is higher for Soil S3 than Soil S2. Soil S2 is the better soil showing less response to fertilizers, but a more regular growth than on Soil S3.

In Soil S3 the interaction N * P was significant and positive in both seasons (Table 7.2.2), weakening the probability of the main effects of N and P, especially in the first season. There were also significant negative quadratic effects especially in Soil S3. In all the fields, blocks and NNM were very highly significant again demonstrating the strong influence of variability on yield.

The responses (ΔY) (t ha⁻¹) to fertilizer N and P can be described as follows.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Season</th>
<th>(ΔY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>1</td>
<td>0.012N - 0.106 * 10⁻³ N² + 0.019P - 0.481 * 10⁻³ P² + 0.255 * 10⁻³ NP</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.009N - 0.038 * 10⁻³ N² + 0.026P - 0.595 * 10⁻³ P² + 0.235 * 10⁻³ NP</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>0.007N + 0.018P (-0.346 for MPR)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.027N - 0.176 * 10⁻³ N² + 0.011P (-0.101 for MPR)</td>
</tr>
</tbody>
</table>

The combinations with maximum yield in Soil S3 were calculated by simultaneous solutions of the first derivatives to N and P. The results are shown in Table 7.2.3. In some cases in Soil S2 the relationships were almost linear and hence the calculated rates for maximum yield were high (infinite). Table 7.2.3 shows for Soil S3, stronger responses in the second than in the first season. Taking into account a recovery fraction of 0.5 for fertilizer N and 0.1 for fertilizer P, maize yield responses to N may vary from 0 to 35 kg per kg N applied and those to P from 0 to 60 kg per kg P applied (Janssen et al., 1990). Compared to these data the obtained responses are only moderate.
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Table 7.2.1. Observed and corrected (for NNM) maize grain yields in t ha\(^{-1}\). The individual figures are the average of eight observations: Two replicates * two N fertilizer types * two P fertilizer types. N and P rates are in kg ha\(^{-1}\).

<table>
<thead>
<tr>
<th>Observed yields</th>
<th>Corrected yields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>P</td>
<td>0</td>
</tr>
<tr>
<td>Soil S3, First season</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.12</td>
</tr>
<tr>
<td>10</td>
<td>1.57</td>
</tr>
<tr>
<td>20</td>
<td>1.32</td>
</tr>
<tr>
<td>40</td>
<td>0.98</td>
</tr>
<tr>
<td>Average</td>
<td>1.24</td>
</tr>
<tr>
<td>Response (t)</td>
<td></td>
</tr>
<tr>
<td>Soil S2, First season</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.39</td>
</tr>
<tr>
<td>10</td>
<td>4.84</td>
</tr>
<tr>
<td>20</td>
<td>4.82</td>
</tr>
<tr>
<td>40</td>
<td>5.37</td>
</tr>
<tr>
<td>Average</td>
<td>4.85</td>
</tr>
<tr>
<td>Response (t)</td>
<td></td>
</tr>
</tbody>
</table>

\(t\) Average response averaged over all P rates (Corrected yields only).
Table 7.2.2. Parameters estimates for the influence of different rates of N (SA or CAN) and P (MPR or TSP) on maize grain yield. CV stand for coefficient of variation and is in %, $aR^2$ stands for adjusted $R^2$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Parameter estimate</th>
<th>Standard error (±)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil S3, First season</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>1.296</td>
<td>0.143</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>0.339</td>
<td>0.050</td>
<td>0.0001</td>
</tr>
<tr>
<td>NNM</td>
<td>0.733</td>
<td>0.171</td>
<td>0.0001</td>
</tr>
<tr>
<td>N</td>
<td>0.012</td>
<td>0.006</td>
<td>0.0649</td>
</tr>
<tr>
<td>N$^2$</td>
<td>-0.106 * 10$^{-3}$</td>
<td>0.070 * 10$^{-3}$</td>
<td>0.1324</td>
</tr>
<tr>
<td>P</td>
<td>0.019</td>
<td>0.013</td>
<td>0.1303</td>
</tr>
<tr>
<td>P$^2$</td>
<td>-0.481 * 10$^{-3}$</td>
<td>0.279 * 10$^{-3}$</td>
<td>0.0874</td>
</tr>
<tr>
<td>N * P</td>
<td>0.255 * 10$^{-3}$</td>
<td>0.113 * 10$^{-3}$</td>
<td>0.0264</td>
</tr>
<tr>
<td>CV (%) = 33.2, $aR^2$ = 0.45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S3: Second season</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.313</td>
<td>0.104</td>
<td>0.0033</td>
</tr>
<tr>
<td>Replication</td>
<td>0.126</td>
<td>0.036</td>
<td>0.0007</td>
</tr>
<tr>
<td>NNM</td>
<td>0.659</td>
<td>0.203</td>
<td>0.0016</td>
</tr>
<tr>
<td>N</td>
<td>0.009</td>
<td>0.005</td>
<td>0.0546</td>
</tr>
<tr>
<td>N$^2$</td>
<td>-0.038 * 10$^{-3}$</td>
<td>0.051 * 10$^{-3}$</td>
<td>0.4535</td>
</tr>
<tr>
<td>P</td>
<td>0.026</td>
<td>0.009</td>
<td>0.0070</td>
</tr>
<tr>
<td>P$^2$</td>
<td>-0.595 * 10$^{-3}$</td>
<td>0.204 * 10$^{-3}$</td>
<td>0.0042</td>
</tr>
<tr>
<td>N * P</td>
<td>0.235 * 10$^{-3}$</td>
<td>0.083 * 10$^{-3}$</td>
<td>0.0053</td>
</tr>
<tr>
<td>CV (%) = 50.6, $aR^2$ = 0.47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S2: First season</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>4.764</td>
<td>0.204</td>
<td>0.0001</td>
</tr>
<tr>
<td>NNM</td>
<td>0.653</td>
<td>0.161</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR</td>
<td>-0.346</td>
<td>0.186</td>
<td>0.0655</td>
</tr>
<tr>
<td>N</td>
<td>0.007</td>
<td>0.003</td>
<td>0.0346</td>
</tr>
<tr>
<td>P</td>
<td>0.018</td>
<td>0.006</td>
<td>0.0046</td>
</tr>
<tr>
<td>CV (%) = 20.2, $aR^2$ = 0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S2: Second season</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>2.601</td>
<td>0.141</td>
<td>0.0001</td>
</tr>
<tr>
<td>Replication</td>
<td>0.039</td>
<td>0.061</td>
<td>0.5269</td>
</tr>
<tr>
<td>NNM</td>
<td>0.820</td>
<td>0.139</td>
<td>0.0001</td>
</tr>
<tr>
<td>MPR</td>
<td>-0.101</td>
<td>0.114</td>
<td>0.3751</td>
</tr>
<tr>
<td>N</td>
<td>0.027</td>
<td>0.007</td>
<td>0.0001</td>
</tr>
<tr>
<td>N$^2$</td>
<td>-0.176 * 10$^{-3}$</td>
<td>0.080 * 10$^{-3}$</td>
<td>0.0304</td>
</tr>
<tr>
<td>P</td>
<td>0.011</td>
<td>0.004</td>
<td>0.0051</td>
</tr>
<tr>
<td>CV = 19.2, $aR^2$ = 0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Management options in enhancing Minjingu PR effectiveness

Figure 7.2.1. Average maize yields (corrected for NNM) in relation to N and P application in Soils S3 and S2. The numbers 1 and 2 after S3 and S2 in the legend means first and second seasons respectively.

Table 7.2.3. Fertilizer N and P rates (kg ha\(^{-1}\)) for maximum yield and corresponding average responses to N and P (kg kg\(^{-1}\)).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Season</th>
<th>Rates</th>
<th>Response to</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>S3</td>
<td>1</td>
<td>118</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>477</td>
<td>116</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>77</td>
<td>∞</td>
</tr>
</tbody>
</table>

na = not applicable.

7.2.4 Discussion
The lack of difference between the different types of N or P could be due to the pattern of application of the N and P fertilizers. MPR was broadcast and TSP was band applied at planting. Fertilizers N were applied in a furrow around the plant six weeks after planting. This implies that only a small fraction of MPR could come into intimate contact with the N fertilizers which is a necessary condition for the PR particles to make effective use of the generated acidity (Rajan, 1982). By the time N was applied the soluble P from TSP must have already left the granules (Leenaars-Leijh, 1985; Henstra et al., 1981) and have been changed to adsorbed or precipitated P. Any possible difference between CAN and SA in proton generation cannot show up and certainly not experimentally in fields with such a high variability as encountered in our trials (Chapter 6).

In Soil S3, there was a positive interaction between N and P application. This may be attributed to the promotion in growth due to N application (Fig. 7.2.1). Improvement in growth created an increased P demand, depletion of soil solution around the roots and a stronger concentration gradient. In reaction to this gradient, dissolution and hence the
availability of MPR, and desorption of adsorbed TSP-P were enhanced. In Soil S2 no N * P interaction was found. This may be ascribed to the relatively good growing conditions at this site (pH, extractable P). As a result N application hardly stimulated P demand. It also explains why TSP was a little better than MPR in Soil S2 (Appendix 6). Moreover any possible liming effect of MPR could not be of benefit in this soil, but it could in the more acid Soil S3.

The significant effect of P observed also in the second season indicates a residual effect of P since it was applied only in the first season. Because there was no significant effect of fertilizer type, the residual effects of TSP-P were the same as those of MPR-P.

All in all, there are three major reasons why the effect of MPR on maize yield was equal to that of TSP in Soil S3: (i) easier dissolution in acid soil, (ii) higher P demand and hence stronger concentration gradient and, (iii) liming effect. These reasons may also explain why there was no strong effect of fertilizer N type on the effectiveness of MPR. In Soil S3, the demand for P was relatively high, and the native soil acidity sufficient to dissolve MPR.

To conclude, the role of SA as an acidifying fertilizer and stimulator of MPR availability could not be confirmed in this study. In the acid Soil S3, the demand for H⁺ ions from external sources to dissolve MPR was negligible; MPR was already as available as TSP on this acid soil. In the more productive Soil S2 with higher soil pH, MPR performed only slightly less than TSP. Hence, any positive effect of an acidifying fertilizer like SA on MPR effectiveness can not be established easily. Further, the pattern of application did not ensure intimate contact between particles of the N and P fertilizers. Responses to N and P were moderate. There was significant residual effect of P for both sources of P fertilizers. The implication of these results is that there is little scope for improving the effectiveness of MPR by combined application of MPR and sulfate of ammonia.

7.3 Influence of different application methods of combinations of Minjingu phosphate rock and soluble phosphates

Abstract

The availability of P from combined MPR and TSP either broadcast or applied in the planting hole was tested under field conditions for two seasons at ARI Mlingano with maize as the test crop. Two soils were used; Soil S2 with a high pH and Soil S3 with a low pH. Best performance was obtained when both MPR and TSP were applied by the same method in the low pH soil (Soil S3). In the relatively high pH Soil S2, the method of application was not important in the first season. The residual effect of TSP on maize grain yield was significant in Soil S3 when TSP was applied in the planting hole. In Soil S2 this occurred when TSP was broadcast. It was concluded that optimal method of P application and of P fertilizer type depends on the conditions of the soil.
7.3.1 Introduction

The effectiveness of phosphate rock (PR) can be enhanced by combined application of PR and a small amount of soluble P source (Kpomblekou-A et al., 1991; Habib et al., 1999). Then, the soluble P such as triple superphosphate (TSP) ensures an early supply of available P to young plants hence stimulating early root growth. This increases subsequently the plant's ability to search for nutrients. Further, through phosphoric acid released during the hydrolysis of the mono-calcium phosphate (MCP) in TSP, the dissolution of PR can be enhanced. Under such conditions the use of PR can be extended to soils low in proton supply (neutral to slightly acid soils) (Hagin and Katz, 1985). For optimal use of acid production during hydrolysis of MCP the method of application should ensure close contact between the two sources of P.

So far, positive effects of partial acidulation of PR or combined application of PR and TSP have been obtained in experiments with homogenous soils with neutral or near alkaline pH. It is not clear whether the positive interaction between PR and TSP also holds when the spatial variability of soil pH and available soil P is high as in many practical fields. Further, we have shown previously (Chapter 5) that PR performs best and almost as good as TSP when small amounts are applied to slightly acidic soils. When large amounts of PR are applied, the availability of P is low.

The present study focuses on the possible interaction between type of fertilizer and method of P application. Small amounts of P were applied as PR and TSP either broadcast or applied in the planting hole. It was hypothesized that PR performs best when broadcast and TSP when applied in the planting hole. The performance of combination of the P fertilizer and application method will depend on local soil conditions. The different combinations of methods of application of MPR and TSP were studied in the field at two contrasting soils (Soil S2 of high pH and Soil S3 of low pH) at ARI Mlingano. The general objective was to study the effectiveness of different application methods of MPR and soluble P combinations. Specifically the experiment aimed at studying the effects of combining MPR with TSP on P availability under different soil conditions and to establish appropriate methods of application of combined MPR and TSP. Results from this study will be used in formulating appropriate methods of application of combined MPR and TSP for recommendation to farmers.

7.3.2 Materials and Methods

For both soils S2 and S3, the experimental design was a complete randomized block in a 2 x 2 factorial arrangement of treatments with four replicates. Each plot received MPR and TSP, both at 20 kg P ha\(^{-1}\) to make a total of 40 kg P ha\(^{-1}\). Factors were application method of MPR (broadcast or in hole) and application method of TSP (broadcast or in hole). Where both or either of the P sources were broadcast they were pre-mixed with a small amount of surface soil uniformly taken from the respective plots and the mixture was spread uniformly on the plot then worked into the soil. When both of the P sources were applied in the planting hole the mixing was done right in the hole. Both MPR and TSP were applied in the first season only to allow a study of their residual effects in the second season. When maize was about six weeks old, CAN was applied at the recommended rate of 50 kg N per hectare.

Analysis of variance was done using the general linear model procedure (GLM) of the SAS program, version 6.12 (SAS Institute Inc. 1997) to determine the effects of treatments on maize grain yield. For treatment comparisons, pair-wise t-tests based upon the least square means were used.
7.3.3 Results

Both the observed maize grain yields and the yields corrected for Nearest Neighbor Means (NNM) (Chapter 6) are summarized in Table 7.3.1. The two do not differ markedly, which should be expected given the small size of the trial (Chapter 6). Yields were higher in Soil S2 than in Soil S3. In both soils during the first season the two methods of application of either P source did not differ (Table 7.3.2). However, in the second season the method of TSP application was significant ($P < 0.1$) in both soils. There was a highly significant ($P < 0.05$) method of MPR * method of TSP interaction in Soil S3 in the first season (Table 7.3.2). This indicates that the effect of the method of MPR application was not the same for both methods of TSP application in Soil S3. The yield was highest when both P fertilizers were applied by the same method, that is, either both are broadcast or put in the planting hole. There was no significant factor effect in the first season in Soil S2.

Table 7.3.3 shows the least square means with standard errors for the significant effects. Maize grain yield in Soil S3 during the first season was significantly higher when both sources of P were either applied in the planting hole or broadcast than when the application method was different for each P source. The lowest yield was from the treatment MPR applied in the planting hole and TSP broadcast (MHTB). In the same soil (Soil S3) during the second season, the residual effect of TSP applied in the planting hole was significantly better than that of TSP broadcast. The situation was just the opposite in Soil S2 where maize grain yield was significantly lower when TSP was applied in the planting hole than when broadcast.

Table 7.3.1. Observed and corrected (for NNM) maize grain yield (average of four replicates), t ha$^{-1}$. M, T, B and H stand for MPR, TSP, broadcast and application in hole respectively.

<table>
<thead>
<tr>
<th>Observed yields</th>
<th>Corrected yields</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil S3, First season</strong></td>
<td><strong>Soil S3, Second season</strong></td>
</tr>
<tr>
<td>Method M</td>
<td>Method T</td>
</tr>
<tr>
<td>MB</td>
<td>TB 4.02</td>
</tr>
<tr>
<td>MH</td>
<td>TB 3.30</td>
</tr>
<tr>
<td>Average</td>
<td>TB 3.66</td>
</tr>
<tr>
<td><strong>Soil S2, First season</strong></td>
<td><strong>Soil S2, Second season</strong></td>
</tr>
<tr>
<td>MB</td>
<td>TB 6.20</td>
</tr>
<tr>
<td>MH</td>
<td>TB 5.91</td>
</tr>
<tr>
<td>Average</td>
<td>TB 6.06</td>
</tr>
<tr>
<td><strong>Soil S3, Second season</strong></td>
<td><strong>Soil S3, Second season</strong></td>
</tr>
<tr>
<td>MB</td>
<td>TB 3.66</td>
</tr>
<tr>
<td>MH</td>
<td>TB 3.88</td>
</tr>
<tr>
<td>Average</td>
<td>TB 3.77</td>
</tr>
</tbody>
</table>
Table 7.3.2. ANOVA table for the influence of different combinations of methods of MPR and TSP application on maize grain yield.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil S3, First season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>0.373</td>
<td>0.373</td>
<td>2.537</td>
<td>0.1397</td>
</tr>
<tr>
<td>Method MPR (MM)</td>
<td>1</td>
<td>0.018</td>
<td>0.018</td>
<td>0.122</td>
<td>0.7360</td>
</tr>
<tr>
<td>Method TSP (MT)</td>
<td>1</td>
<td>0.050</td>
<td>0.050</td>
<td>0.340</td>
<td>0.5703</td>
</tr>
<tr>
<td>MM * MT</td>
<td>1</td>
<td>2.011</td>
<td>2.011</td>
<td>13.680</td>
<td>0.0035</td>
</tr>
<tr>
<td>Error</td>
<td>11</td>
<td>1.620</td>
<td>0.147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>3.866</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 10.2, R^2 = 0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil S2, Season 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>0.142</td>
<td>0.142</td>
<td>0.377</td>
<td>0.5518</td>
</tr>
<tr>
<td>Method MPR (MM)</td>
<td>1</td>
<td>0.163</td>
<td>0.163</td>
<td>0.432</td>
<td>0.5239</td>
</tr>
<tr>
<td>Method TSP (MT)</td>
<td>1</td>
<td>1.395</td>
<td>1.395</td>
<td>3.700</td>
<td>0.0805</td>
</tr>
<tr>
<td>MM * MT</td>
<td>1</td>
<td>0.799</td>
<td>0.799</td>
<td>2.119</td>
<td>0.1731</td>
</tr>
<tr>
<td>Error</td>
<td>11</td>
<td>4.143</td>
<td>0.377</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>6.521</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 27.4, R^2 = 0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil S2, Season 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>0.186</td>
<td>0.186</td>
<td>0.271</td>
<td>0.6130</td>
</tr>
<tr>
<td>Method MPR (MM)</td>
<td>1</td>
<td>0.049</td>
<td>0.049</td>
<td>0.071</td>
<td>0.7941</td>
</tr>
<tr>
<td>Method TSP (MT)</td>
<td>1</td>
<td>1.436</td>
<td>1.436</td>
<td>2.093</td>
<td>0.1760</td>
</tr>
<tr>
<td>MM * MT</td>
<td>1</td>
<td>0.038</td>
<td>0.038</td>
<td>0.055</td>
<td>0.8173</td>
</tr>
<tr>
<td>Error</td>
<td>11</td>
<td>7.549</td>
<td>0.686</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>9.571</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 14.5, R^2 = 0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil S2, Season 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>1.511</td>
<td>1.511</td>
<td>7.371</td>
<td>0.0200</td>
</tr>
<tr>
<td>Method MPR (MM)</td>
<td>1</td>
<td>0.179</td>
<td>0.179</td>
<td>0.873</td>
<td>0.3703</td>
</tr>
<tr>
<td>Method TSP (MT)</td>
<td>1</td>
<td>0.696</td>
<td>0.696</td>
<td>3.395</td>
<td>0.0921</td>
</tr>
<tr>
<td>MM * MT</td>
<td>1</td>
<td>0.013</td>
<td>0.013</td>
<td>0.063</td>
<td>0.8028</td>
</tr>
<tr>
<td>Error</td>
<td>11</td>
<td>2.250</td>
<td>0.205</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>4.304</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%) = 12.4, R^2 = 0.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.3.3. Least square means for effects of method of application of combinations of MPR and TSP on maize grain yield. M, T, B and H stand for MPR, TSP, broadcast and application in hole respectively. LS stand for Least square.

<table>
<thead>
<tr>
<th>Soil S3, First season</th>
<th>Method M</th>
<th>Method T</th>
<th>LS Mean</th>
<th>S.E. (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>B</td>
<td></td>
<td>4.10a</td>
<td>0.20</td>
</tr>
<tr>
<td>B</td>
<td>H</td>
<td></td>
<td>3.48b</td>
<td>0.20</td>
</tr>
<tr>
<td>H</td>
<td>B</td>
<td></td>
<td>3.30b</td>
<td>0.19</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td></td>
<td>4.15a</td>
<td>0.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S3, Second season</th>
<th>Method M</th>
<th>LS Mean</th>
<th>S.E.</th>
<th>Method T</th>
<th>LS Mean</th>
<th>S.E.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td>2.14a</td>
<td>0.22</td>
<td>B</td>
<td>1.94b</td>
<td>0.22</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>2.34a</td>
<td>0.22</td>
<td>H</td>
<td>2.54a</td>
<td>0.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S2, First season</th>
<th>B</th>
<th>5.79a</th>
<th>0.29</th>
<th>B</th>
<th>6.03a</th>
<th>0.29</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>5.68a</td>
<td>0.29</td>
<td>H</td>
<td>5.43a</td>
<td>0.29</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil S2, Second season</th>
<th>B</th>
<th>3.54a</th>
<th>0.16</th>
<th>B</th>
<th>3.87a</th>
<th>0.16</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>3.76a</td>
<td>0.16</td>
<td>H</td>
<td>3.43b</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (P > 0.01) according to pairwise t tests.

7.3.4 Discussion

The better performance when both P sources were applied by the same method in the first season in Soil S3 (Table 7.3.3) is attributed to a closer contact between particles of MPR and TSP being ensured. This closer contact is absent when the application methods of either P source are different and hence the influence of TSP on MPR is minimal. Close contact may promote MPR dissolution by the phosphoric acid released during hydrolysis of monocalcium phosphate in TSP. In Soil S3 the best yield was obtained when the two were applied in the planting hole. There is an indication of possible TSP-P fixation in this low pH soil because lower yields were associated with TSP broadcast (Table 7.3.3). By broadcasting, TSP granules had greater contact with soil particles and a smaller chance to be ‘seen’ by the roots and a higher chance of fixation. This was different in Soil S2 whose pH is relatively high. In view of results in other trials (Chapters 7.1, 7.2 and 7.4) in Soil S2, it is likely that in none of the four treatments there was a big response to P application. In this soil, TSP broadcast was a little better than when applied in the planting hole in the second season, but given the probability value of 9% (Table 7.3.2) it is uncertain whether the effect was really reliable. Nevertheless, it may be concluded that there is no need to apply TSP in the planting hole in Soil S2. This recommendation will greatly reduce labor requirements.

In the second season the residual effects of TSP influenced maize grain yield significantly, depending on how it was applied. When applied to soil, TSP changes from soluble to less soluble forms within few days; with about 20% of the P remaining in the residual granule in the form of tricalcium phosphate and other compounds (Leenars-Leijh, 1985).
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The residual granule, which is highly porous, offers conducive physical environment for root hairs development (Henstra et al., 1981) and hence increasing the plant’s ability to extract P from it. When MPR is present it can be utilized given a possible concentration gradient arising from increased P demand due to growth improvement. Because TSP is the one which changes from soluble to less soluble form, its performance is bound to differ depending on how it was earlier applied and on soil conditions. So in Soil S3 where P fixation is likely to occur, the residual effect of TSP was better when TSP had been applied in the planting hole than when it had been broadcast.

In conclusion the best performance was obtained when both MPR and TSP were applied by the same method in the low pH soil (Soil S3). In the higher pH soil (Soil S2) there was no difference between the application methods. In Soil S3 the residual effect was slightly stronger for TSP applied in the planting hole than for TSP broadcast. Hence, the optimal method of P application and P fertilizer type depends on the conditions of the soil, localized application being of interest in low-pH soils only.

7.4 Influence of incubation of Minjingu phosphate rock with farmyard manure

Abstract

In field trials established at ARI Mlingano during the long and short rains of 1997 the influence of incubation of minjingu phosphate rock (MPR) with farmyard manure (FYM) on the effectiveness of the former was studied on a low and a high pH Rhodic Ferralsol. Proton induced dissolution of MPR incubated with FYM for forty days could not take place given the high pH of the mixture. The final pH (H2O) at the end of incubation was 8.35 for FYM incubated with MPR, which is too high for proton-induced dissolution of MPR. Final pH for FYM incubated alone was 8.14. Both FYM and P fertilizers had significant effects on maize grain yield. There was no interaction between MPR and FYM indicating that the two were acting independently. The residual effects of MPR and TSP on maize grain yield were significant in the high pH soil (Soil S2) while the residual effects of farmyard manure were negative on both soils.

7.4.1 Introduction

Studies on the use of organic manure to enhance the effectiveness of phosphate rocks (PRs) have received quite some attention (Purnomo and Black, 1994; Ikerra et al., 1994). Both positive and negative interactions between PRs and organic manure have been observed (Chien et al., 1990; Khanna et al., 1979). It is has been suggested that protons released during microbial and chemical transformation of organic matter could induce PR dissolution. However, the high pH of organic manure (Japenga and Harmsen, 1990; Wong et al., 1998; Wickama and Mowo, 1999) and that of most PRs in Sub-Sahara Africa (Kpomblekou-A and Tabatabai, 1994a) indicate that the amount of PR dissolved by proton from manure will be small. In his review, Oenema (1980) noted that dissolution of PR during the decomposition of organic residues is possible when the soil microbes can lower the pH to 4.5. Lowering the pH of organic manure-PR mixture to that level is unlikely. Consequently, other factors should be responsible for the positive interactions between manure and PRs that have been observed by some workers. These might be complexation of Ca2+ and other metal impurities in the PRs (Kpomblekou-A and Tabatabai, 1994b), enhancement of the Ca buffer capacity of soils given the high CEC of organic manure (Rajan et al., 1996) and increased mobility of dissolved P (Yang et al., 1994). The later increases the possibility of interception of dissolved P by roots as well as ensuring its removal from the area of dissolution thereby promoting PR dissolution. All these possible factors indicate that an
increase in the effectiveness of PR by combined application with manure is highly site specific. A positive interaction might be expected when the crop responds to manure application and when increased P demand cannot be satisfied by soil and manure. Further, when the manure protects the dissolved P from fixation by soil particles, a positive effect of combined application of manure and PR can be expected too. A negative interaction will occur when manure retards the dissolution of PR directly or when the demand for P can be completely satisfied by the manure.

In this study, it was hypothesized that the improvement of growth conditions through supply of nutrients and modification of soil's physical environment by organic manure in poor soils promote plant growth with as a consequence an increase in P demand. This creates a P concentration gradient that might promote PR dissolution according to the law of mass action. Conversely, when soil physical and chemical conditions will not be improved by application of manure, we expect no positive interaction. This was tested in the field at two contrasting sites at ARI Mlingano by using Minjingu phosphate rock (MPR) either incubated with farmyard manure (FYM) or not. The general objective was to establish the role of farmyard manure in enhancing PR effectiveness. Specifically the research aimed at studying the effects of farmyard manure on MPR, to compare MPR incubated and not incubated with farmyard manure, to compare MPR and triple superphosphate (TSP) under similar conditions and to study the residual effects of the two P sources and the farmyard manure. Results from this study will assist in formulating appropriate recommendations for use by farmers in Tanzania and elsewhere where the two resources are available.

7.4.2 Materials and Methods

The study was carried out at two sites (S2 = Soil S2 of high pH and S3 = Soil S3 of low pH) for two consecutive seasons (see Chapter 7.0). Phosphate rock, TSP and FYM were applied only once in the first season to allow studies on their residual effects. The experimental design was a randomized complete block with nine treatments each replicated four times to make a total of 36 plots per site. The treatments formed a $3^2$ factorial with factors type of P (levels: no P, MPR (100 mesh) and TSP) and type of FYM (levels: no FYM, fresh FYM (applied to soil as a fresh mixture) and incubated FYM (incubated before application). The rate of FYM was 5 t ha$^{-1}$ while that of P was 46.5 kg P ha$^{-1}$. The amount of MPR or TSP to mix with the FYM took into consideration the P content of the FYM (Table 7.4.1). All plots received 50 kg N ha$^{-1}$ as calcium ammonium nitrate, the recommended rate for maize in these areas (Mowo et al., 1993). For plots that received FYM the N content in the FYM (Table 7.4.1) was taken into consideration in arriving at amounts of calcium ammonium nitrate to apply.

| Table 7.4.1. Some chemical properties of the farmyard manure used in the trial (oven dry basis). |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| PH (1:5) | Total (g kg$^{-1}$) |
| H$_2$O | KCl | N | P | K | Ca |
| 8.30 | 7.50 | 12.5 | 2.7 | 8.5 | 5.5 |

Incubation

FYM was obtained from livestock keepers at ARI Mlingano. Incubation of the FYM or FYM and MPR mixture was done in two separate pits. Each pit measured 3.0 m in length, 1.0 m in width and 1.0 m in depth. To avoid contact with the soil a polyethylene sheet was placed at the
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bottom and the sides of the pits. To allow mixing and turning over of the materials from time to time each pit was divided into two portions. Where FYM was incubated with MPR, the latter was divided into 5 equal portions and each portion spread evenly over a layer of FYM at 10 cm thick intervals. Using a fork and a spade the two were thoroughly mixed, with simultaneous additions of rainwater (based on the field capacity of the FYM) to ensure uniform wetting. Where FYM was incubated alone the required amount was introduced to the second pit and thoroughly mixed following the same procedure as for the first pit. The pits were then covered. The field capacity of the mixture was maintained by adding rainwater at intervals of three days. Turning over of the materials was done every five days. This was done by in situ mixing the materials and simultaneously placing the mixture on the other half of the pit. Subsequent turnings followed the same procedure by returning the materials to the former location. Incubation extended for a period of 40 days from 17/02/1997 to 28/03/1997. Since TSP does not need to be solubilized it was not incubated with FYM. During the incubation period the mixtures were sampled four times for pH determination.

Treatments application

Where MPR was broadcast, it was pre-mixed with a small amount of surface soil taken uniformly from the respective plot and the mixture evenly spread over the plot and worked into the soil. This ensured uniform application as well as minimized the unpleasant dusty nature of the PR. When TSP was applied alone it was band applied in a furrow adjacent to the planting holes immediately after maize was planted. FYM alone or incubated with MPR was applied in the planting hole. Mixing of MPR or TSP with fresh FYM and TSP with incubated FYM was also done at the time of application. Calcium ammonium nitrate was applied six weeks after planting.

Analysis of variance was done using the general linear model procedure (GLM) of the SAS program, version 6.12 (SAS Institute Inc. 1997) to determine the effects of treatments on maize grain yield. For treatment comparisons pairwise t-tests based upon the least square means were used.

7.4.3 Results

The pH values of the FYM and MPR were respectively 8.30 and 8.90 (Table 7.4.2). First measurement of the pH was done after six days of incubation. Between day 6 and day 40, when incubation was stopped, the pH drop was negligible; 0.08 pH units in FYM and 0.27 in FYM + MPR mixture. At the end of the incubation period the pH was 8.14 for FYM alone and 8.35 for the FYM + MPR mixture.

Table 7.4.2. Changes in pH with incubation time for FYM and FYM mixed with MPR.

<table>
<thead>
<tr>
<th>Incubation time (days)</th>
<th>FYM</th>
<th>FYM + MPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8.22</td>
<td>8.62</td>
</tr>
<tr>
<td>16</td>
<td>8.20</td>
<td>8.50</td>
</tr>
<tr>
<td>30</td>
<td>8.16</td>
<td>8.36</td>
</tr>
<tr>
<td>40</td>
<td>8.14</td>
<td>8.35</td>
</tr>
</tbody>
</table>

pH of FYM and MPR before incubation was 8.30 and 8.90 respectively.

Visual observation of plant growth showed that germination on plots treated with fresh FYM alone or in combination with MPR or TSP was relatively poor compared to plots that received incubated FYM. This could have been due to the high temperatures associated with decomposing fresh FYM or with NH₃ and NO₂ toxicity.

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Maize grain yield is shown in Table 7.4.3. There are slight differences between actual yields and yields corrected for NNM. In Soil S3 in the first season the performance of P fertilizer averaged over the FYM treatments indicate that MPR was slightly better than TSP. When the performance of FYM was averaged over the P treatments, incubated FYM seems better than fresh FYM. Similar comparisons in Soil S2 show that TSP was relatively better than MPR while FYM behaved similarly like in Soil S3. In both soils yields from residual TSP were slightly higher than from residual MPR while residual FYM lowered yields compared to the control.

Table 7.4.3. Observed and corrected (for NNM) maize grain yield (average of four replicates), in t ha$^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th>Observed yields</th>
<th>Corrected yields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil S3, First season</td>
<td></td>
</tr>
<tr>
<td>FYM</td>
<td>P Control</td>
<td>MPR</td>
</tr>
<tr>
<td>No FYM</td>
<td>1.40</td>
<td>2.43</td>
</tr>
<tr>
<td>Fresh</td>
<td>2.17</td>
<td>3.10</td>
</tr>
<tr>
<td>Incubated</td>
<td>1.49</td>
<td>3.21</td>
</tr>
<tr>
<td>Average</td>
<td>1.69</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>Soil S3, Second season</td>
<td></td>
</tr>
<tr>
<td>No FYM</td>
<td>1.07</td>
<td>2.05</td>
</tr>
<tr>
<td>Fresh</td>
<td>0.87</td>
<td>0.86</td>
</tr>
<tr>
<td>Incubated</td>
<td>1.02</td>
<td>1.46</td>
</tr>
<tr>
<td>Average</td>
<td>0.99</td>
<td>1.46</td>
</tr>
<tr>
<td></td>
<td>Soil S2, First season</td>
<td></td>
</tr>
<tr>
<td>No FYM</td>
<td>4.90</td>
<td>5.10</td>
</tr>
<tr>
<td>Fresh</td>
<td>4.77</td>
<td>4.50</td>
</tr>
<tr>
<td>Incubated</td>
<td>5.25</td>
<td>5.63</td>
</tr>
<tr>
<td>Average</td>
<td>4.97</td>
<td>5.08</td>
</tr>
<tr>
<td></td>
<td>Soil S2, Second season</td>
<td></td>
</tr>
<tr>
<td>No FYM</td>
<td>3.53</td>
<td>3.91</td>
</tr>
<tr>
<td>Fresh</td>
<td>2.85</td>
<td>3.72</td>
</tr>
<tr>
<td>Incubated</td>
<td>2.89</td>
<td>3.53</td>
</tr>
<tr>
<td>Average</td>
<td>3.06</td>
<td>3.72</td>
</tr>
</tbody>
</table>

There were no significant interactions between fertilizer P and FYM in both soils and seasons (Table 7.4.4). In Soil S3, fertilizer P and FYM had significant effects on maize grain yield during the first season ($P < 0.01$ and $P < 0.05$ respectively). There was no difference between MPR and TSP and between fresh and incubated FYM during the first season in this soil (Table 7.4.5). In the second season however, yields due to residual FYM were significantly lower ($P < 0.01$) than control yields and yields coming from residual fresh FYM were significantly lower than those from incubated FYM. There were no significant residual P effects from MPR and TSP. In Soil S2 there were no significant effects of P or FYM on maize grain yields in the first season (Tables 7.4.4 and 7.4.5). In the second season the residual effect of P and FYM were significant ($P < 0.05$). Residual P increased maize grain yield while residual FYM resulted in a drop in maize grain yield compared to the control. The
differences between MPR and TSP and between fresh and incubated FYM were however, not significant.

Table 7.4.4. ANOVA table for the effects of fresh or incubated FYM, MPR incubated or applied with fresh FYM and TSP applied with incubated or fresh FYM, on maize grain yield.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil S3, First season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNM</td>
<td>1</td>
<td>0.479</td>
<td>0.479</td>
<td>0.712</td>
<td>0.4066</td>
</tr>
<tr>
<td>Fertilizer P</td>
<td>2</td>
<td>7.209</td>
<td>3.604</td>
<td>5.355</td>
<td>0.0113</td>
</tr>
<tr>
<td>FYM (F)</td>
<td>2</td>
<td>4.333</td>
<td>2.167</td>
<td>3.220</td>
<td>0.0563</td>
</tr>
<tr>
<td>P * F</td>
<td>4</td>
<td>2.473</td>
<td>0.618</td>
<td>0.918</td>
<td>0.4681</td>
</tr>
<tr>
<td>Error</td>
<td>26</td>
<td>17.499</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td>35.897</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (%)</td>
<td>33.6, R² = 0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Soil S3, Second season|                    |                |             |         |             |
| NNM                  | 1                  | 3.516          | 3.516       | 19.109  | 0.0002      |
| Fertilizer P         | 2                  | 0.513          | 0.256       | 1.391   | 0.2665      |
| FYM (F)              | 2                  | 3.557          | 1.779       | 9.668   | 0.0007      |
| P * F                | 4                  | 1.082          | 0.271       | 1.473   | 0.2402      |
| Error                | 26                 | 4.788          | 0.184       |         |             |
| Total                | 35                 | 14.533         |             |         |             |
| CV (%)               | 32.6, R² = 0.67    |                |             |         |             |

| Soil S2, First season|                    |                |             |         |             |
| NNM                  | 1                  | 0.573          | 0.573       | 0.876   | 0.3577      |
| Fertilizer P         | 2                  | 2.846          | 1.423       | 2.176   | 0.1337      |
| FYM (F)              | 2                  | 0.480          | 0.240       | 0.367   | 0.6962      |
| P * F                | 4                  | 0.379          | 0.095       | 0.145   | 0.9636      |
| Error                | 26                 | 16.999         | 0.654       |         |             |
| Total                | 35                 | 20.412         |             |         |             |
| CV (%)               | 15.6, R² = 0.17    |                |             |         |             |

| Soil S2, Second season|                    |                |             |         |             |
| NNM                  | 1                  | 1.107          | 1.107       | 5.766   | 0.0237      |
| Fertilizer P         | 2                  | 1.398          | 0.699       | 3.641   | 0.0403      |
| FYM (F)              | 2                  | 2.468          | 1.234       | 6.427   | 0.0054      |
| P * F                | 4                  | 1.066          | 0.266       | 1.385   | 0.2651      |
| Error                | 26                 | 4.988          | 0.192       |         |             |
| Total                | 35                 | 13.303         |             |         |             |
| CV (%)               | 12.4, R² = 0.63    |                |             |         |             |
Table 7.4.5. Least squares means for the effects of fresh or incubated FYM, MPR incubated or applied with fresh FYM and TSP applied with incubated or fresh FYM, on maize grain yield.

<table>
<thead>
<tr>
<th>Factor</th>
<th>LS Mean</th>
<th>S.E. (±)</th>
<th>Factor</th>
<th>LS Mean</th>
<th>S.E. (±)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil S3, First season</td>
<td>Type of P</td>
<td></td>
<td>Type FYM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>1.76b</td>
<td>0.25</td>
<td>Control</td>
<td>1.96b</td>
<td>0.24</td>
</tr>
<tr>
<td>MPR</td>
<td>2.89a</td>
<td>0.24</td>
<td>Fresh FYM</td>
<td>2.62a</td>
<td>0.24</td>
</tr>
<tr>
<td>TSP</td>
<td>2.68a</td>
<td>0.24</td>
<td>Incubated FYM</td>
<td>2.75a</td>
<td>0.24</td>
</tr>
<tr>
<td>Soil S3, Second season</td>
<td>Type P</td>
<td></td>
<td>Type FYM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>1.16a</td>
<td>0.13</td>
<td>Control</td>
<td>1.69a</td>
<td>0.12</td>
</tr>
<tr>
<td>MPR</td>
<td>1.46a</td>
<td>0.12</td>
<td>Fresh FYM</td>
<td>0.92c</td>
<td>0.12</td>
</tr>
<tr>
<td>TSP</td>
<td>1.33a</td>
<td>0.13</td>
<td>Incubated FYM</td>
<td>1.34b</td>
<td>0.12</td>
</tr>
<tr>
<td>Soil S2, First season</td>
<td>Type of P</td>
<td></td>
<td>Type FYM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>4.88a</td>
<td>0.25</td>
<td>Control</td>
<td>5.16a</td>
<td>0.23</td>
</tr>
<tr>
<td>MPR</td>
<td>5.09a</td>
<td>0.24</td>
<td>Fresh FYM</td>
<td>5.03a</td>
<td>0.25</td>
</tr>
<tr>
<td>TSP</td>
<td>5.59b</td>
<td>0.24</td>
<td>Incubated FYM</td>
<td>5.37a</td>
<td>0.26</td>
</tr>
<tr>
<td>Soil S2, Second season</td>
<td>Type of P</td>
<td></td>
<td>Type FYM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>3.20b</td>
<td>0.14</td>
<td>Control</td>
<td>3.88b</td>
<td>0.13</td>
</tr>
<tr>
<td>MPR</td>
<td>3.70b</td>
<td>0.13</td>
<td>Fresh FYM</td>
<td>3.40b</td>
<td>0.13</td>
</tr>
<tr>
<td>TSP</td>
<td>3.65b</td>
<td>0.14</td>
<td>Incubated FYM</td>
<td>3.27b</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (P < 0.10) according to pairwise t-tests.

7.4.4 Discussion

The pHs of FYM and MPR are that high (8.30 and 8.90 respectively) that both materials have high affinity for protons (Wong, et al., 1998; Chapter 3). When FYM was incubated either alone or with MPR the drop in pH with increasing incubation period was negligible. The pH of the MPR + FYM mixture was slightly higher at the end of incubation than that of FYM incubated alone which is due to the higher pH of the MPR. So whatever protons might have been produced by the decomposing FYM, the proton demanding MPR neutralized them. It can therefore be said that forty days of incubation had no influence on the dissolution of P in the MPR and that CaCO₃ (Chapter 3) consumed the few protons that were produced. Although a longer incubation period could have lowered the pH further, it would be difficult to have it lowered to levels conducive for effective dissolution of the PR (pH around 4.5, Oenema, 1980).

In the first season in both soils yields averaged over FYM treatments were higher than control yields where P was not applied. Similarly, when the yields were averaged over P they were also high. Therefore both fertilizer P and FYM increased yields. The effect in the poorer Soil S3 was significant compared to the effect on the relatively better Soil S2 in the first season. The lack of response to MPR in Soil S2 in the first season is due to the relatively high pH and available P compared to Soil S3. In this soil (Soil S2), TSP was better than MPR (P > 0.06) because of the relatively favorable pH condition. Similar results were obtained in Trials 7.1 and 7.2 (Chapters 7.1 and 7.2 respectively) where the performance of MPR in the high pH
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Soil S2 was poor compared to that of TSP. In the second season, the residual effects of P were significant in Soil S2 but not in Soil S3. This is slightly different from Trials 7.1 and 7.2 (Chapters 7.1 and 7.2 respectively) where significant residual effects of P were observed in both soils.

In conclusion combined application of farmyard manure and MPR did not increase the effectiveness of MPR. Even in the poor Soil S3, there was no positive interaction. Proton induced dissolution of MPR due to incubation with farmyard manure could not take place because of the high pH of the mixture. The final pH at the end of incubation was 8.35 for FYM incubated with MPR and 8.14 for FYM incubated alone which is too high for any dissolution of P from MPR to take place. Both FYM and P fertilizers had significant effects on maize grain yield. The residual effects of MPR and TSP were positively significant in the high pH Soil S2 while the residual effects of FYM were negative on both soils.
8 General discussion

This chapter discusses the relevance of the results reported in this thesis in line with the objectives outlined in Chapter 1. Summarizing, the main objectives of the study were: (i) to increase the understanding of the factors responsible for PR dissolution in soils and availability of PR to crops, (ii) to investigate the possibility of extending the use of PR in soils less favourable for PR dissolution, and (iii) to study the influence of spatial soil variability on the effectiveness of PR.

Factors responsible for PR dissolution refer to the quality of the fertilizer itself, to crop characteristics, to soil properties, and to management. These factors are discussed, and the chapter concludes by looking into the relevance of the study to agricultural development in Tanzania and suggestion for further research.

Importance of the quality of phosphate rock

Minjingu PR like all PRs is poorly soluble. It requires substantial amounts of protons to release sufficient P for plant uptake. In our study CaCO₃ content was an important factor determining the differences between the PRs tested (Chapter 3). Readily soluble CaCO₃ present in the PRs as impurity dissolves before the inner shells containing calcium phosphate are accessed. Consequently, the higher the CaCO₃ content the less reactive the PR.

Generally, the importance of CaCO₃ content present as impurities is not explicitly considered when assessing the effectiveness of PRs. Under limited proton supply (low HCl concentration) differences in the dissolution of the PRs manifested most. Then, few if any protons will be left to access the inner Ca₃(PO₄)₂ shells as most of them would have been consumed by CaCO₃. During the dissolution Ca is released into the system, which also depress the dissolution process. Although Mali PR was ‘soft’ compared to Minjingu and Khouribga PRs their agronomic performance under conditions of limited protons was not different (Chapter 3). All of them had a substitution value of 0.1. This observation is in agreement with the observation by Khasawneh and Doll (1978) that laboratory testing of PR effectiveness does not necessarily give a correct assessment of a PR’s agronomic effectiveness. The interaction of soil and plants influence the various PRs differently. As a result, a reactive PR in the laboratory is not necessarily an effective PR agronomically.

The results of our study clearly indicate that increasing the rate of PR application decreases its dissolution and hence its agronomic effectiveness (Chapters 3, 4 and 5). This is an important conclusion in our study. In many studies dealing with the effectiveness of PRs, relatively large amounts of PR have been applied relative to the reference fertilizer TSP, to compensate for the low reactivity of PRs. In such cases, the focus was more on the residual effects than on the immediate availability of P from PRs. Results of our study clearly indicate that the effectiveness of PR during the first season is low when the application rate of PR was relatively high.

In Chapters 3 and 4 applied rates were based on expected P recovery. Recovery of P from the ‘soft’ Mali PR was considered higher than from the hard Minjingu and Khouribga PRs. To compensate for the low recovery higher rates were applied with Minjingu and Khouribga than with Mali PR. With the high rates, we also increased the application of CaCO₃ associated with the PR. So instead of a compensatory effect high rates of Minjingu and Khouribga PRs suppressed their dissolution and hence their agronomic effectiveness. This was not observed with Mali PR. These results clearly point to the need to balance PR application rates with proton supply potential. Our results are similar to those by Kanabo and Gilkes (1988); Bolland and
Barrow (1988); Rajan et al. (1991) and Brenes and Bornemisza (1992) who observed decreased performance of PRs at high rates. Working with Minjingu PR Semoka et al. (1992) reported decreasing effectiveness at high application rates but they were not sure of the reason behind this decrease which according to our findings, should be the high CaCC>3 content associated with the high application rates of the PR.

**Importance of crop characteristics**

Leguminous plants are known for their pH lowering effect which has been reported to be proportional with dry-matter production (Beusichem 1984). On the other hand cereals tend to increase the pH in the rhizosphere. In Chapter 4.1, this was studied for cowpea, pigeonpea and maize. Although dry-matter yield increased with plant density there was no appreciable change in soil pH. This we attributed to the pH buffer capacity of the soils and to the fact that the total number of nodules per pot was hardly affected by plant density, which may indicate that also biological N fixation and proton production were hardly affected by plant density. Although pH was measured immediately after harvest, the possibility that produced protons by the legumes could have been neutralized by soil constituents is high. Hence an in-situ monitoring of pH in the rhizosphere would have been a better option to measure soil pH changes. This is however, difficult to implement. We hypothesized that if a PR particle is within the rhizosphere it could be solubilized and that a crop not efficient in utilizing PR can benefit in terms of P nutrition when intercropped with the legume. This was studied in Chapter 4.2 by intercropping maize with cowpea or pigeonpea. Our results show that the legumes were capable of utilizing MPR-P better than maize and they did improve the uptake of MPR-P by maize. These results agree with the observations of Arihara et al. (1991) and Hoshikawa (1991) who noted that when legumes form part of the cropping system they improve the soil available P pool.

From the results discussed above it is clear that the availability of protons is central in the dissolution of PRs, that high rates of PR suppress their dissolution, that cowpea and pigeonpea were capable of taking up more MPR-P than maize and that maize P uptake from MPR was improved in the presence of these legumes. Increasing P and Ca demand will increase PR dissolution. Therefore, acidifying plants and improved growth conditions enable PR use in soils with limited proton supply.

The optimum rate of PR to apply depends on the growth vigor of the plant and its ability to acidify its rhizosphere. Prompted with this line of thought an experiment was established (Chapter 5.1) to look into the response curves of maize, cowpea and pigeonpea. Our results suggest that response to MPR was better than to TSP in low pH soils. This was attributed to rapid dissolution of MPR and the beneficial liming effect of MPR in the low pH soil. In contrast, TSP performed better than MPR in the high pH soil. These results agree with those of Mnkeni et al. (1991) who could not find significant response to MPR on soils high in pH and available P. Our results suggest an optimum MPR-P rate for maize on the test soils of between 31 and 62 mg P per kg of soil. TSP did not show a clear optimum with maize while both P sources did not show a clear optimum with cowpea. Maize and cowpea took up more P than could be utilized for dry-mtter production which might be due to the presence of other growth factors. There was a significant main effect of soil and its interaction with type of P and rate of P in the legumes but not with maize suggesting a possible modification of rhizosphere conditions by the legumes.

**Importance of soil properties and extending the use of PR to less favorable soils**

The consequence of our results is that the range of soils where PR can be used can be extended to include soils not so low in pH. This is possible by adjusting the application rate and employing mechanisms to lower soil pH. Interactions between soil pH and soil available P in
responses to added MPR and TSP were studied in Chapter 5.2 using nine different soils. Our results show that response to P in terms of dry-matter production occurred in soils with low available P and that response to MPR was lower than to TSP on average. The narrow difference in response to P uptake between MPR and TSP at low soil pH was attributed to the higher solubility of MPR at low than at high pH (Chapter 3; Admont et al., 1986; Bolland and Gilkes, 1998) making it more effective as P source. Our results show a possible liming effect by MPR because utilization of absorbed P was better from MPR than from TSP in low pH soils. These results are in agreement with those of Semoka (1989) who reported relatively better performance of Minjingu PR compared to TSP in acid soils. We found a parabola like curve relationship between shoot P content and pH in line with the general pattern of P availability, whereby at low and high soil pH availability of P drops while it is optimum at near neutral pH. The optimum P uptake was at pH (H$_2$O) = 5.7 which is close to results in Kenya by Janssen et al. (1990) and Janssen and Van der Eijk, (1990) where optimum pH (H$_2$O) was 6.0.

Management options for improving MPR effectiveness under field conditions

Our results on method and rate of P application in low pH soils (Chapter 7.1) show that maize grain yield responded better to TSP than to MPR, initially. However, the differences diminished in the second season, which is in agreement with the results of Bromfield et al. (1981) who observed superior performance of single superphosphate compared to Minjingu PR in the first season followed by diminishing difference in subsequent seasons. The improvement of MPR performance with time relative to TSP can be attributed to increased dissolution of MPR with increase in contact time with soil and a concomitant decrease in the effectiveness of TSP with time (Bolland et al., 1988a; Rajan et al., 1996). Similar results have also been reported by Kamasho and Mindasi, 1988; Kumar et al., 1992; Kimbi et al., 1996). Our results suggest that at high soil pH, the method of application was more important to MPR than to TSP. Given the low supply of protons at high soil pH, application of MPR in the planting hole depresses its dissolution due to reduced surface area of contact with the soil. Greater surface area of contact with the soil ensures more supply of protons and more removal of dissolution products, factors which promote PR dissolution.

We could not confirm the role of fertilizer sulfate of ammonia in promoting the dissolution of MPR through acidification (Chapter 7.2). This was probably due to the way the fertilizers were applied, P at planting and N six weeks after planting, as recommended usually. This did not ensure intimate contact between both fertilizer particles. In a similar study, Rajan (1983) could not observe any effect of elemental sulfur when it was applied with PR without mixing. Evidently, for improving the effectiveness of MPR, the fertilizer sulfate of ammonia should be applied concomitant with MPR before planting. For obtaining a high efficiency of the N fertilizer, application should be postponed to about 6 weeks after emergence of the maize, when the demand of N by the crop increases and no longer can be met by the soil itself. Application of the N fertilizer at planting time may lead to high losses, especially in wet seasons. In practice therefore, there is little scope for improving the effectiveness of MPR by combined application of MPR and sulfate of ammonia.

The poor solubility of MPR means that it often cannot meet the P demands of a crop during the early growth stages. Mixing PR with soluble P sources could overcome this. This was tested for MPR and TSP in Chapter 7.3. Our results suggest that better performance is obtained when both P sources are applied by the same method. Apart from meeting early P requirement, phosphoric acid released during the hydrolysis of the monocalcium phosphate in TSP may promote PR dissolution (Hagin and Katz, 1985). This requires intimate contact between particles of both fertilizers, a condition which can be met when they are applied by the same method. Our results
are in agreement with those of Ngatunga et al. (1988) who reported a clear positive effect when MPR was mixed with TSP. A positive interaction between MPR and TSP application was most evident in the low pH and P poor Soil S3. The results indicate that broadcasting MPR and TSP is as effective as placing MPR and TSP near the planting hole. This is an important result, because placement of MPR and TSP near the planting hole is very labor intensive.

The results of the farmyard manure incubation study (Chapter 7.4) show that 40 days of incubation could not lower pH to levels conducive for proton-induced dissolution of MPR. This is deduced from the high pH at the end of incubation (pH (H2O) = 8.35). There are virtually no protons at such high pH. The results of Ikerra et al. (1994) differ from our observations. In their incubation study they attributed an increase in P release to enhancement of MPR dissolution arising from organic acids released during the decomposition of farmyard manure. Although they did not indicate the pH at the beginning and end of incubation it is difficult to attribute the increase in P release to acid induced dissolution of the MPR given their known high pH (Kpomblekou-A and Tabatabai, 1994a; Wickama and Mowo, 1999). The high pH of farmyard manure like most organic manure makes them good soil acidity ameliorants rather than agents for lowering pH (Bessho and Bell, 1992; Wong et al., 1995; Wong et al., 1998).

Table 8.1 summarizes the results of three of the four field trials. The yields are those for 40 kg P (46.5 kg P per hectare for Trial 7.4) and 50 kg N per hectare. The table summarizes the main conclusions:

On the low pH Soil S3 MPR is as good as TSP.
On the high pH Soil S2 TSP is better than MPR.
The low yields in Trials 7.2 and 7.4 on Soil S3 are related to the low pH of the soil in those fields.

Table 8.1. Comparison of maize yields from the field trials.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Season</th>
<th>Soil S3</th>
<th>MPR</th>
<th>TSP</th>
<th>TSP-MPR</th>
<th>pH(KCl)</th>
<th>Soil S2</th>
<th>MPR</th>
<th>TSP</th>
<th>TSP-MPR</th>
<th>pH(KCl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>I</td>
<td>4.59</td>
<td>4.62</td>
<td>+ 0.03</td>
<td>4.9</td>
<td>4.20</td>
<td>5.28</td>
<td>+ 1.08</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>3.16</td>
<td>3.59</td>
<td>+ 0.43</td>
<td>3.32</td>
<td>3.31</td>
<td>- 0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>I</td>
<td>2.00</td>
<td>2.14</td>
<td>+ 0.14</td>
<td>4.4</td>
<td>5.38</td>
<td>5.94</td>
<td>+ 0.56</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>1.14</td>
<td>1.08</td>
<td>- 0.06</td>
<td>4.25</td>
<td>3.82</td>
<td>- 0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>I</td>
<td>2.40</td>
<td>1.98</td>
<td>- 0.42</td>
<td>4.4</td>
<td>5.11</td>
<td>5.53</td>
<td>+ 0.42</td>
<td>5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>2.00</td>
<td>1.90</td>
<td>- 0.10</td>
<td>4.00</td>
<td>3.99</td>
<td>- 0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>I</td>
<td></td>
<td></td>
<td>- 0.08</td>
<td></td>
<td>+ 0.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>II</td>
<td></td>
<td></td>
<td>+ 0.09</td>
<td></td>
<td>- 0.15</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Influence of spatial soil variability on the effectiveness of PR**

Studies on the effect of spatial variability on treatment effects (Chapter 6) were introduced in each of the field trials to try to isolate environmental from treatment effects. This was considered useful given the variability, commonly experienced in the tropics and its effects with respect to masking treatment effects. In our study spatial variability was observed in all the field trials and it was less in the second than in the first season because of the uniform management and the treatments applied. Using the Post-mortem Residual Analysis and the Nearest Neighbor Means we found that the techniques were capable of isolating environmental from treatment effects. This was more relevant in the larger than the smaller
General discussion

trials. Soil pH was the major factor in explaining the yield variation and it was not confounded with soil available P.

Implication of the study and future research proposals

Most Tanzanian farmers cannot afford the costly industrial P fertilizers. Consequently, cropping continues without P fertilization. This has led to soil fertility degradation and declining yields being experienced in almost all crops. This situation should be reversed. Our results have shown that Minjingu PR applied directly could be a cheaper alternative source of P to crops.

It is clear that the availability of protons is central in the dissolution of PRs, that high rates of PRs suppress their dissolution, that cowpea and pigeonpea are capable of taking up more MPR-P than maize and that maize P uptake from MPR can be improved in the presence of these legumes. Increasing P and Ca demand will increase PR dissolution. Therefore, acidifying plants and improved growth conditions enable PR use in soils with limited proton supply. The use of PRs on soils rather high in pH is possible when strategies are adopted that increase the PR dissolution capacity of the soil-plant-system and when appropriate combinations of MPR and soluble P sources coupled with proper application methods are adopted.

We therefore give the following recommendations:

(i) Farmers should adopt annual application of small amounts of MPR.
(ii) Combined application of MPR and TSP using the same application methods for both at least in the first season followed by application of small amounts of MPR in subsequent seasons.
(iii) The incorporation of cowpea and pigeonpea in the cropping system should be intensified in order to exploit their potential in utilizing the sparingly soluble MPR. When intercropping of legume with cereals is desired the choice of crops should ensure compatibility to minimize the adverse effects of competition. To ensure released protons act on MPR particles, small amounts of MPR should be placed close to the plant roots.
(iv) Improvement of other growth factors through balanced nutrition and improved management to trigger P demand. This will improve MPR dissolution in reaction to P concentration gradient.
(v) Minjingu Phosphate Company and the Agricultural Extension Department using the available research results should embark on a strategy to popularize MPR use among Tanzanian farmers. Establishment of demonstration plots managed by farmers and extension officers, use of leaflets and audio-visual facilities to show to farmers examples of successful use of MPR and training of extension staff on current research findings about the use of MPR are strategies that must be adopted.

Further research on MPR use should include:

(i) Intensive soil pH and pH buffer capacity analysis to identify soils with high potential for PR use.
(ii) Identification of more leguminous crops effective in rhizosphere acidification.
(iii) Indentification of compatible mixtures of legume and other crops suitable for intercropping.
(iv) Studies on the influence of spatial soil variability on treatment effects in all field trials. This should be preceded by assessment of spatial soil variability using for example, uniformity trials before the actual experiments start. The use of the Post-
Chapter 8

mortem Residual Analysis and Nearest Neighbor Means techniques as means of isolating environmental from treatment effects will allow a more correct interpretation of results from field trials.

(v) Studies on how farmers cope with variability in their fields in order to develop appropriate strategies in managing it profitably.
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**References**


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Summary

In Tanzania, P is one of the plant nutrients limiting agricultural production. Reasons put forward include low soil P availability and P fixation by soils. However, few farmers use industrial P fertilizers due to their high costs. Therefore, the Government has placed high priority in utilizing locally available phosphate rocks to address the problem of P nutrition in crops.

Minjingu phosphate rock is a reworked guano (bird droppings, feathers and bones), which was originally deposited on a rock outcrop in the formerly more extensive Lake Manyara some 100 km south west of the northern city of Arusha in Tanzania. With time the deposits were transformed in the alkaline lake waters into the phosphate beds found today. Minjingu phosphate rock (MPR) consists of a low carbonate substituted fluorapatite also known as francolite. It is considered an effective P source suitable for direct application when used in the right agro-ecological conditions.

In acid soils with sizeable P and Ca sinks the availability of MPR is assured. In soils deficient in P but rather high in pH, strategies are required to make the PR available. Very little is known on the use of MPR under such conditions, and the work described in this thesis was initiated to partly fill that knowledge gap. It has been directed towards identifying soils and conditions where MPR can be used effectively.

The main objectives of the study were: (i) to increase the understanding of the factors responsible for PR dissolution in soils and availability of PR to crops, (ii) to investigate the possibility of extending the use of PR in soils less favorable for PR dissolution, and (iii) to study the influence of spatial soil variability on the effectiveness of PR. Knowledge on the various factors influencing the effectiveness of MPR will ensure its optimal exploitation in improving crop production in Tanzania. The research consisted of laboratory, greenhouse and field experiments.

In a laboratory experiment, answers were sought on the amounts of P that could be extracted from PRs under conditions of limited and unlimited supply of protons, and the influence of shaking time on extractable P (Chapter 3). Next, the phosphate release potential of a Rhodic Ferralsol from Tanga was examined, and also the response of maize to different PRs on this soil with low proton supply potential. These experiments were necessary in planning our field research on enhancing the effectiveness of MPR and on extending the use of PRs to soils with low proton supply potential. Differences between the PRs manifested most at low HCl concentration, and were greatly influenced by their content of CaCO₃. Apparently the CaCO₃ present as impurities in the PRs and having a high affinity for protons, easily dissolved and consumed protons that would have been available for the dissolution of calcium phosphate in the PR particles. Therefore, Minjingu and Khouribga, with relatively high CaCO₃ content, were classified as ‘hard’, and Mali PR with relatively low CaCO₃ content as ‘soft’. Agronomically, the three PRs were not different when applied to maize in the soil whose proton supply was low. They all had, compared to triple super phosphate a substitution value of 0.1. High rates depressed the agronomic effectiveness and substitution value of the hard PRs, because the large quantities of accompanying CaCO₃ consumed more protons. Hence the substitution value of a PR cannot be considered as a product characteristic.

When confronted with soils low in protons (high pH soils), mechanisms to optimize or produce more protons should be adopted. Some plants, particularly legumes relying on biological nitrogen fixation for their source of N, are known for their ability to acidify the rhizosphere. The extent of acidification by growing plants utilizing atmospheric N is a
function of their dry-matter production. This was tested for cowpea and pigeonpea (grain-legumes) and maize in Chapter 4.1. Increase in dry-matter production had negligible effect on the pH of the soil. We attribute this to the high pH buffer capacity of the soil.

Rhizosphere acidification by legumes could improve PR availability, and non-legumes intercropped with such legumes might benefit in terms of its P nutrition. These hypotheses were tested in a pot experiment by intercropping maize with either cowpea or pigeonpea (Chapter 4.2). Also in this experiment, the dissolution and hence agronomic effectiveness of MPR was depressed, when high rates were used. Cowpea and pigeonpea utilized MPR-P better than maize thus confirming the first hypothesis. The uptake of MPR-P by maize was improved when it was intercropped with the legumes, confirming the second hypothesis. The high competitiveness of the legumes, however, depressed maize growth and this was more important with cowpea than with pigeonpea. For the choice of which crops to grow in an intercropping system, one should therefore look into the compatibility of the crops in question to minimize the depressive effect of one crop on the other.

The proton supply potential of a soil dictates the optimum amount of PR that can be applied before high rates work to the disadvantage of the PR. Crops capable of acidifying their rhizosphere will increase this optimum. This hypothesis was tested in Chapter 5.1 by studying the response curves of maize, cowpea and pigeonpea on a relatively low and relatively high pH Rhodic Ferralsol under greenhouse conditions. A stronger response to MPR was observed in the low pH compared to the high pH soil. Only maize treated with MPR showed a possible optimum of between 31 to 62 mg P kg$^{-1}$ soil. For maize and cowpea a certain maximum dry-matter production was found, being a plateau rather than an optimum. Maize and cowpea took up more P than was required. Statistically significant interactions were found for the legumes, but not for maize; for cowpea between soil and type of P and between soil and rate of P application, and for pigeonpea between soil and rate of P application. This indicates that the choice of type and rate of P-fertilizer is more depending on soil type in the case of legumes than in the case of maize.

Given the strong influence soils have on P fertilizers (Chapter 5.1) it was considered necessary to study the response to MPR and TSP in more soils with different combinations of pH and available P. This is covered in Chapter 5.2. In a pot experiment with maize, nine soils were used together forming the combinations of three levels of pH and three levels of available P. Response to P was only observed where soil available P was low. At low pH, difference between MPR and TSP in terms of P uptake response was narrow compared to that at medium and high pH. This we attribute to a higher MPR solubility at low than at high pH. At low pH, a better utilization of absorbed P was found from MPR-P than from TSP-P, which we attribute to a liming effect of MPR.

From the preceding greenhouse experiments it can be concluded that (i) proton supply is important for PR dissolution, (ii) high rates of PR reduce its effectiveness, and (iii) reactivity based on acid extraction does not give a correct assessment of a PR's agronomic effectiveness, because soil and plants too influence the effectiveness of PR. In the greenhouse one is often confronted with small soil volumes implying that the contact between soil and fertilizer particles is intensive and roots exploit almost all the soil. Greenhouse trials may therefore sometimes give a distorted picture of the efficacy of PRs in practice. The performance of PRs under practical conditions needs to be assessed in the field because there the soil volume is relatively large and also factors beyond the control of man can influence the effectiveness of PRs. We therefore established a series of trials in the field (Chapter 7) on a low and a high pH Rhodic Ferralsol to
study a range of factors that can be exploited in enhancing the effectiveness of MPR. Maize was the test crop. In all these trials, the effects during the first as well as during the second season after application of the fertilizers were studied.

To start with, we have tried to establish appropriate rates and application method of MPR or TSP (Chapter 7.1). In the low pH Soil S3 the method of P application was not important. In the high pH Soil S2 the method of P application was important particularly for the poorly soluble MPR. The best method for both MPR and TSP was broadcast application. In this soil (Soil S2) when either source of P was applied in the hole, yield response was lower than when it was broadcast and response to TSP was 3 times more than to similarly applied MPR. The optimum rate of application in the low pH soil was 38 kg P ha\(^{-1}\) for MPR and 49 kg P ha\(^{-1}\) for TSP. In the high pH soil, the optimum rate of P at the best method of application (broadcast) was 146 kg ha\(^{-1}\) for MPR and 123 kg ha\(^{-1}\) for TSP. The residual effects of MPR and TSP on maize grain yields were almost the same on both soils.

In Chapter 7.2 we tested the hypothesis that acidifying N fertilizers increase MPR effectiveness in two ways: through production of protons and through an increase in P requirement. The latter is a result of the improved growth by N addition. The influence of sulfate of ammonia on MPR effectiveness could not be confirmed. The possible cause was that the two fertilizers had not been mixed and applied at the same time and hence were not in contact with each other, possibly released protons could therefore not act on the MPR. Minjingu PR was applied at planting while sulfate of ammonia was applied six weeks after planting in accordance with local recommendations. The reasoning behind this advice is that early application of N fertilizers might lead to high N losses (via leaching) before peak crop requirement. In conclusion, there is little scope for improving MPR effectiveness through combined MPR-SA application.

The effectiveness of PR may be improved when mixed with soluble P sources. The method of application of such mixtures that will ensure optimum performance should be known. This is covered in Chapter 7.3 where different combinations of methods of application of MPR and TSP are studied. When the two were applied by the same method we observed best performance in the low pH soil whereas in the high pH soil the method of application of the mixture was not important. A stronger residual effect was obtained when TSP was applied in the planting hole (than when broadcast) in the low pH soil, while in the high pH soil this occurred when it was broadcast. It is concluded that farmers should opt for broadcast application because it is not as labor intensive as application in the planting hole.

In the literature, sometimes farmyard manure (FYM) is thought to have a role in enhancing PR effectiveness when the two are incubated. The underlying hypotheses are that (i) decomposing farmyard manure releases protons, (ii) organic anions could chelate Ca in the PR, and (iii) P demand increases because of growth promotion by manure resulting in a higher P concentration gradient around the roots. This was the basis of Chapter 7.4. We conclude that given the high pH of the incubated FYM-MPR mixture (the final pH at the end of 40 days of incubation was 8.35), proton induced dissolution of MPR could not take place. Both fertilizer materials had significant effects on maize grain yield. There was, however, no interaction between MPR and FYM indicating that the two were acting independently. Residual effects of MPR and TSP on maize grain yield were significantly positive on the high pH Soil S2 while the residual effects of FYM were negative on both soils.

Environmental factors can strongly influence treatment effects and completely mask the manifestation of a treatment effect. This inevitably leads to erroneous conclusions and
**Summary**

recommendations to farmers. The researcher needs to know spatial soil variability and must be able to eliminate its influence on treatment effects in order to equip the farmers with the necessary knowledge to use scarce and hence expensive resources profitably. Therefore aspects of spatial soil variability were introduced in all the field trials (Chapter 6). We used the Post-mortem Residual Analysis and the Nearest Neighbor Means to isolate environmental from treatment effects. This analysis proved useful especially in the large trials, but spatial variability was observed everywhere, even within plots. Especially soil pH was important in influencing maize yields. Yields were 4 tons per ha higher on soils with pH (KCl) around 5.3 than on soils with pH (KCl) around 4.3. If manure was applied, the yield difference due to this pH difference was about 2 tons per ha.

Finally in Chapter 8 the main results on enhancing the effectiveness of PR in Tanzania and some recommendations for future research are presented. It is concluded that the CaCO$_3$ content of Minjingu PR makes it a hard PR under laboratory extraction but agronomically it can be an effective source of P to plants. This will happen when applied in appropriate soils (low in pH, P and Ca), say in soils with pH (KCl) less than 5 and P-Olsen less than 4 mg kg$^{-1}$.

The efficacy of MPR can be increased by producing protons or increasing the P concentration gradient in the soil. Production of protons can be achieved by incorporating leguminous crops, but in practice this will be noticed only in soils with a very low buffer capacity. The chance that intercrops take advantage of the proton production by legumes is considered extremely poor, the more so because the intercrop is often out-competed by the legumes. In order to employ the intercrop option, one has to start to identify the compatibility of crops to grow in an intercropping system.

The presented research has shown that the effect of MPR on P-supply to crops cannot be increased with higher application rates; increasing the rates has a contrary effect because it decreases the solubility of MPR. In this context, it is recommended more research to be directed towards assessing the proton supply potential of different soils and the relation between this potential and the optimum MPR application rate.

Our study could not find any positive effect of manure on the availability of MPR; the effects of MPR and manure were just additive and there was no interaction effect.

Under field conditions one is often confronted with such large spatial soil variability that it cannot be exploited in practice. Moreover, only a part of variability in crop growth seems to be caused by soil heterogeneity; changing weather conditions also cause a lot of variance, while soil-weather interactions make the picture still more complex. Nevertheless it would be good to assess which spatial variability is relevant for crop growth, and to develop methods enabling the farmer to consider the relevant spatial soil variability in his management decisions.
Samenvatting

In Tanzania is fosfor (P) een van de nutriënten die de plantaardige landbouwproductie beperken. Oorzaken die hiervoor worden genoemd zijn de geringe P beschikbaarheid en de P vastlegging in de bodems. Toch gebruiken wegens de hoge kosten maar weinig boeren fosfaatkunstmest. Daarom heeft de regering hoge prioriteit gegeven aan de benutting van locaal voorkomend ruw fosfaat of natuurfosfaat voor de aanpak van het probleem van de fosfaatvoeding van gewassen.

Minjingu natuurfosfaat is een omgezette vorm van guano (bestaande uit uitwerpselen, veren, en skeletten van vogels) die oorspronkelijk was afgezet in het vroeger uitgestrekte Lake Manyara ongeveer 100 km ten zuidwesten van de stad Arusha in het noorden van Tanzania. Met verloop van tijd veranderden de afzettingen in het alkalische water van het meer in de fosfaat-bedden die heden ten dage daar gevonden worden. Minjingu natuurfosfaat (MPR = Minjingu Phosphate rock) bestaat uit een fluorapatiet waarin weinig carbonaat is gesubsstitueerd, ook wel bekend als francoliet. Het wordt beschouwd als een effectieve P bron die onder de juiste agro-ecologische omstandigheden geschikt is voor direct gebruik.

In zure gronden, waar gebrek is aan zowel fosfaat als calcium, is de beschikbaarheid van MPR gewaarborgd. In gronden met een tekort aan P en een tamelijk hoge pH, zijn echter speciale strategieën nodig om de PR (= phosphate rock) beschikbaar te maken. Er is zeer weinig bekend over de bruikbaarheid van MPR onder zulke omstandigheden. Het onderzoek beschreven in dit proefschrift werd geïnitieerd om een deel van die leemte in kennis op te vullen. Het was gericht op de identificatie van gronden en omstandigheden in Tanzania die effectief gebruik van MPR mogelijk maken.

De hoofddoelen van de onderhavige studie waren: (i) het inzicht te vergroten in de factoren die het oplossen van PR in de grond en de beschikbaarheid van PR voor het gewas controleren, (ii) te onderzoeken welke mogelijkheden er bestaan om het gebruik van PR uit te breiden naar gronden met minder gunstige eigenschappen voor het oplossen van PR, (iii) na te gaan wat de invloed is van de ruimtelijke variabiliteit in de bodem op de effectiviteit van PR. Kennis over de verschillende factoren die de effectiviteit van MPR beïnvloeden is nodig voor een optimale exploitatie ter verbetering van de gewasproductie in Tanzania. Het onderzoek werd uitgevoerd via laboratorium-, kas- en veldproeven.

In een laboratoriumproef werd nagegaan wat de invloed is van de zuurconcentratie (hoeveelheid H+) en de schudtijd op de hoeveelheid P die uit verschillende PRs geëxtraheerd wordt (Hoofdstuk 3). Verder werd in een kasproef onderzocht, hoeveel P geleverd kan worden door een Rhodic Ferralsol uit Tanga, en hoe mais in deze grond met een gering zuurleverend vermogen reageert op toediening van verschillende PR's. Deze experimenten waren nodig voor de planning van ons veldonderzoek naar de verhoging van de effectiviteit van MPR en naar mogelijke toepassing van MPR op gronden met een gering zuurleverend vermogen. Verschillen tussen de PRs kwamen het duidelijkst naar voren bij lage HCl concentraties en ze waren gerelateerd aan het gehalte aan CaCO3. Klaarblijkelijk loste het CaCO3, dat als onzuiverheid in de PRs aanwezig is en een grotere affiniteit voor protonen heeft dan apatiet, gemakkelijker op. Daarbij werden protonen verbruikt die anders beschikbaar zouden zijn geweest voor het oplossen van calciumfosfaat in de PR deeltjes. Op basis hiervan werden Minjingu en Khouribga met relatief veel CaCO3 gekwalificeerd als 'hard' en Mali PR met relatief weinig CaCO3 als 'zacht'. De drie PRs waren echter even effectief als P-bron voor mais in de grond met een gering zuurleverend vermogen. Alle hadden, vergeleken met tripelsuperfosfaat een 'vervangingswaarde' van 0.1. Hoge giften verlaagden de effectiviteit en de vervangingswaarde van de harde PRs, omdat door de grotere
Samenvatting

hoeveelheden CaCO₃ nog meer protonen werden weggevangen. Daarom kan de vervangingswaarde van een PR niet opgevat worden als een produktkarakteristiek.

In gronden met weinig protonen (hoge pH), moeten mechanismen worden geïntroduceerd om extra protonen te produceren. Sommige planten, in het bijzonder leguminosen die voor hun N-voorziening op biologische stikstofbinding aangewezen zijn, staan bekend om hun vermogen de rhizosfeer te verzuren. De mate van verzuring door groeiende stikstofbindingende planten is een functie van hun drogestofproductie. Dit is getest voor de peulvruchten koeienboon (Vigna unguiculata L.Walp.) en duivenerwt Cajanus cajan (L.Milsp.) en voor mais in Hoofdstuk 4.1. Verhoging van de drogestofproductie had een verwaarloosbaar effect op de pH van de grond. We schrijven dit toe aan de grote pH buffer capaciteit van de grond.

In Hoofdstuk 4.2 zijn de hypothesen dat (i) de rhizosfeerverzuring door leguminosen de beschikbaarheid van MPR verbetert en (ii) niet-leguminosen als tussengewas tussen zulke leguminosen daarvan voor hun P-voeding kunnen profiteren, getoetst in potproeven met mais als tussengewas tussen ofwel koeienboon ofwel duivenerwt. Ook in deze proef namen bij hoge giften de oplosbaarheid en de landbouw kundige effectiviteit van MPR af. Koeienboon en duivenerwt maakten beter gebruik van MPR-P dan mais en bevestigden daarmee de eerste hypothese. De opname van MPR-P door mais als tussengewas werd verbeterd t.o.v. mais in monocultuur, waarmee de tweede hypothese werd bevestigd. Door het sterke concurrentievermogen van de leguminosen, met name van koeienboon, werd echter de groei van mais als tussengewas onderdrukt. Bij de keuze van de hoofdgewas en tussengewas moet daarom gelet worden op het competitievermogen van de gewassen.

Bij toenemende giften van PR zijn steeds meer protonen nodig voor het oplossen van het CaCO₃ in de PR. Dit betekent dat het zuurleverend vermogen van een bodem de maximale hoeveelheid PR, die kan worden opgelost, bepaalt. Gewassen die hun rhizosfeer verzu ren kunnen dit maximum verhogen. Deze hypothese is getoetst in Hoofdstuk 5.1 door in een kasproef de opbrengstkrommen vast te stellen van mais, koeienboon en duivenerwt in twee Rhodic Ferralsols, met respectievelijk een relatief lage en een relatief hoge pH. De reactie op MPR was sterker in de grond met de lage pH. Alleen voor mais kon een optimale MPR-gift worden afgeleid en die lag tussen 31 en 62 mg P per kg grond. Bij mais en koeienboon werd een zekere maximale drogestofproductie bereikt; dit maximum een soort plateau en geen duidelijk optimum. Mais en koeienboon namen bij hoge giften meer P op dan strikt genomen nodig was, maar bij duivenerwt bleef de drogestofopbrengst toenemen bij toenemende P-opname. Er werden statistisch significante interacties gevonden voor de leguminosen maar niet voor mais: voor koeienboon tussen grondsoort en type en grondsoort en dosering van de P meststof, en voor duivenerwt tussen grondsoort en P-dosering. Dit wijst er op dat de keuze van type P-meststof en hoogte van de P-gift meer grondsoortafhankelijk is bij de leguminosen, dan bij mais.

Gelet op de invloed van de grondsoort op de werkzaamheid van P-meststoffen, (Hoofdstuk 5.1) werd het noodzakelijk geacht de reacties op MPR en TSP in meer gronden, verschillend in pH en beschikbaar P, te bestuderen. In de in Hoofdstuk 5.2 beschreven kasproef met mais als testgewas werden negen gronden gebruikt, die samen de combinaties vormden van drie niveaus van pH en drie niveaus van beschikbaar P. Een reactie van de maisopbrengst op P werd alleen gevonden in de gronden met laag beschikbaar P. Bij een lage pH, was het verschil in P-opname tussen MPR en TSP geringer dan bij een middelmatige en hoge pH. Dit schrijven we toe aan de betere oplosbaarheid van MPR op de gronden met een lage pH. Voorts werd, op de gronden met een lage pH, het opgenomen MPR-fosfaat in de plant beter
Samenvatting

benut dan het opgenomen TSP-fosfaat. Dit effect interpreteren we als een gevolg van de betere groeimomstandigheden, teweeggebracht door het bekalkingseffect van MPR.

Uit de voorgaande laboratorium- en kasexperimenten kan geconcludeerd worden dat (i) de voorraad protonen van groot belang is voor het oplossen van PR, (ii) hoge PR-giften de effectiviteit ervan kunnen verlagen, en (iii) de extractie met zuur geen correct beeld kan geven van de effectiviteit van de PR in de praktijk, omdat die ook door bodem en gewas beïnvloed wordt. Verder merken we op dat in kasproeven de hoeveelheden grond vaak gering zijn, waardoor het contact tussen grond en meststof intensief is en de wortels bijna de gehele grond kunnen exploiteren. Kasproeven kunnen daardoor een vertekend beeld van de effectiviteit van een PR in de praktijk geven. De werking van PRs onder praktijkmomstandigheden moet in het veld worden vastgesteld, omdat daar het volume aan grond relatief groot is, en bovendien factoren buiten de invloedssfeer van de mens mede van belang zijn voor de effectiviteit van PRs.

We hebben daarom een serie veldproeven uitgevoerd (Hoofdstuk 7) op twee gronden (Rhodic Ferralsols), een met een lage en een met een hoge pH, met mais als het testgewas. In al deze proeven ging het zowel om het effect van de meststof in het seizoen van de toediening als om het residuair effect in het seizoen daarna.

Om te beginnen probeerden we de meest geschikte niveaus en methoden van toediening van MPR en TSP vast te stellen (Hoofdstuk 7.1). De optimum gift van MPR in de grond met de lage pH was 38 kg ha$^{-1}$ P, terwijl die voor TSP 49 kg ha$^{-1}$ P bedroeg; in deze grond was de reactie op TSP in het plantgat drie keer zo sterk als die op MPR in het plantgat. In de grond met de hoge pH was de methode van toediening van belang voor MPR. Bij plaatsing in het plantgat werd geen goed resultaat verkregen en was de optimale gift 35 kg ha$^{-1}$ P, terwijl die voor breedwerpig strooien 146 bedroeg. De corresponderende optimum giften voor TSP waren 105 (plantgat) en 123 kg ha$^{-1}$ P (breedwerpig). De residuaire effecten van MPR en TSP waren ongeveer gelijk.

In Hoofdstuk 7.2 toetsten we de hypothese dat N-meststoffen met een verzurende werking op twee manieren de effectiviteit van MPR kunnen verhogen: door de productie van protonen en door een verhoging van de behoefte aan P. Dat laatste is een gevolg van de door de toediening van N verbeterde groei. De invloed van zwavelzure ammoniak op de effectiviteit van MPR kon niet worden bevestigd. De mogelijke oorzaak was dat de twee meststoffen niet gelijktijdig waren toegediend en dus ook niet met elkaar in contact kwamen; eventueel geproduceerde protonen konden daardoor niet goed met de MPR reageren. MPR was toegediend bij het zaaien en zwavelzure ammoniak weken daarna, conform de lokale praktijk. Dit wordt gedaan om te voorkomen dat vroeg toedienen van zwavelzure ammoniak leidt tot uitspoeling van N voor aanvang van de periode van maximale vraag naar N door het gewas. De conclusie is dat gecombineerde toediening van MPR en zwavelzure ammoniak weinig perspectief biedt als maatregel om de effectiviteit van MPR te verhogen.

De effectiviteit van PR kan mogelijk verhoogd worden door PRs te mengen met oplosbare P meststoffen. Daarbij is de methode van toediening van zulke mengsels van belang. De juiste methode van toediening van verschillende combinaties van MPR en TSP is het onderwerp van Hoofdstuk 7.3. In de grond met de lage pH zagen we het beste resultaat wanneer de twee meststoffen op dezelfde manier werden toegediend, terwijl in de grond met de hoge pH de methode van toediening niet van belang was. In de grond met de lage pH was het residuair effect het beste wanneer TSP geplaatst werd in het plantgat, terwijl in de grond met de hoge pH met breedwerpig strooien een beter residuair effect verkregen werd. Voor de praktijk kan geconcludeerd worden dat de boeren het best kunnen kiezen voor breedwerpig strooien, omdat dat minder arbeid kost dan plaatsing in het plantgat.
Samenvatting

In de literatuur wordt aan stalmest soms een rol toegekend in het bevorderen van de effectiviteit van PR wanneer de twee worden geïncubeerd. De onderliggende hypothesen zijn dan dat (i) bij de omzetting van stalmest door micro-organismen protonen vrijkomen, (ii) organische anionen chelaten vormen met het Ca in de PR, en (iii) de behoefte aan P toeneemt door de door de stalmest gestimuleerde groei en daardoor de P-concentratiegradiënt rondom de wortels verhoogd wordt. Deze veronderstellingen vormen de basis voor de veldproef beschreven in Hoofdstuk 7.4. We concludeerden dat gezien de hoge pH van het mengsel van geïncubeerde stalmest en MPR - de pH na 40 dagen incubatie was 8.35 - eventueel vrijgekomen protonen geen bijdrage hebben kunnen leveren aan het oplossen van MPR. Beide meststoffen hadden een significant effect op de maisopbrengst. Er werd echter geen interactie-effect van MPR en stalmest gevonden wat erop wijst dat de twee onafhankelijk van elkaar werkten. Het residuair effect van MPR en TSP op de maisopbrengst was significant positief, terwijl dat van stalmest negatief was.

Omgevingsfactoren kunnen een sterke invloed hebben op de behandelingseffecten en die volledig maskeren. Dat leidt onvermijdelijk tot verkeerde conclusies en aanbevelingen voor de boeren. De onderzoeker heeft kennis nodig van de ruimtelijke bodemvariabiliteit en moet in staat zijn om de invloed daarvan op de behandelingseffecten te elimineren om de boeren de juiste informatie te kunnen verschaffen over het best mogelijke gebruik van schaarze en dus kostbare hulpbronnen. Daarom werd in alle veldproeven aandacht aan de ruimtelijke bodemvariabiliteit besteed (Hoofdstuk 6). We gebruikten de zogenaamde ‘Post-mortem Residual Analysis’ en de ‘Nearest Neighbor Means’ methode om de omgevingseffecten van de behandelingseffecten te scheiden. Deze analyse bleek vooral nuttig in de grote proeven, maar ruimtelijke variabiliteit kwam overal voor, zelfs binnen de individuele veldjes. Vooral de pH was van belang. De opbrengst van mais van 4 ton per ha hoger op gronden met pH(KCl) rond 5.3 dan op gronden met pH(KCl) rond 4.3. Als stalmest was toegediend, was het opbrengstverschil ten gevolge van dit pH verschil ongeveer 1 ton per ha.

Tenslotte worden in Hoofdstuk 8 de belangrijkste resultaten met betrekking tot het verbeteren van de effectiviteit van PR besproken en enige aanbevelingen voor toekomstig onderzoek geformuleerd. Geconcludeerd wordt dat weliswaar het CaCO₃ gehalte van Minjingu PR een harde PR maakt in het laboratorium, maar dat in het veld MPR een effectieve bron van P voor de plant kan zijn. Dat is mogelijk in de daarvoor geschikte gronden (laag in pH, P and Ca), om de gedachte te bepalen in gronden met een pH(KCl) lager dan 5 en P-Olsen lager dan 4 mg/kg. De effectiviteit van MPR kan verhoogd door protonen te produceren of de P-concentratiegradiënt in de grond te vergroten. In principe zijn leguminosen in staat protonen te produceren, maar in de praktijk zal daarvan alleen in gronden met een zeer geringe buffercapaciteit iets te merken zijn. De kans dat tussengewassen tussen leguminosen kunnen profiteren van de zuurproductie van de leguminosen is dan ook zeer gering teachen, te meer omdat de positie van het tussengewas wordt verslechterd door de competitie met de leguminos. Wil men in dezen iets bereiken, dan moet begonnen worden met de identificatie van gewassen die geschikt zijn voor gebruik als tussengewas. Het hier beschreven onderzoek heeft aangetoond dat het effect van MPR op de fosfaatvoeding van het gewas niet versterkt kan worden door de gift van MPR te verhogen; verhoging van de gift werkt juist averechts doordat de oplosbaarheid van MPR dan gaat afnemen. In dit verband wordt aanbevolen meer onderzoek te verrichten naar de bepaling van het zuurleverend vermogen van de grond en de relatie tussen dat vermogen en de optimale MPR-gift. Van een gunstige invloed van stalmest op de beschikbaarheid van MPR was in ons onderzoek niets te constateren; de effecten van MPR en stalmest waren uitsluitend additief en er was geen interactie-effect.
In het veld wordt men geconfronteerd met zo’n grote variabiliteit op korte afstand dat daarmee in de praktijk niet te werken valt. Bovendien lijkt slechts een deel van de variabiliteit in de gewasopbrengst veroorzaakt te worden door bodemheterogeniteit; de veranderlijke weersomstandigheden veroorzaken ook veel spreiding terwijl de interacties tussen weer en bodem het beeld nog complexer maken. Desalniettemin zou het goed zijn om vast te stellen welke ruimtelijke bodemvariabiliteit relevant is voor het gewas, en om voor de boer methoden te ontwikkelen die hem als manager in staat stellen met de relevante ruimtelijke bodemvariabiliteit rekening te houden.
Curriculum vitae

Jeremias Mowo was born in Kilimanjaro, Tanzania on December 1st 1953 where he did both his primary and secondary education. After high school and a one-year military service at Mafinga National Service Central Training School and Makambako TPDF (Tanzania Peoples Defence Forces), he joined the University of Dar es Salaam, Morogoro campus graduating with honors in Agricultural Science in 1979. From 1979 to 1981 he worked as agronomist in cotton based agro-systems in Western Tanzania under the Ministry of Agriculture before joining Wageningen Agricultural University for a Masters degree in Soil Science between 1981 and 1983. Between 1983 and 1990 he continued his work as agronomist in Western Tanzania. In 1990 he was transferred to the National Soil Service in Tanga, where he was National Coordinator for Soil and Fertilizer Use research. In 1994 he was admitted to the Ph.D. sandwich program in the Department of Environmental Sciences, sub-Department of Soil Science and Plant Nutrition, Wageningen Agricultural University (now Wageningen University and Research Center). In 1998 he was appointed coordinator of the Lushoto benchmark site of the African Highlands Ecoregional Program. He has worked in various collaborative research networks including the network on Management of Vertisols in Africa under the International Board for Soil Research and Management (IBSRAM) and the Alley Farming Network for Tropical Africa (AFNETA) under the International Institute for Tropical Agriculture (IITA).
Appendices

Appendix 1. Profile description for Soils S1 to S3.

Soil S1

Profile: JGM-1
Project: RF/RG/93/002
Region: Tanga
District: Muheza
Location: About 500 m west of ARI residential house in MATI premises.
Elevation: 183 m.a.s.l.
Landform: Peneplain
Topography: Undulating to rolling. Slope: 2%; Convex.
Land use: Abandoned cashew plantation with dense grass and shrub vegetation.
Natural drainage class: Well drained.
Described by: Jumanne M. Shaka on 01-08-1994

Soils: Very deep, well drained, friable, clay

Ap 0 - 19 cm: dark reddish brown (2.5YR 3/4, dry), dark red (2.5YR 3/6 moist); clay; moderate, coarse and fine, subangular blocks; hard dry, friable moist, sticky and plastic wet; common, large and medium pores; many, coarse roots; clear and smooth boundary to

AB 19 - 31 cm: dark red (2.5YR 3/6, dry), dark reddish brown (2.5YR 3/4, moist); clay; moderate, coarse and fine, subangular blocks; slightly hard dry friable moist, sticky and plastic wet; common fine and medium pores; many, very fine and few coarse roots; diffuse and wavy boundary to

Bt1 31 - 48 cm: dark red (2.5YR 3/6, dry), reddish brown (2.5YR 4/4, moist); clay; moderate, medium and fine subangular blocky elements; slightly hard dry, friable moist, sticky and plastic wet; patchy, thin, cutans; many, very fine pores; many, very fine and few coarse roots; diffuse and wavy boundary to

Bt2 48-73 cm: Reddish brown (2.5YR 4/4, moist); clay; weak, fine, subangular blocky structural elements; very friable moist, sticky and plastic wet; patchy, thin, cutans; few, very fine pores; few very fine roots; diffuse and wavy boundary to

Bt3 73 - 110 cm: Dark reddish brown (2.5YR 3/4 moist; clay; weak, fine, subangular blocks; very friable moist, sticky and plastic wet; patchy, thin, cutans; very few, very fine pores; few fine and very few, very fine roots; diffuse and wavy boundary to

Bt4 110 - 162 cm: Dark reddish brown (2.5YR 3/4, moist); clay; weak, fine and medium, subangular blocky elements; very friable moist, sticky and roots.

Appendices

Appendix I continued.

Analytical data for Profile JGM-1 (Soil S1)*.

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<th>Ap</th>
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<td>BS (%)</td>
<td>62</td>
<td>34</td>
<td>37</td>
<td>41</td>
<td>34</td>
<td>43</td>
</tr>
</tbody>
</table>

na = not applicable

*Data differ slightly from the data presented before (Table 2.3) because of a slightly different sampling site.
Appendices

Appendix 1 continued.

Soil S2

Profile: JGM-2  
Project: ARF/RG/93/002  
Region: Tanga  
District: Muheza  
Location: About 30 m north of ARI residential house in MATI premises.  
Elevation: 180 m.a.s.l.  
Landform: Peneplain  
Topography: Undulating. Slope: 2%; Convex.  
Land use: Fallow with a dense grass and shrub vegetation.  
Natural drainage class: Well drained.  

Soil: Very deep, well drained, dark red clays with a thick compacted top soil (upper two horizons).  

Ap 0 - 24 cm: very dusky red (10R2.5/2) moist; sandy clay; firm moist, very sticky and very plastic wet; weak medium subangular blocks; many fine pores; many fine roots; clear smooth boundary to

Bw1 24 - 40 cm: dusky red (10R3/4) moist; clay; firm moist, very sticky and very plastic wet; weak medium subangular blocks; many fine pores; many fine roots; gradual smooth boundary to

Bw2 40 - 70 cm: dark red (10R3/6) moist; clay; firm moist, very sticky and very plastic wet; weak medium subangular blocks; many fine pores; common fine roots; diffuse smooth boundary to

BW3 70 - 150 cm: dark red (10R3/6) moist; clay loam; firm moist, sticky and plastic wet; weak medium subangular blocks; many fine pores; few fine roots.

Appendices

Appendix 1 continued.

Analytical data for Profile JGM-2 (Soil S2)¹.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth cm</th>
<th>Ap</th>
<th>Bt1</th>
<th>Bt2</th>
<th>Bt3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay %</td>
<td>45</td>
<td>54</td>
<td>56</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Silt</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>51</td>
<td>41</td>
<td>42</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Texture class</td>
<td>sand clay</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>pH H₂O : 2.5</td>
<td>5.9</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>pH KCl : 2.5</td>
<td>4.8</td>
<td>4.3</td>
<td>4.4</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Organic C mg kg⁻¹</td>
<td>17</td>
<td>7</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total N</td>
<td>1.5</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>C/N</td>
<td>11</td>
<td>10</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>P-Bray-I mg kg⁻¹</td>
<td>2</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
<td></td>
</tr>
<tr>
<td>CEC: (NH₄Ac) mmol(+)/kg⁻¹</td>
<td>91</td>
<td>87</td>
<td>51</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>&quot;</td>
<td>17</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>&quot;</td>
<td>13</td>
<td>8</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Exch. K</td>
<td>5.9</td>
<td>2.2</td>
<td>1.3</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Exch. Na</td>
<td>2.8</td>
<td>2.4</td>
<td>1.8</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>TEB</td>
<td>39</td>
<td>20</td>
<td>13</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>BS %</td>
<td>43</td>
<td>23</td>
<td>26</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>CEC clay mmol(+)/kg⁻¹</td>
<td>200</td>
<td>160</td>
<td>90</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

¹ Data differ slightly from the data presented before (Table 2.3) because of a slightly different sampling site.
Appendices

Appendix 1 continued.

Soil S3

Profile: JGM-3
Project: ARF/RG/93/002
Region: Tanga
District: Muheza
Location: About 400 m from Mzambaraoni village, 50 m off the road to Azimio.
Elevation: 180 m.a.s.l.
Landform: Peneplein
Topography: Undulating. Slope: 2%; Convex.
Land use: Fallow with a dense grass and shrub vegetation.
Natural drainage class: Well drained.

Soil: Very deep, well drained, dusky/dark red clays with a relatively thick topsoil. The upper part of the profile (Horizon 1 and 2) is compacted.

AP 0 - 23 cm dark reddish brown (2.5YR3/4) moist; clay; firm moist, very sticky and very plastic wet; moderately weak coarse subangular blocky; many fine and few medium pores; many fine roots; clear smooth boundary to

Bt1 23 - 34 cm dark red (10R3/6) moist; clay; hard dry, firm moist, very sticky and very plastic wet; moderately weak medium subangular blocks; many fine pores; many fine root; clear smooth boundary to

Bt2 34 - 70 cm dark red (10R3/6) moist; clay; soft dry, firm moist, very sticky and very plastic wet; weak medium subangular blocks; many fine pores; fine roots; diffuse smooth boundary to

Bt3 70 - 140 cm dark red (10R3/6) moist; clay; soft dry, firm moist, sticky and plastic wet; weak medium subangular blocks; many fine pores; common fine roots; slightly powdery.

Appendices

Appendix I continued.

Analytical data for profile JGM-3 (Soil S3)\(^1\).

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Ap</th>
<th>Bt1</th>
<th>Bt2</th>
<th>Bt3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth cm</td>
<td>0 - 23</td>
<td>23 - 34</td>
<td>40 - 60</td>
<td>100 - 120</td>
</tr>
<tr>
<td>Clay %</td>
<td>53</td>
<td>69</td>
<td>56</td>
<td>60</td>
</tr>
<tr>
<td>Silt %</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Sand %</td>
<td>43</td>
<td>29</td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>Texture class</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
<td>Clay</td>
</tr>
<tr>
<td>pH H(_2)O 1:2.5</td>
<td>5.3</td>
<td>4.5</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>pH KCl 1:2.5</td>
<td>4.8</td>
<td>4.1</td>
<td>4.8</td>
<td>4.4</td>
</tr>
<tr>
<td>Organic C mg kg(^{-1})</td>
<td>15</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total N mg kg(^{-1})</td>
<td>1.3</td>
<td>0.7</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>C/N</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>P-Bray-I, mg kg(^{-1})</td>
<td>1</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>CEC: (NH(_4)Ac) mmol(+)/kg(^{-1})</td>
<td>81</td>
<td>114</td>
<td>70</td>
<td>6.0</td>
</tr>
<tr>
<td>Exch. Ca mmol(+)/kg(^{-1})</td>
<td>11</td>
<td>4</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>Exch. Mg mmol(+)/kg(^{-1})</td>
<td>14</td>
<td>7</td>
<td>8</td>
<td>1.4</td>
</tr>
<tr>
<td>Exch. K mmol(+)/kg(^{-1})</td>
<td>7.2</td>
<td>1.8</td>
<td>1.2</td>
<td>0.04</td>
</tr>
<tr>
<td>Exch. Na mmol(+)/kg(^{-1})</td>
<td>4.0</td>
<td>1.5</td>
<td>3.9</td>
<td>0.24</td>
</tr>
<tr>
<td>TEB mmol(+)/kg(^{-1})</td>
<td>36</td>
<td>14</td>
<td>16</td>
<td>1.9</td>
</tr>
<tr>
<td>BS %</td>
<td>44</td>
<td>12</td>
<td>23</td>
<td>32</td>
</tr>
<tr>
<td>CEC clay mmol(+)/kg(^{-1})</td>
<td>150</td>
<td>170</td>
<td>130</td>
<td>10</td>
</tr>
</tbody>
</table>

\(^1\) Data differ slightly from the data presented before (Table 2.3) because of a slightly different sampling site.
Appendix 2. Details on the double pot technique.

The double pot technique (Janssen 1974, 1990) is based on the fact that plants can simultaneously take up nutrients from soils and from a nutrient solution. It is used in identifying nutrients which are in short supply in soil without using chemical analysis. Two pots are used, a top pot containing the soil to be studied and a bottom pot containing nutrient solution. The top pot has a gauze bottom through which roots pass to reach the nutrient solution below. The nutrient to be studied is omitted from the nutrient solution and growing seedlings can only take it up from the soil. In another set of pots the nutrient solution contains all nutrients (complete solution). The difference in growth between plants on complete solution and those on solution missing the nutrient under study is then a measure of the supply of that nutrient by the soil.

**Plant growth**

Growth is measured by the relative increase in plant size (analogous to relative growth rate) per unit of time. Plant size in this connection is defined as the sum of the lengths of the individual leaves. Leaf length is measured from the base to the apex (leaf and blade).

Relative increase in plant size (denoted by $R_s$) is derived as follows:

\[ R_s = \frac{1}{S} \frac{dS}{dt} \]

which for the period between $t_1$ and $t_2$ integrates to:

\[ R_s = \frac{(\ln S_2 - \ln S_1)}{(t_2 - t_1)}. \]

Where: $R_s$ is the relative increase in plant size per day.

S1 and S2 are plant size.

$t_1$ First measurement of plant size.

$t_2$ Second measurement of plant size.

**Sufficiency quotient.**

Sufficiency quotient (SQ) is the index used to express the difference in growth between plants on deficient and on complete nutrient solution and is derived as shown below.

\[ SQ = \frac{(R_s)_{E}}{(R_s)_{C}}. \]

where $SQ_E$ = sufficiency quotient for element E.

$(R_s)_{E}$ = the relative rate of increase in plant size day$^{-1}$ for plants on solution without E.

$(R_s)_{C}$ = the relative rate of increase in plant size day$^{-1}$ for plants on complete solution.

SQ is time dependant and differ from crop to crop. It also depends on the nutrient being studied. For maize when N and P are examined, the most appropriate time interval was between the fourth and the eighth leaf stages and the first measurement is done after the nutrient reserve in the seed is exhausted.
Appendices

Appendix 3. Composition of nutrient solution used in pot experiments.

<table>
<thead>
<tr>
<th>Nutrient salt</th>
<th>Concentration</th>
<th>Nutrient solutions</th>
<th>Milliliters stock solution per liter of nutrient solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>molarity</td>
<td>g L⁻¹</td>
<td>Nutrient solutions</td>
</tr>
<tr>
<td>Ca(NO₃)₂·4H₂O</td>
<td>2</td>
<td>472</td>
<td>1</td>
</tr>
<tr>
<td>KNO₃</td>
<td>1</td>
<td>101</td>
<td>2</td>
</tr>
<tr>
<td>NH₄H₂PO₄</td>
<td>1</td>
<td>115</td>
<td>1</td>
</tr>
<tr>
<td>MgSO₄·7H₂O</td>
<td>1</td>
<td>246.5</td>
<td>1</td>
</tr>
<tr>
<td>CaCl₂·6H₂O</td>
<td>1</td>
<td>219</td>
<td>-</td>
</tr>
<tr>
<td>KCl</td>
<td>1</td>
<td>74.6</td>
<td>1</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>1</td>
<td>174</td>
<td>-</td>
</tr>
<tr>
<td>NH₄NO₃</td>
<td>1</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Fe-EDTA</td>
<td>0.1</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Fe-citrate</td>
<td>0.1</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>Micronutrient mixture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₃BO₃</td>
<td>2.86</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>MnSO₄·4H₂O</td>
<td>2.03</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.06</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CuSO₄·5H₂O</td>
<td>0.16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(NH₄)₆Mo₇O₂₄·4H₂O</td>
<td>0.04</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
**Appendix 4.** Chapter 5.2. Average maize shoot dry-matter yield (g pot⁻¹) of the highest and lowest yielding pots per treatment. Data have been calculated per pot. (See Table 5.2.3).

<table>
<thead>
<tr>
<th>Soil pH (KCl)</th>
<th>Control</th>
<th>MPR, mg pot⁻¹</th>
<th>TSPg, mg pot⁻¹</th>
<th>TSPp, mg pot⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>62.5</td>
<td>125</td>
<td>62.5</td>
</tr>
<tr>
<td>4.1</td>
<td>3</td>
<td>1.01</td>
<td>1.17</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.76</td>
<td>2.70</td>
<td>2.85</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>1.87</td>
<td>1.98</td>
<td>2.14</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>1.88</td>
<td>1.95</td>
<td>2.17</td>
</tr>
<tr>
<td>4.9</td>
<td>3</td>
<td>1.95</td>
<td>1.49</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.22</td>
<td>1.36</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>1.81</td>
<td>2.23</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>1.66</td>
<td>1.69</td>
<td>1.53</td>
</tr>
<tr>
<td>6.2</td>
<td>3</td>
<td>1.43</td>
<td>1.47</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.46</td>
<td>1.55</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>1.63</td>
<td>1.83</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>1.51</td>
<td>1.62</td>
<td>1.74</td>
</tr>
<tr>
<td>Average over pH</td>
<td>3</td>
<td>1.46</td>
<td>1.38</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.81</td>
<td>1.87</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>1.77</td>
<td>2.01</td>
<td>1.87</td>
</tr>
<tr>
<td>General average</td>
<td></td>
<td>1.68</td>
<td>1.75</td>
<td>1.81</td>
</tr>
</tbody>
</table>
### Appendix 5. Chapter 5.2. Detailed contrasts for the ANOVA of shoot DM yield. (See Table 5.2.4).

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Degrees of freedom</th>
<th>Contrast SS</th>
<th>Mean Square</th>
<th>F value</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M vs T</td>
<td>1</td>
<td>0.108</td>
<td>0.108</td>
<td>1.137</td>
<td>0.2890</td>
</tr>
<tr>
<td>Rates MT</td>
<td>1</td>
<td>0.188</td>
<td>0.188</td>
<td>1.979</td>
<td>0.1622</td>
</tr>
<tr>
<td>MT * rate</td>
<td>1</td>
<td>0.058</td>
<td>0.058</td>
<td>0.611</td>
<td>0.4348</td>
</tr>
<tr>
<td>Tp vs Tg</td>
<td>1</td>
<td>0.015</td>
<td>0.015</td>
<td>0.158</td>
<td>0.6918</td>
</tr>
<tr>
<td>Control vs rest</td>
<td>1</td>
<td>0.237</td>
<td>0.237</td>
<td>2.495</td>
<td>0.1167</td>
</tr>
<tr>
<td>pH * fertilizer treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH/M vs T</td>
<td>2</td>
<td>1.063</td>
<td>0.531</td>
<td>5.589</td>
<td>0.0046</td>
</tr>
<tr>
<td>pH/rates MT</td>
<td>2</td>
<td>0.331</td>
<td>0.165</td>
<td>1.737</td>
<td>0.1796</td>
</tr>
<tr>
<td>pH * MT/rate</td>
<td>2</td>
<td>0.282</td>
<td>0.141</td>
<td>1.484</td>
<td>0.2306</td>
</tr>
<tr>
<td>pH/Tp vs Tg</td>
<td>2</td>
<td>0.106</td>
<td>0.053</td>
<td>0.558</td>
<td>0.5751</td>
</tr>
<tr>
<td>pH/control vs rest</td>
<td>2</td>
<td>0.530</td>
<td>0.265</td>
<td>2.789</td>
<td>0.0650</td>
</tr>
<tr>
<td>avP * fertilizer treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>avP/M vs T</td>
<td>2</td>
<td>0.879</td>
<td>0.440</td>
<td>4.632</td>
<td>0.0113</td>
</tr>
<tr>
<td>avP/rates MT</td>
<td>2</td>
<td>0.409</td>
<td>0.204</td>
<td>2.147</td>
<td>0.1205</td>
</tr>
<tr>
<td>avP * MT/rate</td>
<td>2</td>
<td>0.598</td>
<td>0.299</td>
<td>3.147</td>
<td>0.0640</td>
</tr>
<tr>
<td>avP/Tp vs Tg</td>
<td>2</td>
<td>0.565</td>
<td>0.282</td>
<td>2.968</td>
<td>0.0545</td>
</tr>
<tr>
<td>avP/control vs rest</td>
<td>2</td>
<td>0.159</td>
<td>0.080</td>
<td>0.842</td>
<td>0.4356</td>
</tr>
<tr>
<td>pH * avP * fertilizer treat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH/avP/M vs T</td>
<td>4</td>
<td>1.270</td>
<td>0.318</td>
<td>3.347</td>
<td>0.0119</td>
</tr>
<tr>
<td>pH/avP/rates MT</td>
<td>4</td>
<td>0.433</td>
<td>0.108</td>
<td>1.137</td>
<td>0.3410</td>
</tr>
<tr>
<td>pH/avP * MT/rate</td>
<td>4</td>
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M = MPR  
T = TSP (Tg = TSP granular, Tp = TSP powder)  
avP = Available P
Appendix 6. Chapter 7.2. Average observed and corrected (for NNM) maize grain yield in t ha\(^{-1}\). N and P rates are in kg ha\(^{-1}\). CAN = Calcium ammonium nitrate, SA = Sulfate of ammonia.

6A. Soil S3, First season

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Appendices

Appendix 6 continued.

6C. Soil S2, First season

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163
### Appendix 6 continued.

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